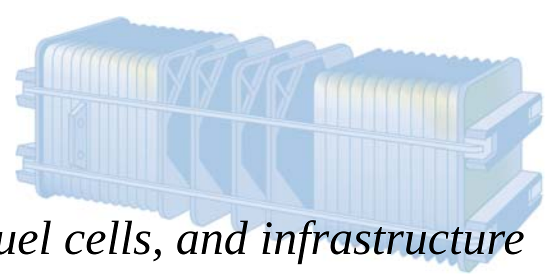
U.S. Department of Energy
Energy Efficiency and Renewable Energy

Regulators' Guide to Permitting Hydrogen Technologies



hydrogen, fuel cells, and infrastructure

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This Guide was developed through a collaborative effort involving the National Fire Protection Association, the International Code Council, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory.

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Overview

1.0 Program Description and Objectives

The mission of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program within the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy is to research, develop, and validate fuel cells and hydrogen production, delivery, and storage technologies for transportation and stationary applications. The objectives of the program are

- to dramatically reduce dependence on foreign oil
- to promote the use of diverse, domestic, and sustainable energy resources
- to reduce carbon emissions from energy production and consumption
- to increase the reliability and efficiency of electricity generation.

Codes and standards are needed to ensure safety as well as to commercialize hydrogen as a fuel. To accomplish its codes and standards objectives, staff of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program work with code development organizations, code officials, industry experts, and national laboratory scientists to draft new model codes and equipment standards that cover emerging hydrogen technologies for consideration by the various code-enforcing jurisdictions.

The program focuses on three primary activities to assist the commercial acceptance of the technologies:

- Develops training programs for state and local officials that explain the technologies with case studies.

- Accelerates the identification of gaps in the standards development process and provides methods to close the gaps.

- Supports the codes and standards adoption process.

In support of the program objectives, this guide was developed through a collaborative effort involving National Fire Protection Association, the International Code Council, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory. The guide will be updated and enhanced as the Hydrogen, Fuel Cells, and Infrastructure Technologies Program and its technologies evolve.

2.0 Hydrogen Basics

2.1 Historical and Current Uses of Hydrogen

For the past 50 years, gaseous hydrogen has been used in large quantities as a feedstock in petroleum refining and the chemical and synthetic fuels industries. Examples include making ammonia for fertilizer and removing sulfur in petroleum refining for such products as reformulated gasoline. Hydrogen is used also in the food processing, semiconductor, glass, and steel industries, as well as by electric utilities as a coolant for large turbine generators.

In 1996, total worldwide consumption of hydrogen was more than 14 trillion cubic feet. Consumption in the United States in 1996 was approximately 3 trillion cubic feet. Almost all of the hydrogen used is *captive*—that is, consumed at the refinery or chemical plant where it is produced. Nevertheless, a safe and reliable hydrogen distribution network,consisting of liquid hydrogen delivery trucks, gaseous hydrogen tube trailers, and dedicated hydrogen pipelines, has been developed over the years.

2.2 Hydrogen: Similarities to and Differences from Other Common Fuels

Gaseous hydrogen has many similarities to conventional fuels now being used routinely—gaseous fuels such as methane (i.e., natural gas) and propane and liquid fuels such as gasoline. However, there are some major differences in its properties compared to conventional fuels, as discussed below. ***In general, hydrogen is neither more nor less inherently hazardous than gasoline, propane, or methane***. Consequently, the physical properties of hydrogen and the hazards relating to those properties must be understood in order to design safe hydrogen facilities and hydrogen-powered equipment—particularly for emerging uses of hydrogen.

2.2.1 Key Physical Properties

With respect to safety, the most important properties of hydrogen—compared to gasoline, natural gas, and propane—are as follows:

- *density* – Hydrogen is the lightest of all the elements.

- *buoyancy* – At room temperature, gaseous hydrogen has a very low density compared to air and the other fuels. If it were to leak from a container, it would rise more rapidly than methane, propane, or gasoline vapor and quickly disperse.

- *diffusion* – Although gas transport from diffusion is much less than gas transport due to buoyancy, hydrogen diffuses through air much more rapidly than other gaseous fuels.

- *color, odor, taste, and toxicity* – Hydrogen, like methane and propane, is a colorless, odorless, tasteless, and nontoxic gas.

- *flammability and flame characteristics* – The flammability of hydrogen, as a function of concentration level, is greater than that for methane, propane, or gasoline vapor. Unlike the others, however, hydrogen burns with a low-visibility flame in the absence of impurities. In fact, in daylight, a hydrogen fire is almost invisible.

- *ignition energy* – Hydrogen can be ignited by a very small amount of energy if its concentration is neither lean nor very rich. (and the humidity is low).

- *detonation limits* – Hydrogen is detonable over a very wide range of concentrations when confined. However, unlike the other common fuels, it is difficult to detonate when unconfined.

- *flame velocity* – Hydrogen has a faster flame speed than the other fuels if its concentration is neither very lean nor very rich.

- *ignition temperature* – Compared to the other fuels, hydrogen has a higher ignition temperature.

2.2.2 Leak Prevention and Containment

With respect to safety issues, leak prevention is an important consideration and system design issue. Hydrogen leakage—through paths such as welds, corrosion defects, valves, flanges, diaphragms, gaskets, and various types of seals and fittings—is an important factor in evaluating fire and explosion hazards.

Hydrogen diffuses more rapidly through solid materials than do the other fuel gases. For example, hydrogen will diffuse through the walls of polyethylene pipes at two to three times the energy flow rate of methane. However, the flow rates are so small they rarely produce significant safety concerns.

Hydrogen also can cause a significant deterioration in the mechanical properties of some metals, an effect known as *hydrogen embrittlement*. The effects of embrittlement and diffusion must be considered in design, material selection, and operation in order to minimize the long-term likelihood of leaks as well as catastrophic failure of containment vessels.

If there is a brief leak, hydrogen will rise more rapidly than either methane or propane and will disperse quickly. Hazard levels in unconfined outdoor spaces will be reduced to safe levels in a much shorter time than will those of the other fuels. Propane and gasoline vapors are both heavier than air. Consequently, they will tend to remain at ground level because they disperse more slowly. ***Hydrogen's rapid dispersion rate is its greatest safety asset.***

With a dominant buoyant effect and very high diffusion velocity, hydrogen released from brief leaks mixes with air more rapidly than other fuels. Indoors, the rapid dispersal of hydrogen may increase or decrease fire hazard, depending upon the size and geometry of confinement. In an open or outdoor area, hydrogen will disperse more quickly than do all other fuels. Consequently, regardless of whether the application involves use of hydrogen indoors or outdoors, design for safe operations becomes a guiding principle.

2.2.3 Key Properties of Hydrogen Relating to Fires and Explosