California Hydrogen Business Council

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

Hydrogen Safety Considerations for California

October 2025

Table of Contents

List of Abbreviations

AEM	Anion Exchange Membrane
AHJ	Authority Having Jurisdiction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CARB	California Air Resources Board
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CHBC	California Hydrogen Business Council
CHS	Center for Hydrogen Safety
CSA	CSA Group
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIGA	European Industrial Gases Association
EPA	Environmental Protection Agency
ESD	Emergency Shutdown Device
ESS	Emergency Shutdown System
FCEB	Fuel Cell Electric Bus
FCEV	Fuel Cell Electric Vehicle
FCPM	Fuel Cell Power Module
FERC	Federal Energy Regulatory Commission
FMCSR	Federal Motor Carrier Safety Regulations
FMVSS	Federal Motor Vehicle Safety Standards
GH_2	Gaseous hydrogen
HSP	Hydrogen Safety Panel
IBC	International Building Code
IFC	International Fire Code
ISO	International Standards Organization
LFL	Lower Flammable Limit
LH_2	Liquid hydrogen
MEGC	Multi-Element Gas Container
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration

OSHA	Occupational Safety and Health Administration
PHA	Process Hazards Analysis
PHMSA	Pipeline and Hazardous Materials Safety Association
PRD	Pressure Relief Device
PSM	Process Safety Management
RBPS	Risk-Based Process Safety
SAE	Society of Automotive Engineers
SMR	Steam-Methane Reformation
TPRD	Thermally-Activated Pressure Relief Device
UN GTR	United Nations Global Technical Regulation
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
ZEMU	Zero-Emissions Multiple Unit

Summary

Hydrogen is increasingly recognized as a key clean energy fuel. While it is new to many, it has been used safely in industrial applications for a century. The current shift toward broader adoption introduces hydrogen to new stakeholders. These include policy makers, permitting officials, first responders, and the general public, who have limited experience with the fuel. This transition presents both opportunities and challenges, particularly in ensuring that safety knowledge is effectively communicated.

Hydrogen, like other common fuels such as gasoline, propane, and natural gas, is flammable. However, the general public may not be as familiar with hydrogen, which can influence perceptions and reactions to initial incidents. A notable safety failure could hinder hydrogen's acceptance. It is essential to recognize that all fuels pose inherent risks requiring specific safety practices to mitigate them. For example, in industrial settings such as chemical plants, hydrogen has been safely managed for decades by following best practices. Applying established safety practices to new applications and sectors will aid in gaining wider public acceptance of hydrogen.

This document reviews various hydrogen production methods and applications, alongside general safety practices designed to address risks similar to those associated with other fuels. The study finds that the key challenge in moving toward hydrogen use is not related to the fuel itself but to limited knowledge regarding safe management.

It is important for organizations within the hydrogen sector to focus on safety in order to maintain public confidence and benefit over time. This includes sharing expertise between experienced personnel and new participants, offering training for officials and emergency responders, and incorporating safety considerations into technology development and regulatory approval processes.

1. Introduction

California has long been a leader in addressing environmental issues and climate change. From establishing the California Air Resources Board (CARB) in the 1960s, to implementing legislation like the Global Warming Solutions Act of 2006 (AB 32) [1] and the 100 Percent Clean Energy Act of 2018 (SB 100) [2], the state has advanced policies to reduce air and climate pollutants for decades. This has resulted in sustained public and private sector actions to develop clean energy solutions compliant with the state's emissions standards. Clean hydrogen technologies have also emerged as core to a portfolio of solutions to achieve decarbonization policy goals, as well as improve local air quality.

Hydrogen has been used in industrial processes since the early 1900s. These early use cases are several degrees removed from the general public, and the lack of direct experience with the fuel contributes to a knowledge gap and misconceptions around hydrogen's existing uses and safety. This dynamic is changing due to efforts to expand hydrogen to new use cases, including through the buildout of a public hydrogen refueling network in California under AB 8 in 2013. Average consumers have had the ability to purchase and refuel hydrogen-power fuel cell electric vehicles for over a decade. Additionally, hydrogen distribution and use has become viable across several sectors, including for the electricity grid (power generation and energy storage) as well as heavy duty mobility applications.

With the opportunity to expand the use of hydrogen, there is a need to educate stakeholders, transfer expertise to newcomers, and create a strong, transparent, and inclusive safety culture.

1.1 Purpose of This Document

The California Hydrogen Business Council (CHBC) and Center for Hydrogen Safety (CHS) developed this document to summarize hydrogen's properties and risks compared to other energy resources. The document also provides application-based safety considerations and established standards and best practices to mitigate safety risks for the following:

- Production: steam-methane reforming (a process that produces hydrogen from natural gas), electrolytic (a method of producing hydrogen using electricity)
- Transmission and Distribution: dedicated hydrogen pipelines; blending in natural gas infrastructure
- Storage
- End-uses: on-road vehicles and refueling; direct hydrogen use for power generation with fuel cells

This document:

- Summarizes hydrogen safety risks and mitigations
- Educates newcomers examining hydrogen production, distribution, and use
- Addresses common misconceptions around new energy solutions like hydrogen
- Provides transparent, science-based information

Hydrogen, while a potential clean energy solution, is often misunderstood. Without clear, science-based information, concerns around hydrogen can increase. An overview document provides transparent data and information on risks, safety measures, and real-world performance. This report supports the expansion of hydrogen systems for energy, transportation, and industry, while fostering a safety culture to guide regulations and build public trust.

2. Methodology

The content presented in Section 3 through Section 5, and the Appendices, has been provided primarily by CHS [3]. Where appropriate, information from external sources has been referenced. All other material is drawn from CHS resources, including webinars, eLearning modules, and presentations.

As a recognized leader in hydrogen safety, CHS's mission is to provide guidance, education, and collaborative forums to enable the safe and transformative benefits of hydrogen. CHS serves as a global champion for hydrogen safety, fosters a vibrant and engaged safety community, and acts as a premier resource for applied hydrogen safety practices.

Much of the safety information in this document—along with other documents developed for CHS's internal use—have been supported or wholly created by the Hydrogen Safety Panel (HSP) [4]. Established in 2003, the panel supports the U.S. Department of Energy (DOE) commercialization of fuel cell technologies. The panel consists of 24 members with expertise from commercial, industrial, government, and academic sectors. The Panel's activities include reviewing equipment and facility designs, assessing risks and safety plans, and conducting site safety reviews. To date, the HSP has conducted over 700 project review activities, developed more than 250 FAQs, created 16 safety guidelines, and established over 100 best safety practices.

The scope of this document is intentionally broad. It is not designed to provide an exhaustive evaluation of every safety consideration in the hydrogen sector. Instead, it aims to:

- Illustrate the wide range of potential hydrogen safety considerations.
- Outline the fundamental regulatory frameworks that underpin hydrogen safety practices.

In addition, selected production methods and applications—identified by CHS and CHBC as particularly relevant to California's hydrogen landscape—are given greater emphasis throughout the report.

3. Hydrogen Safety and the Path to Adoption

Hydrogen is increasingly recognized as a clean energy fuel and used in many new and existing applications, but it is not new. For over a century, hydrogen has been used safely in industrial applications. What is new is the expansion of hydrogen into the broader energy landscape and into expanded markets, bringing it to the attention of new stakeholders—emerging technology developers, regulatory authorities, emergency responders, and the general public.

As new applications emerge, the transfer of safety knowledge and best practices from experienced users to newcomers becomes essential. Unlike legacy fuels such as gasoline and natural gas, hydrogen does not benefit from widespread familiarity or public tolerance for early mistakes. A single high-profile incident has the potential to slow adoption significantly.

Hydrogen's limited public track record contrasts with society's century of experience handling gasoline and natural gas. Incidents involving those fuels are common, yet broadly accepted. For example:

- **Gasoline fueling stations (2014–2018):** An average of 4,150 fires per year in the U.S., resulting in three civilian deaths, 43 fire injuries, and $30 million in property damage annually (NFPA) [5].
- **Highway vehicle fires (2023):** Roughly 208,500 incidents per year for all vehicle fuel types, leading to 367 deaths, and 1,100 injuries (NFPA) [6].

These statistics underscore an important point: familiarity with a fuel does not eliminate risk. However, experience demonstrates that outcomes improve through education, practice, and awareness.

3.1 National Data

Public acceptance of hydrogen is a critical enabler for scaling hydrogen infrastructure. To better understand baseline awareness and attitudes, CHS conducted a national and Hydrogen Hub State survey in late 2024, administered by the Marist Poll. The results provide insight into how the public perceives hydrogen's role in the U.S. energy transition.

The survey differentiated between adults nationally and those adults residing in the 16 federally designated Hydrogen Hub States (Hub State Adults). At the time of data collection, these states were anticipated to receive significant federal investments for hydrogen deployment. The interpretation of survey results should consider the broader context of policy uncertainty associated with the transition to a new presidential administration.

The following key findings were derived from the survey results:

- **Attitudes Toward Hydrogen**
  - 65% of Hub State Adults (including Californians) and 62% of adults nationally say they are comfortable with hydrogen powering homes and businesses.
  - California Hub residents report the highest comfort levels (70%) with hydrogen energy.
  - Awareness, however, remains uneven: while 52% of Californians have heard a great or good amount about hydrogen, 61% of Hub State Adults and 65% of Americans overall have heard little or nothing.
  - Of National Adults who reported being concerned about hydrogen as an energy source, only 2.4% mentioned the Hindenburg as their primary association.
- **Public Interest**
  - Strong majorities—79% of Americans and 83% of Hub State Adults—want to learn more about hydrogen, with safety as the top topic of interest.
  - Californians, with higher awareness and stronger renewable preferences, represent a particularly engaged and informed audience.

These survey results indicate both momentum and barriers for hydrogen adoption. While awareness remains limited nationally, strong public interest in learning more about hydrogen—particularly regarding safety—suggests a clear opportunity for federal and state programs to build trust through education and transparent safety practices. Subsequent sections of this report examine technical safety considerations and best practices that can support the promotion of safety awareness.

3.2 Hydrogen's Unique Properties

Hydrogen's properties demand distinct design considerations and mitigation strategies.

- **Small molecule size:** Leaks more easily than other gases.
- **Flammability:** Easily ignited and releases significant energy.
- **Dispersion:** Highly buoyant, disperses quickly in open air, but can accumulate in enclosed or poorly ventilated areas.
- **Material interactions:** Can embrittle metals and distort plastics.
- **Storage:** Requires very high pressures in gaseous form or very low temperatures in liquid form to facilitate extended operating times.

Considering these properties, the public knowledge of safe handling procedures is, perhaps, one of the more significant challenges with its use. Apart from legacy industrial applications, hydrogen is unfamiliar to many individuals, and initial mistakes may impact future perceptions of its use. Many hydrogen-related incidents are attributed to human error, which can be reduced through proper training and knowledge sharing.

To reduce risks and support growth, the hydrogen ecosystem must prioritize safety across all levels. This includes:

- **Knowledge transfer:** Sharing expertise from long-standing industrial users with new market entrants.
- **Training programs:** Preparing user groups, Authorities Having Jurisdiction (AHJs), and first responders.
- **Early integration:** Embedding safety considerations into technology development, design, and permitting.

Safety should not be treated as a regulatory obligation but as a foundation for trust, resilience, and success. A strong safety record builds credibility with regulators, investors, customers, and the public. It also improves efficiency, strengthens workforce morale, and creates a competitive advantage in the marketplace.

3.3 Conclusion

Hydrogen offers tremendous potential as a clean energy fuel, but its future depends on a culture of safety. By embedding safety into every level of the value chain, the industry can build trust, reduce risks, and secure the long-term success of hydrogen technologies.

4. Hydrogen Properties and Comparison to Other Fuels

Hydrogen's unique technical properties—such as its high buoyancy, wide flammability range, and low ignition energy—require specialized attention. Challenges like undetectable leaks, invisible flames, and rapid gas dispersion necessitate tailored engineering solutions. In addition, hydrogen's interaction with materials can lead to embrittlement, making the selection of compatible components critical for system longevity and integrity. However, similar to hydrogen, all other fuels also have their own properties that require standards to enable safe handling and use.

Because gasoline, natural gas, and propane are widely used and familiar, comparing their properties and hazards with hydrogen provides valuable context. These comparisons help policymakers, industry, and the public make informed decisions, ensuring hydrogen is evaluated realistically alongside established fuels.

Table 1: Comparison of Hydrogen with Other Fuels

Property	Hydrogen	Gasoline	Natural Gas	Propane
Buoyancy Relative to Air	14x Lighter	Vapor is 3.75x Heavier	2x Lighter	1.5x Heavier
Flammability Range in Air (%)	4 – 75	1.4 - 7.6	5 - 15	2.1 - 10.1
Most Easily Ignited Mixture in air	29%	2%	9%	~4%
Minimum Ignition Energy[1] (mJ)	0.02	0.8	0.28	0.25
Flame Temperature	4,010˚F	3,590˚F	3,562˚F	3,596˚F
Energy by Weight	2.8x > Gasoline	43 MJ/kg	~1.2x > Gasoline	~1.05x > Gasoline
Energy by Volume (liquid form)	4x < Gasoline	120 MJ/Gallon	1.5x < Gasoline	~1.3x < Gasoline
Toxicity	Non-Toxic	Toxicity Varies depending on additives	Toxicity Varies depending on additives	Toxicity Varies depending on additives

To mitigate risks, every hydrogen-related project must begin with a comprehensive hazard analysis. Safety systems, including effective ventilation, real-time leak detection, emergency shutdown protocols, and strategically placed sensors, are vital. Equally

[1] Minimum Ignition Energy at optimal (stoichiometric) ratio.

important is the ongoing inspection and maintenance of materials and equipment to ensure continued performance when exposed to hydrogen.

The following table highlights hydrogen's specific properties, related hazards, and examples of safe facility and system design to mitigate risks.

Table 2: Hydrogen Properties, Hazards, and Mitigation Strategies

	Hydrogen's Property/Hazard	Examples of Beneficial Mitigation Strategies
Flammability	Wide flammability range, between 4%-75% in air.	• Keep concentrations in air below the Lower Flammable Limit (LFL) of 4%. • Use in well-ventilated spaces to dilute potential leaks. • Vent or exhaust hydrogen directly outdoors.
Ignition Behavior	Hydrogen ignites very easily (ignition energy ~0.02 mJ, is about 50 times less than a static electricity spark). *For this reason, the ignition source for many hydrogen incidents cannot be reliably identified.*	• Maintain hydrogen levels below the LFL. • Eliminate ignition sources (open flames, sparks, static). • Ground and bond equipment to prevent static buildup.
Explosions	Hydrogen's high burning velocity increases explosion severity.	• Keep concentrations below the LFL. • Allow free space around hydrogen equipment. • Reduce congestion near hydrogen systems to limit damage potential.
Autoignition	High-pressure hydrogen releases can ignite without an external spark.	• Minimize fittings and connections to reduce leaks.
Buoyancy and Size	Hydrogen rises quickly in open air but can accumulate indoors. It leaks easily through small openings.	• Provide ventilation: air inlets low, exhaust outlets high. • Install leak detection and automatic shutoffs. • Select materials resistant to hydrogen permeation. • Place systems in large, open areas.
Stored Energy	High-pressure hydrogen contains significant stored	• Follow compressed gas handling standards.

	energy. Vessel rupture can cause severe damage.	• Use properly designed pressure relief systems.
Cryogenic Liquid Hydrogen	Must be kept at –423°F. Extreme cold causes frostbite and can freeze air, creating oxygen-enriched environment (fire risk) and other embrittlement effects.	• Use non-combustible flooring (e.g., concrete or gravel). • Restrict ignition sources near cryogenic zones. • Use compatible materials for repeated cryogenic exposure. • Cryogenic leaks will create white vapor clouds (indirect leak indicator).
Hydrogen Flames	Hydrogen burns with an almost invisible flame and emits low amounts of radiant heat.[2] Higher flame temperatures than other common fuels.	• Use UV/IR flame detectors or thermal imaging cameras. *Flames may be visible at night or when hydrogen is burning with other materials such as plastics, oils, gasoline, etc.*
Leaks	Hydrogen is colorless, odorless, and tasteless, making leaks more difficult to detect.	• Install fixed gas detectors at likely leak points and exhausts. • Use handheld or personal monitors. • Monitor piping flow/pressure for anomalies. • Employ pipe-in-pipe designs with annulus monitoring. • Use automatic shutoff/isolation systems. • Add flow-restricting orifices to minimize leak rates. *Use audible cues in high-pressure gaseous systems. The hissing sound of escaping gas can indicate a leak.*
Embrittlement	Hydrogen diffuses into certain metals, causing embrittlement and failure.	• Use tested, compatible materials for hydrogen service. • Select materials carefully based on pressure, temperature, and service history.

[2] Hydrogen burns as a near-invisible flame with low amounts of radiant heat due to the lack of carbon in the combustion reaction. Radiant heat is the heat that can be felt when standing near a flame.

4.1 Explosion Risk

Hydrogen exhibits combustion characteristics that can significantly increase the severity of incidents.

Hydrogen has a high burning velocity, much higher than that of other fuels. A high burning velocity means that hydrogen-air mixtures burn rapidly, increasing the potential for explosions and high overpressures. In some cases, combustion can turn into a detonation, which is an explosion where the flame travels faster than the speed of sound, creating powerful shock waves.

Hydrogen ignition events contain more energy than that of other fuels and are more likely to result in damaging pressure waves due to its high flame speed. For example, debris from a hydrogen incident can be projected much farther from the source than in comparable events with propane or natural gas.

Delayed ignition presents a scenario that requires greater caution. If hydrogen is allowed to accumulate without ignition, especially in confined spaces, the eventual ignition can be highly destructive. The accumulated gas can ignite all at once, leading to high overpressures and the potential for detonation.

The risk of explosion is addressed by incorporating safety systems such as emergency shutdown systems and ventilation to reduce leaks to less than the LFL. Providing free and open space around hydrogen equipment allows leaks to dissipate quickly, preventing ignition. It also reduces the magnitude of ignition events by allowing generated pressure waves to dissipate without being further amplified due to surrounding structures or equipment.

4.2 Ignition Characteristics

Hydrogen requires significantly less energy to ignite than other fuels. A weak ignition source that might fail to ignite natural gas or gasoline can readily ignite hydrogen. This low ignition energy increases the likelihood of unintentional ignition when flammable mixtures are present.

For conventional fuels like gasoline, natural gas, and propane, the most easily ignited mixture occurs close to the LFL. Hydrogen behaves differently: its most easily ignited concentration is about 29% in air, well above its LFL. Safe facility design aims to keep hydrogen concentrations below the LFL. In practice, hydrogen dilutes rapidly and more commonly results in ignition at concentrations near the LFL, producing lower overpressures and less damage than ignition at 29%.

4.3 Flame Temperature and Radiant Heat

Pure hydrogen flames are nearly invisible in daylight because they contain no carbon. For the same reason, they emit very little radiant heat, which is the heat you feel when standing near a fire. Note that flames from hydrogen-related incidents are often made visible by other materials burning alongside the hydrogen, such as the combustible materials of a car, or contaminants like dust.

Hydrogen has the highest flame temperature among the compared fuels. In contrast with flames produced by gasoline, propane, or natural gas, which generate considerable radiant heat detectable from a distance, hydrogen's heat is largely concentrated within the flame. Consequently, while hydrogen flames have a higher temperature, the result is that the heat from hydrogen fires may only be noticeable when in close proximity.

4.4 Odorization and Behavior during Leaks

Gasoline vapors and propane are heavier than air and tend to accumulate near the ground, creating hazards that can be difficult to disperse. Natural gas is lighter than air but disperses relatively slowly. Hydrogen, by contrast, is much lighter than air and disperses rapidly, which can reduce the duration of flammable cloud hazards in open environments.

Unlike natural gas, hydrogen is not currently odorized for two primary reasons:

1. **Fuel cell contamination:** Conventional odorants, such as the sulfur-containing mercaptans used in natural gas, can poison fuel cell catalysts, dramatically degrading performance and leading to premature failure of the equipment.
2. **Dispersion mismatch:** Because hydrogen is exceptionally light and diffuses rapidly, many candidate odorants will not be able to disperse along with the hydrogen gas, reducing their effectiveness.

Fixed and portable detectors are used to identify leaks in lieu of odorants.

4.5 Conclusion

Compared with gasoline, propane, and natural gas, hydrogen disperses quickly outdoors, which can reduce some hazards, but it is also easier to ignite and carries more energy by weight. These differences highlight why direct comparisons are critical for evaluating hydrogen safety.

Further information on hydrogen properties and hazards can be found in ***Appendix A***, while detailed descriptions of mitigation strategies can be found in ***Appendix B***.

5. Application-based Safety Considerations and Review of Standards and Best Practices to Mitigate Risks

5.1 Production

As hydrogen deployment accelerates across sectors, it is essential to understand how safety practices and regulatory frameworks apply to the production of hydrogen. This section outlines key safety considerations and relevant standards for two common production methods: electrolysis and steam-methane reforming (SMR).

5.1.1 Hydrogen Production Overview

In general, hydrogen is not freely found in nature and must be separated from other compounds—such as water or hydrocarbons—through energy-intensive processes.[3] There are many ways to produce hydrogen, each with distinct safety profiles and technical requirements. Production methods range from hydrogen sourced from coal gasification ("brown hydrogen") to electrolysis sourced with energy from renewables ("green hydrogen"), which is often considered the preferred approach for hydrogen production in the context of decarbonization.

While multiple production pathways exist, this report focuses on:

- Electrolysis – increasingly used in clean hydrogen projects.
- SMR – the dominant production method in the U.S. [7]

5.1.2 Electrolysis

What is Electrolysis?

- Process that uses electricity to split water into hydrogen (fuel) and oxygen (byproduct).
- Several technologies are available: alkaline (mature), proton exchange membrane (PEM, efficient and high-purity), solid oxide (high-temperature, emerging technology), and anion exchange membrane (AEM, still in development).
- Increasingly used for clean hydrogen production powered by renewable electricity.

[3] There is new information available that suggests there may be deposits of geological hydrogen that occur naturally.

Key Hazards

- Gas crossover: hydrogen and oxygen streams can mix, creating explosion risk if concentrations exceed flammability limits [8].
- Startup and upset conditions: higher risk periods when equipment or membranes may not perform as designed.
- Electrolyte handling and exposure: electrolyte can be corrosive and can cause injury to personnel or damage to equipment if not handled appropriately.

Mitigation Strategies to Promote Safety

- Integrated safety systems protect both the electrolyzer and the facility [9].
- Emergency shutdowns trigger automatically if leaks, fires, or equipment failures are detected.
- Protective measures include isolating hydrogen storage, cutting power, venting safely, and maintaining ventilation.
- Independent certification of electrolyzers ensures designs meet rigorous safety standards.
- Collaboration with permitting authorities, fire officials, and safety experts strengthens risk management.

Relevant Safety Codes and Guidelines

- NFPA 2 (Hydrogen Technologies Code) – main U.S. safety framework for hydrogen production and use.
- CSA/ANSI B22734 – certification standard for electrolyzer equipment (adopted from international ISO standard).
- NFPA 70 (National Electrical Code) and NFPA 497 – requirements for electrical safety in hazardous areas.
- OSHA/EPA: U.S. – process safety and accident prevention rules.
- Other standards (CGA, ASME, NFPA) provide detailed rules for piping, venting, and explosion prevention.

5.1.3 Steam-Methane Reforming

What is Steam-Methane Reforming?

- The primary industrial method for producing hydrogen today [7].
- Involves reacting natural gas with steam at high temperature and pressure.
- Half of the hydrogen is produced from the natural gas and half from water.
- Produces hydrogen but also generates significant carbon dioxide (CO_2).
- Currently accounts for the majority of global hydrogen production.

Key Hazards

- Fire and explosion risk: both hydrogen and methane are highly flammable.
- High-pressure and high-temperature systems: failures in equipment under these conditions can have severe consequences.

Mitigation Strategies to Promote Safety

- Engineering protections such as relief valves, leak detection, and explosion-resistant equipment design.
- Process controls including balanced steam-to-gas ratios and continuous temperature and pressure monitoring.
- Operational safety measures like worker training, maintenance protocols, and emergency response planning.

Relevant Safety Codes and Guidelines

- NFPA: Hydrogen, compressed gases, and industrial furnaces codes.
- API: Material safety in hydrogen-rich environments.
- OSHA/EPA: U.S. process safety and accident prevention rules.
- ISO/EIGA: International hydrogen production and plant safety standards.

5.2 Pipelines

5.2.1 Hydrogen Pipelines

Where are Hydrogen Pipelines?

- The U.S. currently operates about 1,600 miles of dedicated hydrogen pipelines, mostly along the Gulf Coast; California has about 27 miles [10], [11]. These systems have operated safely for decades.
- Expansion beyond industrial corridors requires new technical and regulatory frameworks.

Key Hazards

- High-pressure hydrogen can leak or rupture if welds or materials fail, creating significant fire and explosion risks.
- Compressor stations, valve manifolds, and other above-ground facilities must also meet local safety, zoning, and noise requirements.
- Public opposition and lawsuits over environmental approvals are often as big a risk to timelines as technical safety issues.

Mitigation Strategies to Promote Safety

- The Pipeline and Hazardous Materials Safety Association (PHMSA), an agency within the DOT, regulates hydrogen pipeline safety under 49 CFR Part 192 (gas) covering design, construction, operation, and maintenance. While PHMSA does not issue construction permits, operators must meet all requirements and are subject to audits, inspections, and compliance reviews.
- Operators must register with PHMSA and file entries in the National Pipeline Mapping System. Special permits are needed only when deviating from standards.
- The California Health and Safety Code contains requirements that govern the handling, storage, and transmission of hazardous materials.
- Cal/OSHA Code of Regulations Title 8, General Industry Safety Orders establishes minimum workplace safety standard, and Part 5473 includes language specific to hydrogen systems and storage [12].
- EPA requires Risk Management Plans (40 CFR 68) for facilities handling >10,000 lbs hydrogen, which may include associated compressor or storage facilities [13].
- OSHA PSM applies to facilities handling >10,000 lbs hydrogen, though stand-alone pipelines may be exempt [14].

- The U.S. Army Corps of Engineers (USACE) issues Clean Water Act Section 404 permits for wetlands and water crossings; The U.S. Fish and Wildlife Service (USFWS) ensures Endangered Species Act compliance.
- Local authorities regulate road crossings, zoning approvals, and above-ground structures such as compressor stations. Compliance with local planning, safety, and noise ordinances is required.
- Pipeline operators bear full responsibility for compliance with all engineering standards (e.g., ASME B31.8, B31.12) and are accountable if incidents occur.

Relevant Safety Codes and Guidelines

- PHMSA: 49 CFR Part 192 (gas pipelines).
- ASME B31.8 (Gas Transmission) and B31.12 (Hydrogen Piping and Pipelines).
- API, NFPA, CGA: Incorporated industry standards for design, construction, and venting.
- EPA, USACE, USFWS, OSHA: Environmental and occupational safety oversight.

5.2.2 Natural Gas-Hydrogen Blends

What are NG–H_2 Blended Pipelines?

- Blending hydrogen into natural gas pipelines is being explored as a transitional strategy to decarbonize the gas system while leveraging existing infrastructure.
- The U.S. has more than 3 million miles of natural gas pipelines, offering scale for hydrogen integration [15].
- Several projects globally and within the U.S. are currently blending hydrogen or are evaluating such projects' feasibility, safety, and regulatory considerations. Some key projects include:
  - California projects led by investor-owned utilities are testing up to 20% hydrogen blends by volume in distribution systems [16].
  - Hawai'i Gas has operated up to 15% hydrogen in natural gas for over 50 years in its synthetic natural gas system [17].
  - International pilots like the Hy4Heat project (UK) have studied appliance safety and flame behavior for hydrogen use [18].
  - ATCO is piloting hydrogen blending in both Australia (Clean Energy Innovation Hub [19]) and Canada (Fort Saskatchewan project [20]).
  - The HyDeploy project in the UK has conducted blending trials to assess safety and performance in distribution systems [21].
  - Enbridge's Delta, Utah hydrogen blending project is demonstrating hydrogen-natural gas integration in a utility-scale system [22].

Key Hazards

- Hydrogen can cause embrittlement of metals, gaskets, and seals that were not originally designed for its properties, which may compromise pipeline integrity.
- Because hydrogen disperses differently from methane, existing leak detection systems may not perform reliably, requiring new technologies or recalibration.
- End-use appliances, such as burners, boilers, and fuel cells, may experience safety or performance issues and need to be tested and certified with higher concentrations of hydrogen in the natural gas system.
- Odorization presents challenges, since the mercaptans used in natural gas do not work effectively at higher hydrogen blends.

Mitigation Strategies to Promote Safety

- Best practice guidance on natural gas-hydrogen blends is being developed by a CHS working group and will address materials compatibility, leak detection, appliance testing, system retrofitting, and emergency responder training.

- FERC currently regulates interstate natural gas pipelines under the Natural Gas Act, including those with minor blended constituents.
- Approvals are currently case by case under FERC's review process, with opportunities for public comment and stakeholder engagement.
- PHMSA safety standards apply to pipeline integrity, materials, and operations. Operators must certify compliance in FERC applications.

Relevant Safety Codes and Guidelines [23]

- FERC: Natural Gas Act authority for interstate pipelines, though the threshold at which a blend becomes a "hydrogen pipeline" is currently undefined.
- PHMSA: Pipeline safety standards for design, construction, and operations [24].[4]
- EPA, USACE, USFWS, DOE: Environmental, security, and permitting roles.
- CGA and ASME standards: Guidance on materials, venting, and design.
- API Recommended Practice 1173, Management of Hazards Associated with Location of Pipelines Near Electric and Other Utilities, was developed to address safety in the design, construction, and operation of natural gas pipelines and other hazardous liquid pipelines. It can be used as a framework for natural gas-hydrogen blended pipelines.

[4] PHMSA issued a solicitation in March 2024 to address gaps in regulations related to NG-H2 blended pipelines.

5.3 H_2 Transport, Distribution and Delivery

What is Hydrogen Transport?

- Hydrogen can be transported as a compressed gas or as a cryogenic liquid.
- Gaseous hydrogen (GH_2) is typically carried in steel or composite-reinforced cylinders
  at pressures ranging from 2,400 to 8,000 psi.
- Composite-wrapped cylinder trailers, including multi-element gas containers (MEGCs), equipped with thermally-activated pressure relief devices (TPRDs) are increasingly common. The TPRDs activate to prevent overpressurization when the cylinders are exposed to heat.
- Liquid hydrogen (LH_2) is transported in double-walled, vacuum-insulated tanker trucks operating at low pressures (below 150 psi).
- Both methods allow hydrogen to be distributed from production sites to end users at scale.

Key Hazards

- High-pressure gaseous cylinders pose risks of rupture or explosion if compromised.
- TPRDs, while protective, can create leak hazards and operational challenges for first responders—excessive cooling during firefighting can delay their activation.
- Vehicle accidents involving LH_2 tankers can damage vacuum insulation systems; if vacuum insulation fails, venting may be required.
- Venting of LH_2 is prohibited during transit, but if required during an emergency can cause logistical disruptions on highways and roads, as well as sometimes cause public concern from the visible white water vapor clouds formed at the vent system.

Mitigation Strategies to Promote Safety

- Cylinders and tankers are engineered with multiple layers of protection: TPRDs, burst disks, vent systems, and reinforced construction.
- Emergency response protocols and training for gaseous and LH_2 incidents are evolving to account for unique behaviors during incidents.
- LH_2 tanks are naturally robust due to the double wall construction. Controlled venting procedures allow safe removal of hydrogen from damaged liquid tanks.
- U.S. Department of Transportation (DOT) Special Permits are used for GH_2 trailers. Their scope applies mainly to the cylinders and associated components, not the full vehicle system, leaving parts of the transport design unassessed. This creates a gap where responsibility shifts to state highway authorities, many of which lack the specialized expertise and resources to evaluate advanced hydrogen systems.

Relevant Safety Codes and Guidelines

- DOT Federal Motor Carrier Safety Regulations (FMCSR) govern compressed gas and cryogenic liquid transport.
- CGA guidelines provide detailed requirements for vessel and trailer design, venting, and pressure relief devices.
- International standards (ISO, EIGA) set global benchmarks for cylinder construction, tanker design, and safe hydrogen transport.
- New GH_2 transport vehicle designs often rely on DOT Special Permits, since innovation has outpaced codified regulations. DOT Special Permits ensure compliance with vehicle performance and safety testing.

5.4 Storage

What is Hydrogen Storage?

- Storage is essential for ensuring the safe and efficient use of hydrogen across applications, whether stationary or mobile, gaseous or liquid.
- Gaseous and liquid hydrogen is stored similarly to the transport solutions discussed in Section 5.3.
- Many facilities utilize mobile solutions as temporary or permanent storage, such as gaseous tube trailers, gaseous cylinder banks, or liquid trailers.
- The choice of storage method depends on application needs, required capacity, and specific safety considerations.

Key Hazards

- High-pressure gaseous cylinders and LH_2 vessels can rupture or leak if not properly designed, maintained, or equipped with safety devices.
- Pressure relief devices (PRDs) must be hydrogen-compatible and properly installed.
- The most common failures are when PRDs operate unintentionally, causing inadvertent releases of hydrogen through the vent stack, though their consequence in this case is typically minimal.
- LH_2 storage faces unique cryogenic challenges. LH_2 vessels experience "boil-off" losses when there is insufficient usage. Vent stack blockages in LH_2 tanks can prevent boil-off from relieving pressure, causing vessel rupture. This can happen if water enters the vent stack and it freezes as a result of improper design or firefighting efforts.

Mitigation Strategies to Promote Safety

- Stationary gaseous and liquid vessels are designed and constructed to the ASME Boiler and Pressure Vessel Code (BPVC), which establishes requirements for structural integrity and safe operation.
- Storage systems are equipped with PRDs to prevent overpressurization, with requirements for materials and installation guided by hydrogen safety standards.
- LH_2 tanks use vacuum insulation and venting systems designed to safely manage boil-off under both normal and emergency conditions.
- Firefighter training emphasizes safe response to LH_2 incidents, particularly avoiding water application to vent stacks to prevent freezing and blockage.

Relevant Safety Codes and Guidelines

- ASME BPVC: governs design and construction of stationary gaseous vessels and LH_2 tanks.
- CGA G-5.5: establishes venting system requirements for hydrogen storage.
- NFPA codes: provide facility-wide requirements for hydrogen storage integration and protection.
- International standards (ISO, EIGA): set global benchmarks for materials, design, and testing of both gaseous and liquid hydrogen storage systems.

5.5 End Uses

The potential applications of hydrogen are as diverse as those of any fuel. This section will first examine hydrogen's historical role, particularly in high heat industrial processes, then explore its near-term promise in transportation and power generation. It will also highlight emerging markets and consider how hydrogen use may evolve in the long term.

5.5.1 Industrial Applications

What is Hydrogen in Industrial Applications?

- Hydrogen has long been used in industrial processes such as refining, metals production, and chemical manufacturing.
- These processes can involve large volumes of hydrogen and demand rigorous safety management.
- Facilities that contain more than 10,000 pounds of hydrogen must comply with OSHA's Process Safety Management (PSM) program.
- Even smaller-scale operations benefit from applying a risk-based process safety (RBPS) framework that mirrors PSM principles.
- In California, hydrogen is particularly relevant for refineries, chemical plants, and potential pilot projects in steelmaking and cement, all sectors with high energy demand that show strong potential for decarbonization.

Key Hazards

- Large usage of hydrogen in industrial processes increases the scale and potential impact of any release.
- High-pressure and high-temperature operations raise the probability and consequences of equipment failures.
- Hydrogen embrittlement can degrade metals, welds, and pressure boundaries over time, requiring rigorous material selection and inspection.
- Changes to processes, equipment, or materials without proper review (termed "Management of Change") may introduce unforeseen hazards.
- Human error (e.g. from insufficient training) can compromise safe operations.

Mitigation Strategies to Promote Safety

- OSHA's PSM framework requires structured hazard management through Process Hazard Analyses, mechanical integrity programs, and Management of Change protocols.
- Standard Operating Procedures guide safe operations across large-scale processes.
- Emergency planning and response protocols prepare facilities to act quickly during hydrogen incidents.
- Personnel receive ongoing training to understand risks and follow safety procedures.
- Incident investigations ensure lessons learned are fed back into improved safety practices.

Relevant Safety Codes and Guidelines

- OSHA 29 CFR 1910.119: Process Safety Management requirements for facilities storing and processing quantities of hydrogen above the threshold.
- NFPA codes and standards address hydrogen fire and explosion hazards.
- API standards for safe handling of hydrogen-rich environments.
- ASME Boiler and Pressure Vessel Code for pressure-containing equipment.
- CGA standards for safe hydrogen storage, venting, and handling.

5.5.2 Transportation Fuel

Where is Hydrogen as a Transportation Fuel Used?

- Hydrogen is an emerging alternative fuel for vehicles where battery electric options face performance or range limitations.
- Fuel cell electric vehicles (FCEVs) are entering the light-duty market, with examples such as the Toyota Mirai, and others.
- Hydrogen powered heavy-duty trucks and fuel cell buses are gaining traction due to rapid refueling capabilities and suitability for high-duty-cycle longer-distance operations.
- Fuel cell rail applications such as San Bernardino County's Zero-Emissions Multiple Unit (ZEMU) train and the Sierra Northern Railway locomotive in West Sacramento highlight hydrogen's potential for transit beyond roads. These projects represent public investment in building hydrogen's role in California's transportation landscape.

Key Hazards

- Hydrogen is stored in vehicles at high pressure, requiring robust containment and pressure relief systems.
- Fuel leaks may create flammable atmospheres, especially in confined or crash-damaged spaces.
- First responders must be trained to handle hydrogen incidents, as safety protocols differ from gasoline or natural gas vehicles.
- Emerging applications, such as rail, lack comprehensive hydrogen-specific regulations, increasing reliance on adapted standards and risk-based approaches.

Mitigation Strategies to Promote Safety

- Vehicle gaseous fuel tanks and fueling systems comply with CSA/ANSI HGV standards for compressed hydrogen storage. There is work ongoing to expand the scope of these codes to onboard LH_2 as these applications are developed.
- Hydrogen fuel tanks are designed with relief devices to vent hydrogen from the fuel tanks when exposed to fire to prevent damaging overpressurization of the cylinders.
- Fueling station design follows NFPA 2, NFPA 70, and applicable building and fire codes.
- Heavy-duty truck, fuel cell bus, and light-duty fuel cell vehicle fuel systems are designed to UN GTR No. 13 Phase 2, requiring leak detection, hydrogen isolation, and ignition source prevention [25].
- Safety systems include leak sensors that trigger driver warnings, system shutdowns, and hydrogen isolation when concentrations exceed thresholds.

- As demonstrated by the ZEMU project, rail projects can adapt existing standards for facilities and infrastructure, supplemented by risk-based safety frameworks.

Relevant Safety Codes and Guidelines

- CSA/ANSI HGV standards for hydrogen vehicle fuel containers and systems.
- NFPA 2 and NFPA 70 for fueling station safety and electrical design.
- ASME BPVC and piping codes (B31.3, B31.12) for station storage and delivery systems.
- International codes such as the International Building Code (IBC) and International Fire Code (IFC).
- SAE fueling component regulations and protocols for safe hydrogen vehicle refueling.
- UN GTR No. 13 Phase 2 for heavy-duty truck hydrogen safety.

5.5.3 Emerging Markets

Hydrogen is increasingly being examined for emerging applications such as maritime port operations, aviation, and stationary power generation. Each of these markets brings distinct safety considerations.

- In maritime settings, hydrogen may be used for fueling vessels or powering cargo-handling equipment, where confined spaces and crowded port facilities increase the risk of accumulation and ignition if leaks occur.
- Aviation applications introduce challenges with simultaneous aircraft fueling and passenger loading, as this practice is essential to maintaining commercial airline logistics.
  Use of LH_2 for onboard aircraft fuel is also an issue since maintaining cryogenic temperatures is critical; boil-off and venting must be managed appropriately.
- For stationary power generation and microgrids, siting near buildings raises concerns about hydrogen storage in populated areas.
- These hazards highlight the importance of flexible permitting processes and the development of evolving codes and standards. First-of-their-kind projects play a critical role in shaping the foundation of future codes and standards, providing the initial framework that can later be refined and expanded to address the unique requirements of new technologies and applications.

6. Policy Considerations

Safe deployment of hydrogen underpins public trust and visible safety protections help build confidence in hydrogen as a clean energy solution. Codes and standards provide a consistent baseline, making it easier for local jurisdictions to evaluate projects, while clear policy guidance reduces permitting delays, ensuring projects can be deployed safely and quickly. Informed decision-making helps balance innovation and safety, so California can scale clean hydrogen while protecting communities. Proactive safety governance in turn positions California as a leader, setting an example for hydrogen adoption nationally and internationally.

6.1 Public Safety

With respect to public safety, ensuring hydrogen safety in any application protects workers, surrounding communities, and critical infrastructure. Government officials should:

1. Enforce OSHA's PSM program and align with Cal/OSHA standards, which are essential to maintain safety in California's industrial facilities.
2. Encourage adoption of RBPS principles in smaller-scale facilities to raise the safety baseline across the industry.
3. Implement policies to support workforce training, emergency responder preparedness, and risk communication, which will establish and reinforce safe operating procedures as hydrogen use expands in California's industrial sector.
4. Provide consistent regulatory oversight to reduce risks from flammable gases, toxic exposures, and high-pressure operations.

6.2 Transport of Hydrogen

Codes and standards should be updated as new transport designs arrive to ensure they are deployed safely. Stakeholders should:

1. Certify that entire transport systems (not just cylinders) undergo comprehensive review to prevent accidents.
2. Apply safe, predictable, and well-regulated transport pathways, which are essential for California's hydrogen expansion, increasing both public trust and efficient logistics.
3. Update codes and strengthen the federal–state review process to streamline permitting, improve safety consistency, and reduce delays for new transport technologies.
    a. Local approvals for compressor stations, crossings, and zoning must be streamlined and coordinated with federal processes.
4. Blending offers a near-term decarbonization pathway, and safety and performance issues can be addressed by establishing blending thresholds confirmed to be safe prior to scaling.
    a. Progress on blending will depend on policies that encourage pilot projects, establish timely standards, and define the regulatory boundaries for hydrogen concentrations in natural gas pipelines. Learnings from blending demonstrations should guide regulatory action to update existing standards or develop new standards where appropriate.

6.3 Hydrogen Storage and Transportation

Policy decisions on infrastructure investments and safety frameworks will directly shape how quickly hydrogen vehicles can scale in California's clean transportation system. Continually updating codes, first responder training programs, and insurance/liability clarity are all essential to build public confidence in hydrogen-powered transportation. Stakeholders should:

1. Support hydrogen transportation with clear, harmonized safety regulations across light-duty, heavy-duty, and rail sectors, which will allow different vehicle classes and fueling systems to meet consistent safety expectations.
2. Establish regulations that confirm storage systems can withstand both high pressures and cryogenic conditions. Safe and reliable storage underpins California's hydrogen expansion strategy, supporting both local fueling and regional distribution.
3. Enhance coordination among CARB, Caltrans, and federal regulators to align emissions goals with safety oversight.
4. Rail projects such as the ZEMU train are demonstrations; success will depend on adapting standards quickly and creating a regulatory framework that can scale with new deployments.

6.4 Industrial Applications

As industries such as steel and cement begin pilot projects with hydrogen, policymakers must ensure that safety standards evolve alongside these new applications.

1. Update or establish clear codes and standards for hydrogen in high-temperature industrial processes. Steel (e.g., direct reduction, furnaces) and cement (kilns, burners) often operate at high temperatures, sometimes with hydrogen in fuel or reducing roles.

7. Want to Learn More About Hydrogen and How to Use It Safely?

There are many online and training resources available to help those working with hydrogen. A few highlighted examples include:

7.1.1 Design and Safety Guidance

- *H2Tools.org* – A resource from the U.S. Department of Energy and Pacific Northwest National Laboratory offering data, incident lessons learned, technical references, and safety planning tools.
- *Hydrogen Safety Panel* – Offers contracted expert reviews of hydrogen installations and emerging safety issues.
- *Center for Hydrogen Safety eLearnings*, *Webinars*, and *Fundamentals of Hydrogen Safety Credential* – A series of educational resources for those looking to boost their fundamental knowledge of hydrogen safety.
- *NREL Hydrogen Technologies Safety Guide* – Offers practical recommendations on risk mitigation, leak detection, and emergency response.
- *Hydrogen Safety Panel's Hydrogen Equipment Certification Guide* – Assists code officials, designers, owners, evaluators, and others with the application of the listing and approval requirements pertinent to the design and/or installation of hydrogen equipment as regulated by the model codes.

7.1.2 Permitting and First Responder Resources

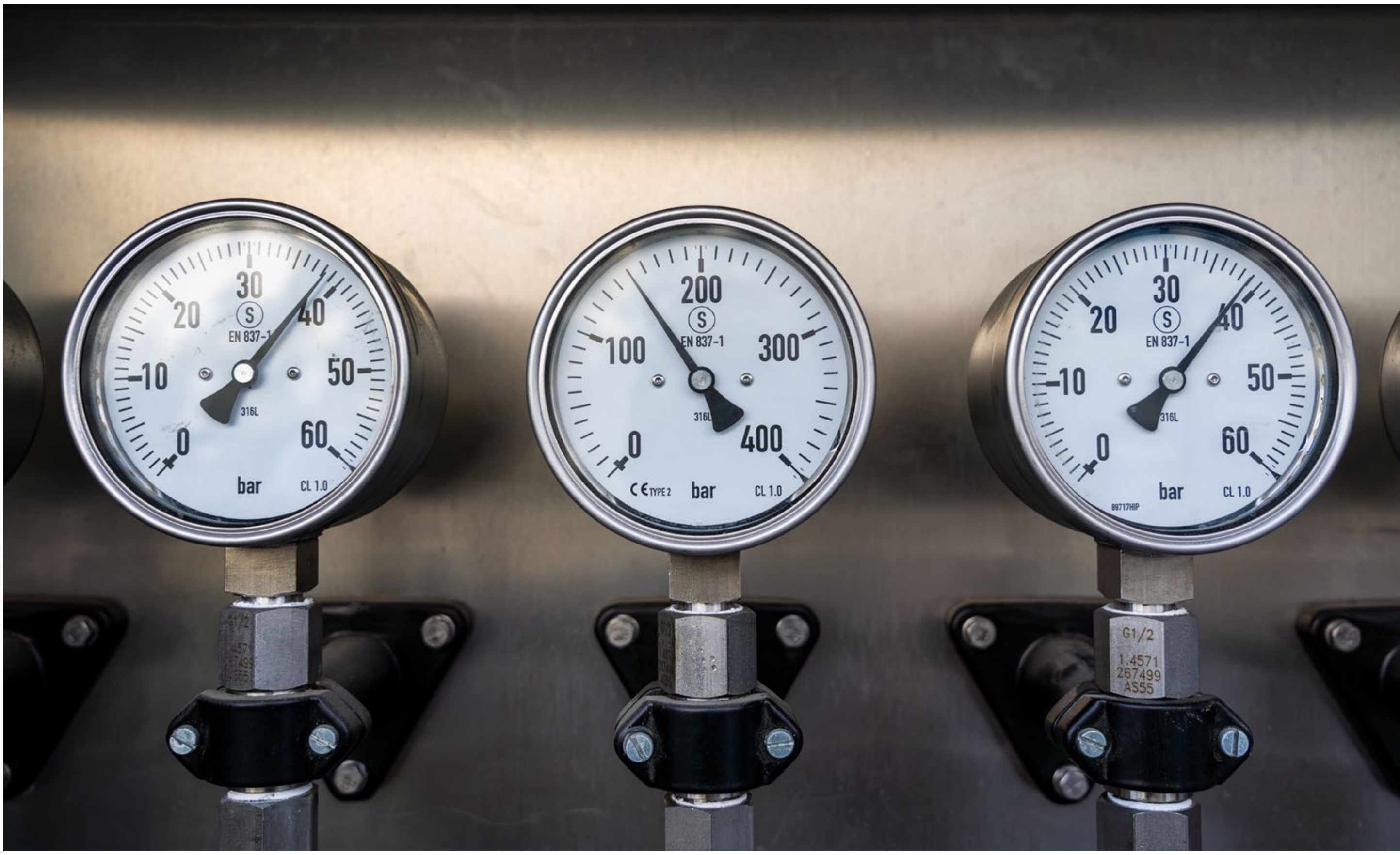
- *CHS's First Responder Micro Training* – This four-part multimedia course aims to better inform incident responders and support the safe handling and use of hydrogen in a variety of fuel cell applications.
- *Hydrogen Tools' Permitting Hydrogen Fueling Station – Four-Part Video Series* – This free video series, available on H2Tools.org, gives AHJs and other interested parties a quick orientation in permitting hydrogen fueling stations.
- *International Code Council's Hot Topics – Hydrogen Fuel* – Provides information on ICC's hydrogen resources.
- *NFPA 2 Plan Review Checklist and National Permit Guide for Hydrogen Fueling Stations* – The Hydrogen Fueling Station Plan Review Checklist (the Checklist) assists users in demonstrating compliance with NFPA 2, 2016 Edition. The Checklist simplifies both the project development and safety review processes.
- *DOE's Code Official Training Course* – Though updated in 2016, this course can be a useful resource with end-of-module questions to reinforce key concepts.

8. Conclusion

Just like gasoline, propane, and natural gas, hydrogen is a hazardous material—but it can also be used safely. A century of industrial experience has established proven practices that provide a strong foundation for its expansion into new sectors.

As hydrogen transitions from established industrial applications to a fuel and new markets in California's emerging clean energy economy, prioritizing safe and responsible use will be essential to building public trust and supporting widespread adoption.

Safety should not be viewed as a barrier, but as a catalyst for innovation and acceptance. By transferring institutional knowledge from experienced users to new stakeholders, training regulators and first responders, and embedding safety principles early in technology development, hydrogen's benefits can be realized while fostering continued progress and public confidence. Ultimately, investing in safety is not just a regulatory requirement – it will provide a strategic advantage that will accelerate the adoption of hydrogen-powered technologies and secure a bright future for the industry.



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Appendix A:
More About Properties and Hazards

A.1 Leaks

A.1.1 Gaseous Hydrogen Leaks

Hydrogen has several unique characteristics that strongly influence its propensity to leak:

- Hydrogen is a gas at normal temperature and pressure.
- It is 14 times lighter than air, causing it to rise rapidly, in some cases making leaks difficult to detect and control.
- Hydrogen lacks odor and color, making it hard to detect without specialized equipment.
- Its small molecular size allows it to diffuse and leak through materials that are typically considered impenetrable and leak more easily through valves and fittings.

These properties are critical in the context of safety and leak detection. Key factors that influence the behavior and hazards of gaseous hydrogen (GH_2) leaks include:

- Density and buoyancy: After pressure effects are lost, hydrogen's low density leads to rapid vertical rise and dilution in well-ventilated, open environments, which can reduce the duration of flammable concentrations. Conversely, in enclosures, pits, or under ceilings/roofs, hydrogen can accumulate near the top and form flammable clouds if ventilation is inadequate. Small leaks in open-air environments are not generally a significant hazard, as the hydrogen quickly dissipates to concentrations below the Lower Flammable Limit (LFL).
- High diffusivity and permeability: Hydrogen can permeate through seals and materials more readily than other gases, increasing the likelihood of small, chronic leakage.

The energy density of hydrogen gas is between 120 and 142 megajoules per kilogram (MJ/kg). The volumetric energy density of GH_2 at normal conditions is 0.09 kilograms per cubic meter (kg/m^3). Consequently, hydrogen is typically stored at high pressure or as a cryogenic liquid.

High-pressure GH_2 systems contain a substantial amount of stored energy. This is true not only for hydrogen but for any compressed gas, whether it be air, nitrogen, or other gases. When that pressure is suddenly released, such as during a line break or vessel rupture, it can produce projectiles even in the absence of combustion. If the released hydrogen encounters an ignition source, a jet fire (a flame resulting from the combustion of a gas jet flow), deflagration (a subsonic combustion process that propagates through heat transfer), or both, may occur.

Additionally, GH_2 released from high-pressure systems will initially travel in the direction of the leak before starting to dissipate. Once the pressure behind the leak decreases, the hydrogen will tend to rise due to its buoyancy and then disperse rapidly.

A.1.2 Liquid Hydrogen Releases

Liquid hydrogen (LH_2) must be cooled to -423°F to remain in liquid form.

An LH_2 spill or venting scenario forms a white water vapor cloud due to the extreme cold condensing ambient water vapor in the air. The hydrogen itself remains invisible. This visual indication can help responders identify that a release is occurring, but it does not map perfectly to the flammable region, which evolves rapidly as the hydrogen warms and disperses.

Even in outdoor, well-ventilated areas, flammable concentrations of hydrogen will be present near the leak before complete dispersion occurs. The vapors from LH_2 are neutrally buoyant when initially released, but for most accidental LH_2 release volumes, the cold hydrogen gas warms and dissipates quickly. As a result, the hazard profile shifts over time:

- Initial phase – dominated by cryogenic risks such as frostbite, material embrittlement, asphyxiation, and oxygen enrichment.
- Later phase – dominated by flammability hazards as the gas disperses and mixes with air.

A particularly distinctive hazard of LH_2 releases is the condensation and freezing of ambient air on cold surfaces. This process can create oxygen-enriched environments, which can significantly increase the severity of subsequent ignition or fire.

A.2 Material Compatibility and Embrittlement

The small molecular size of hydrogen allows it to diffuse into certain metals, resulting in embrittlement. This degradation mechanism weakens the material's structure, potentially leading to failure and leaks. There is no universal material solution for hydrogen service; rather, suitability depends on application-specific conditions such as pressure, temperature, mechanical loading, and duration of exposure. The Sandia Technical Reference can provide information on metals compatibility testing and historical use with various hydrogen applications, which can support analysis of metal compatibility [26].

Material compatibility considerations extend to polymers used in hydrogen systems. Common applications include liners for hoses and Type IV hydrogen storage vessels, gaskets, and seals such as O-rings. Hydrogen can be absorbed into incompatible polymer materials, causing swelling that degrades their sealing performance and leads to leaks. Failed O-rings are a common source of leaks in hydrogen systems and should therefore be inspected frequently.

Appendix B:
More About Prevention and Mitigation Strategies

The safe utilization of hydrogen necessitates adherence to relevant codes and standards as well as the incorporation of established engineering and operational best practices. This section delineates critical considerations for the design of hydrogen facilities and systems, leveraging industry experience to mitigate risk and secure long-term safety. A more exhaustive compilation of hydrogen codes and standards can be found in ***Appendix D***.

B.1 General Loss Prevention Measures

Preventing fire and explosion events is a top priority in hydrogen facility design. The first line of defense is to avoid loss of containment, leading to the formation of flammable mixtures. This is achieved through robust leak prevention, effective ventilation, and ensuring rapid dilution of any released hydrogen to concentrations below the LFL. Early leak detection, automatic system isolation, and shutdown can minimize the duration and extent of a release.

The following general considerations can be used to help guide safe design:

- Follow applicable codes and standards
- Locate hydrogen systems outdoors where possible, and limit the amount of hydrogen used and stored indoors or in enclosed areas;
- Reduce the amount of hydrogen used and stored onsite;
- Reduce hydrogen pressures, when possible, to limit the volume of potential leaks;
- Provide ventilation;
- Vent and discharge hydrogen outdoors to safe locations;
- Provide early leak detection; and
- Provide system emergency shutdown and isolation capabilities.

B.2 Siting and Separation Distances

Ensuring proper clearance is crucial for mitigating risks to individuals and property during a release or ignition event, as well as facilitating safe emergency access. As the prevalence of hydrogen usage rises, there is an increasing demand to situate facilities within densely populated areas, presenting a challenge between usability, regulatory compliance, and safety considerations. This often complicates the approval process, leading many sites to seek alternative solutions that deviate from the prescriptive requirements of the International Fire Code and NFPA, the foundational fire codes referenced in the U.S.

B.3 Ventilation

Proper ventilation is essential alongside siting and separation distances to minimize risks effectively. Ventilation plays a vital role in reducing the potential accumulation of flammable gases.

- Outdoor environments: Hydrogen naturally disperses if overhead structures that could trap gas are avoided.
- Indoor environments: Mechanical ventilation should be designed to keep hydrogen concentrations below the LFL by:
    - Exhausting air at elevated points, where hydrogen tends to accumulate.
    - Supplying fresh air at lower levels to promote full circulation throughout the enclosure or room.

It is important to note that no practical indoor ventilation system can rapidly dilute a significant release from a pressurized vessel, pipe rupture, or blowdown. However, it will help reduce the size of the flammable cloud and duration of the associated risk. In spaces where heavier-than-air flammable gases or vapors are also present, both low and high exhausts may be necessary.

B.4 Leak Detection

B.4.1 Detectability Challenges

In the absence of engineered leak detection systems, relying on human senses for leak detection, such as how natural gas is identified by its mercaptan odorant, offers limited effectiveness for hydrogen:

- Audible indicators: In high-pressure systems, the hissing sound produced by escaping gas can serve as an immediate indicator of a leak in the absence of sensors. However, this method proves unreliable in noisy environments and when dealing with low leak rates.
- Visual indicators (gaseous hydrogen): Pure GH_2 leaks generally present no visible markers. Once ignited, hydrogen flames may sometimes produce heat waves that can be faintly seen, but these flames remain pale and nearly invisible in daylight, complicating detection. When hydrogen combustion occurs alongside other materials, smoke and additional combustion byproducts may render the flame more visible.
- Visual indicators (liquid hydrogen): LH_2 releases can generate a white vapor cloud, not from the hydrogen itself, which remains invisible, but due to the condensation of ambient moisture and air at cryogenic temperatures.

B.4.2 General Leak Detection Strategies

Detecting and controlling leaks is crucial for safety. Some key strategies include:

- Performing regular inspections of equipment and storage facilities to identify and repair potential leak points.
- Utilizing hydrogen detectors to provide early warning of leaks. These detectors are often installed in areas where hydrogen is stored or used.
- Implementing strict safety protocols during hydrogen handling and storage to minimize the risk of leaks. This includes procedures for proper ventilation and the rapid dilution of released hydrogen.
- Ensuring material compatibility to prevent hydrogen permeation and leakage through seals and joints.
- Minimizing fittings and joints in piping systems to reduce leak points. Training personnel on the safe handling and detection of hydrogen to respond effectively to potential leaks.

B.4.3 Hydrogen Gas Detection

B.4.3.1 Detection Methods and Functions

Hydrogen gas leaks can be identified through several methods, including:

- Fixed gas detectors installed in enclosures or near potential release points. Fixed gas detectors are the industry standard for continuous hydrogen leak detection and provide reliable monitoring in high-risk areas.
- Portable monitors or personal monitors worn by personnel. Portable monitors transmit warnings via alarms or flashing lights when dangerous levels of gas are present.
- Pressure or flow monitoring in stable piping systems. This approach is well suited for hydrogen systems with intermittent operations, such as fueling stations. Deviations can signal a leak, triggering automatic shutoff valves or other safety measures to minimize risk.
- Pipe-in-pipe system designs with annular space monitoring. This approach is well-suited for piping routed through concealed or inaccessible areas.

Effective leak detection enables a series of automatic and manual safety functions, including:

- Automatic shutoff and system isolation: Prevents further leakage by stopping the flow of hydrogen.
- Equipment and/or power shutdown: Reduces the risk of ignition sources near the leak.
- Ventilation system activation or control: Helps disperse leaked hydrogen to prevent accumulation.
- Audible and visual alarms to alert personnel: Ensures timely evacuation and response to the leak.

B.4.3.2 Placement and Coverage Challenges

Hydrogen gas detection systems currently rely on spot detectors, as there is currently no commercially available wide-area hydrogen-specific detection technology. These spot detectors can be effective, but only if hydrogen reaches the sensor. If a leak occurs and the gas disperses away from the detector, the leak may go unnoticed.

Acoustic detection systems are becoming more common at larger hydrogen facilities. These systems identify the unique sound signature produced by a pressurized gas leak, which may be audible even when the gas itself is invisible and undetectable by traditional means.

Best practice is to pair acoustic detectors with traditional spot detectors. This layered approach combines:

- The early, wide-area coverage provided by acoustic detection.
- The concentration-specific monitoring offered by spot detectors.

Strategic placement is critical for effectiveness. Common practices include:

- Positioning spot detectors near exhaust ducts, where airflow carries leaked hydrogen toward the sensor.
- Installing detectors at the highest points in enclosures, ensuring detectors will be located where leaked hydrogen will collect.

Guidance in current codes and standards is limited, so designers often turn to supplemental methods, such as:

- Smoke or airflow testing to visualize gas movement and validate detector coverage.
- Computational Fluid Dynamics (CFD) modeling to simulate dispersion and optimize detector placement.

While CFD can provide detailed accuracy, its cost and complexity often make it impractical for smaller or lower-risk installations.

B.4.4 Hydrogen Flame Detection

Hydrogen flames are challenging to see with the naked eye, particularly in daylight, making reliable flame detection crucial for safe operations.

Detection technologies have evolved over time:

- Ultraviolet sensors: provided early sensitivity but were prone to false alarms from sunlight and reflections.
- UV/infrared sensors: improved reliability but still faced challenges in bright or reflective environments.
- Multiband infrared sensors (current standard): use multiple infrared wavelengths to identify the unique signature of hydrogen flames, offering higher selectivity and fewer false activations.

This development shows a trend towards more selective and durable detection systems that support timely emergency response and improve safety at hydrogen facilities.

In emergency situations, thermal imaging cameras can assist first responders in locating hydrogen flames. Additionally, hydrogen fires in real-world contexts often involve other combustibles that produce visible flames or smoke, improving visual detectability and aiding response efforts.

An important principle in hydrogen safety is that, in many cases, allowing a hydrogen flame to continue burning may be safer than extinguishing it prematurely. A burning hydrogen jet fire consumes the released gas at its source, preventing accumulation and the risk of delayed ignition. Once the gas supply is cut off, the flame will extinguish on its own when the fuel is fully consumed.

B.4.5 Addressing Cryogenic Leaks

When addressing cryogenic LH_2 leaks, mitigation controls should include:

- Restricting ignition sources and hot work in areas where cryogenic air condensation is plausible.
- Using materials and coatings compatible with oxygen-rich environments in areas that may experience repeated cryogenic exposure.

A crushed gravel bed is often cited as a practical design feature for outdoor LH_2 storage, as it limits the lateral spread of releases, reducing the chances of the hydrogen reaching ignition sources. The granular structure accelerates the transition to GH_2 and subsequent dilution and dissipation. Crushed gravel is noncombustible unlike other combustible ground coverings such as asphalt.

B.5 Ignition Source Mitigation

Due to hydrogen's extremely low ignition energy, it is critical that ignition sources are managed and eliminated around areas where hydrogen could potentially leak.

B.5.1 Identification of Ignition Sources

Ignition sources vary widely and can include:

- Static electricity
- Electric discharge
- Mechanical impact
- Open flames
- Hot surfaces
- Equipment sparks

B.5.2 Electrical Equipment Classification

To reduce the likelihood of electrical equipment becoming an ignition source for leaked hydrogen, electrical equipment located in close proximity to hydrogen systems must be appropriately rated.

- In the United States, electrical equipment in close proximity of hydrogen systems should meet requirements for Class I, Group B environments as specified in applicable codes such as NFPA 70.
- Alternative approaches may be used, such as purged or pressurized enclosures designed in accordance with NFPA 496.
- The use, arrangement, and reliability of any alternative methods are subject to review and approval by the AHJ.

B.5.3 Grounding and Bonding

Grounding and bonding of equipment is intended to prevent discharged static electricity from becoming an ignition source near leaked hydrogen. Bonding equalizes charge between pieces of equipment, or between equipment and adjacent things, while grounding dissipates any generated charges to the earth.

All hydrogen equipment should be grounded and bonded in accordance with the California Electrical Code and NFPA 77 to prevent ignition of leaked hydrogen.

B.6 Shutdown and Isolation

B.6.1 Emergency Shutdown Systems (ESS)

Effective isolation is essential for controlling and terminating hydrogen releases, as hydrogen fires cannot be extinguished without removing the fuel source.

An ESS should activate in response to:

- Detection alarms
- Fire alarms
- Ventilation system loss
- Manual activation via Emergency Shutdown Devices (ESDs)

When triggered, the ESS should:

- De-energize electrical components not rated to be in close proximity to hydrogen systems
- Close all automatic shutoff control valves
- Coordinate with other safety systems, such as fire alarms

ESDs should be strategically placed both on the hydrogen equipment and at a remote location at least 25 feet away to allow safe access during an emergency.

Finally, the ESS should be integrated with overall system isolation, ensuring that once activated, the fuel source is fully controlled.

B.6.2 Isolation

Isolation valves are essential for separating bulk hydrogen storage from both upstream and downstream systems to limit the scale of potential releases. For indoor applications, it is particularly critical to install an isolation valve at the point where hydrogen piping enters the building. This measure reduces the quantity of hydrogen that could be involved in a release or ignition event inside the facility, thereby improving overall safety.

B.7 Material Compatibility

Hydrogen can cause embrittlement in certain metals, leading to cracks, leaks, and system failures. Material selection depends on factors such as pressure, temperature, and service conditions, as well as whether the system experiences constant or repeated pressure cycling. Embrittlement is most likely to occur at moderate temperatures below 392 °F, with repeated cycling generally more damaging than steady pressure. At higher temperatures, high-temperature hydrogen attack is also a concern. Hydrogen can diffuse into metals, leading to the formation of methane gas and, ultimately, cracks in the metal.

Metals generally recommended for high-pressure hydrogen service:

- Austenitic stainless steels
- Copper and copper alloys
- Certain nickel and high-nickel alloys (depending on conditions)

Metals generally avoided in high-pressure hydrogen service:

- Most nickel alloys (outside specific applications)
- Gray, ductile, and malleable cast irons
- High-strength steels (especially under cycling conditions)

Because no single rule applies universally, careful evaluation of operating conditions is essential to ensure long-term safety and durability.

B.8 Venting

Venting is a critical safety consideration in hydrogen system design. Proper venting ensures that hydrogen does not accumulate in enclosed or hazardous areas, and that equipment remains protected from overpressurization. Because of hydrogen's unique properties, vent system design requires specific approaches that differ from those used for other gases.

Key considerations for hydrogen vent systems include:

- Outdoor and safe-area discharge – Hydrogen must always be vented to the outdoors and away from areas where accumulation could occur or where personnel could be exposed to hazardous levels of thermal radiation.
- Pressure relief integration – Vent systems are often paired with pressure relief designs to safely release hydrogen and prevent vessel overpressurization.
- Termination elevation – Vent discharges should be directed out or upward and at elevation, avoiding discharge toward the ground, personnel, other equipment, or potential ignition sources.
- Standards compliance – Systems must be designed in accordance with CGA G-5.5 to ensure safety and regulatory compliance.
- Prevention of blockages – Vent systems, especially for LH_2, must be designed to avoid water accumulation. Any water present can freeze at cryogenic temperatures, potentially blocking the vent line and creating an overpressurization hazard.

Careful adherence to design standards and best practices is essential to ensure safe and reliable operation.

B.9 Hazard Analysis

All hydrogen projects, irrespective of scale, must undergo a comprehensive hazard analysis. The project team should conduct this assessment to quantify the potential consequences and likelihood of release, ignition, and escalation. Considerations for completing hazard analyses include:

- The type and depth of the assessment—whether qualitative hazard reviews or quantitative risk assessments—should correspond to the complexity and risk profile of the specific application.
- The assumptions and results of the analysis must be clearly documented.
- Deviations from the design used for the hazard assessment and commissioning of the facility should be carefully evaluated against the original assessment to ensure continued compliance with initially approved safety standards.

This report provides a brief overview of a few key considerations, but there are numerous additional factors to consider.

Appendix C:
More About Applications
C.1 Electrolysis
C.1.1 Key Hazards and Mitigations

Oxygen-Hydrogen Crossover

Electrolyzers present unique hazards and design considerations that go beyond general hydrogen safety. One of the most significant risks is oxygen–hydrogen crossover, where hydrogen migrates into the oxygen stream during startup, upset conditions, or membrane degradation [8]. While normally below flammability limits, crossover concentrations can rise to dangerous levels.

A tragic example occurred in 2019 in Gangneung, South Korea, when crossover in an alkaline electrolyzer caused an explosion that destroyed a research building and damaged structures up to 150 meters away. This case illustrates why rigorous monitoring and protective design are critical.

More information on this incident can be found in the 2019 CHS Conference Proceedings [27].

Safety System Integration

Effective hazard assessments for electrolyzer systems should account for both the electrolyzer unit itself and the broader facility context in which it operates [9]. A common oversight in safety planning is the failure to conduct an integrated review of how various facility systems interact under normal and abnormal conditions. This can lead to gaps in protection, particularly during emergency events.

An emergency shutdown may be initiated by one or more of the following conditions:

- Ventilation system failure
- Hydrogen leak detection
- Excessive H_2-O_2 crossover
- Fire detection
- Critical process deviations

Once an ESD is initiated, the response strategy should focus on rapid risk mitigation while preserving critical safety functions. Typical shutdown actions include:

- Isolation of hydrogen storage
- De-energization of the electrolyzer
- De-energization of unclassified electrical equipment
- Safe venting of hydrogen
- Continued operation of ventilation and purge systems

C.1.2 Safety Codes and Standards

Safety for electrolyzers is governed by a combination of codes and standards that address both the equipment and the surrounding facility environment. Two of the most important standards currently in use are NFPA 2 and CSA/ANSI B22734. These form the foundation of safe electrolyzer deployment in North America.

For larger electrolysis systems, a risk-based engineering evaluation is necessary to ensure safety, particularly with respect to gas handling, electrical hazards, and venting strategies. More information on the design of large-scale electrolysis systems can be found in CHS's webinar, Hydrogen Safety for Large Scale Electrolyzer Projects [28].

Effective application of these standards ensures that electrolyzer systems are not only designed and constructed safely, but are also fully integrated into the broader safety infrastructure of the facility. As electrolyzers scale up, however, existing codes may not always be sufficient—project-specific hazard analyses are critical for all hydrogen projects, as is stakeholder collaboration, which could include engagement with fire officials, permitting authorities, and safety experts early in the design process.

C.2 Transport

C.2.1 Regulatory Considerations for New Transport Designs

Newer gaseous hydrogen transport vehicle designs often incorporate vessels designed to DOT Special Permits rather than existing codified regulations. Special Permits are reviewed and approved on a case-by-case basis, but they typically evaluate only the aspects of the vessel, its associated components, and its support structure.

These Special Permits generally do not assess the full transport vehicle configuration, and this has created a regulatory gap. Responsibility for such reviews often falls to individual state highway authorities, many of which lack the specialized expertise and resources to evaluate these complex systems effectively. This gap highlights the need for coordinated federal-state review processes and regulatory updates to comprehensively address emerging hydrogen transport technologies.

C.3 End Uses

C.3.1 OSHA Process Safety Management (PSM)

Per OSHA, facilities with an inventory over 10,000 pounds (lb) of hydrogen in storage and processing equipment requires compliance with OSHA PSM, as outlined in 29 CFR 1910.119. PSM is a structured program designed to ensure that large-scale chemical processes are reviewed and managed using a risk-based approach.

The following key components of PSM help ensure the safe management of hydrogen in industrial applications:

1. Process Safety Information: Provides detailed information about the hazards associated with the hydrogen process, including data on chemicals, equipment, and operational parameters.
2. Process Hazard Analysis (PHA): Systematic review and identification of hazards associated with hydrogen processes helps assess risks to ensure that appropriate controls are implemented.
3. Operating Procedures: Establishes standard operating procedures to guide safe and efficient hydrogen use in various processes.
4. Mechanical Integrity: Ensures that equipment used in hydrogen processes is designed, maintained, and inspected to prevent failures or leaks.
5. Management of Change: Addresses the safe management of changes to processes, equipment, or materials that could impact safety.
6. Pre-Startup Safety Reviews: Reviews the safety measures and operational procedures before starting up new or altered hydrogen processes.
7. Training: Mandates ongoing safety training for personnel involved in hydrogen-related operations, ensuring they are aware of risks and safety protocols.
8. Incident Investigation: Conducts thorough investigations following incidents or near misses to identify root causes and prevent recurrence.
9. Emergency Planning and Response: Develops and implements emergency response plans to handle potential hydrogen-related accidents or emergencies.
10. Ignition Source Control: Establishes controls to prevent the introduction of ignition sources in areas where hydrogen is stored or used.

Hydrogen's use in industrial applications is a well-established practice with diverse applications across multiple sectors. To ensure safety, compliance with OSHA's PSM standards is crucial for facilities containing large quantities of hydrogen. The key elements of PSM, including hazard analysis, operating procedures, and emergency planning, form the foundation for safely managing hydrogen in industrial environments. Even when PSM does not prescriptively apply, projects and organizations are encouraged to adopt a risk-based process safety (RBPS) approach that aligns with the key pillars of PSM.

C.3.2 Transportation

Hydrogen is emerging as one of the most promising alternative fuels for the U.S. transportation sector, offering advantages in vehicle performance, fueling convenience, and operational efficiency where battery electric vehicles face limitations.

C.3.2.1 Transit

Transit agencies are increasingly evaluating fuel cell electric buses (FCEBs) as part of their long-term fleet planning, recognizing their potential for extended range, rapid refueling, and suitability for high-duty-cycle operations.

In addition to meeting standard manufacturing and U.S. DOT requirements applicable to buses, FCEBs must comply with a range of specialized hydrogen safety standards, including:

- Fuel tanks
  - Relevant CSA/ANSI HGV standards, such as CSA/ANSI HGV 2: Compressed Hydrogen Gas Vehicle Fuel Containers
  - UN GTR 13 Phase 2, adopted in the U.S. by the National Highway Traffic Safety Administration (NHTSA), and Federal Motor Vehicle Safety Standards (FMVSS)
- Fueling station design
  - NFPA 2: Hydrogen Technologies Code
  - NFPA 70: National Electrical Code
  - International Building Code (IBC)
  - International Fire Code (IFC)
- Hydrogen storage and supply systems
  - ASME Boiler and Pressure Vessel Code (BPVC)
  - DOT FMCSR
  - ASME B31.12: Hydrogen Piping and Pipelines / ASME B31.3: Process Piping
  - CGA G-5.5: Hydrogen Vent Systems
  - Other applicable Compressed Gas Association (CGA) standards
- Hydrogen dispensers at fueling stations
  - Relevant Society of Automotive Engineers (SAE) specifications, such as SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles
  - Relevant CSA/ANSI HGV standards

C.3.2.2 Heavy-Duty Trucks

Several manufacturers are actively developing fuel cell electric Class 8 trucks; however, these vehicles have not yet been deployed at a commercial scale. Hydrogen safety goals for Class 8 trucks, both during normal operation and following a crash, are based on the requirements in United Nations Global Technical Regulation (UN GTR) No. 13, Phase 2, Global Technical Regulation for Hydrogen and Fuel Cell Vehicles.

The following diagram, provided by Kenworth, outlines the various components associated with their T680 fuel cell electric heavy-duty truck. Each tank is provided with a temperature-actuated pressure relief device (TPRD) to relieve pressure when the tank is exposed to excessive amounts of heat. Though the truck is provided with similar electrical systems as a battery-electric truck, the batteries are smaller and less extensive.

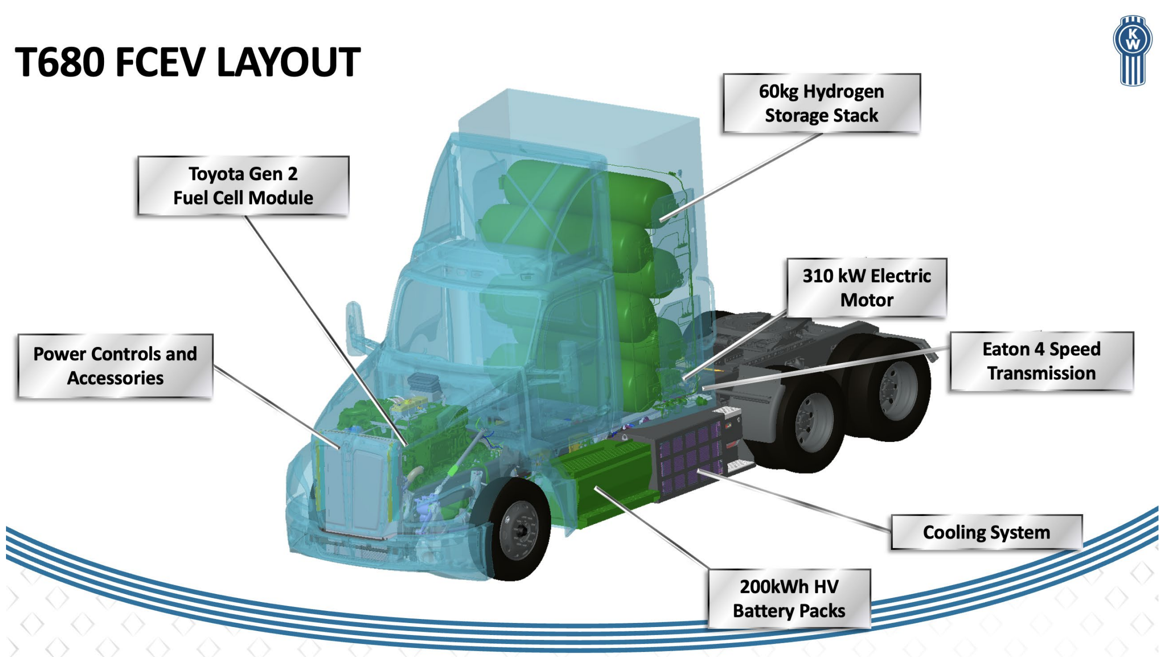

Figure 1: Kenworth T680 Fuel Cell Electric Truck

Fuel cell trucks are equipped with many safety features, some of which are outlined below:

- The hydrogen storage system is designed to contain hydrogen safely during service conditions and vehicle accidents.
- Pockets within the vehicle where hydrogen can accumulate have limited volume.
- There are no ignition sources in the areas where hydrogen can leak.
- Leak detection sensors are used to warn the driver, isolate the hydrogen, and shut down the fuel cell power module (FCPM):
  - When 3% v/v H_2 is detected, the driver is notified.
  - When 4% v/v H_2 is detected, the driver is notified “red”, the hydrogen storage is isolated, and the fuel cell system is shut down.
  - H_2 detector malfunction: Driver warning indication “yellow.”
- The uncontrolled release of hydrogen into the fuel cell exhaust is prevented.
- Hydrogen systems are protected from high-energy flying debris.

Appendix D:

Applicable Codes and Standards for Hydrogen Facility and System Design

Many existing codes and standards establish the requirements for hydrogen systems [29]. The table below outlines some of the most widely recognized and applicable standards in the United States.

Federal Regulations		
OSHA Regulations 29 CFR 1910 Subpart H		Safe storage, use, and handling of hydrogen in the workplace[5]
DOT Regulations 49 CFR 171-179		Safe transport of hydrogen in commerce
U.S. National Codes		
International Fire Code (IFC) / NFPA 1, Fire Code		Storage, use, and handling of compressed gases and cryogenic fluids, applicable to gaseous hydrogen and liquid hydrogen, respectively. Motor vehicle dispensing facilities and repair garages where servicing hydrogen vehicles
International Building Code (IBC)		Facilities supporting hydrogen uses, including, but not limited to, the design, construction, and alteration of the built environment of such facilities.
International Fuel Gas Code (IFGC)		Applies where hydrogen is used as a fuel or feedstock for appliances, processes, and fuel cells, and includes requirements for flammable gas piping.
International Mechanical Code (IMC)		Design and construction of mechanical ventilation systems serving indoor hydrogen facilities, including but not limited to laboratory exhaust systems.
Hydrogen Technologies Specific Fire Codes and Standards		
NFPA 2, Hydrogen Technologies Code		Provides a structured framework for the safe use, storage, and handling of hydrogen technologies. This code works in coordination

[5] The OSHA requirements are based on NFPA codes from the late 1960s. The current version of NFPA 2 is typically accepted as meeting the requirements of 29 CFR 1910 Subpart H.

		with model codes and is selectively referenced by the I-Codes to address a wide range of hydrogen systems, facilities, and applications.
NFPA 55, Compressed Gases and Cryogenic Fluids Code		Compressed gases and cryogenic fluids. Previous editions of this code contained many requirements related to hydrogen. These requirements are shifted to NFPA 2 in more recent editions of NFPA 55.
NFPA 853, Standard for the Installation of Stationary Fuel Cell Power Systems		Covers installation of all commercial fuel cells including hydrogen PEM fuel cells
Hydrogen Technologies Component, Performance, and Installation Codes		
ASME B31.3 and B31.12, Piping and Pipelines		Piping design and installation code that also covers material selection. B31.12 will be sunsetted in the near future, with the applicable requirements moving to B31.3 and B31.8.
ASME Boiler and Pressure Vessel Code (BPVC)		Design of steel alloy and composite pressure vessels
CGA G-5.5 and H Series		Hydrogen components and systems, including vent systems
CGA S Series		Pressure relief devices for containers
CSA/ANSI B22734:23, Hydrogen generators using water electrolysis / UL Subject 2264		Equipment standard for hydrogen generators using water electrolysis. Based in part on its international counterpart, ISO 22734.
UL 61010-1, Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use		Equipment standard for small-scale hydrogen generators using water electrolysis (less than 3 kg/day generated)
CSA/ANSI FC1, Fuel cell technologies		Equipment standard for fuel cell technologies
CSA/ANSI HGV 4 Series		Hydrogen fueling station components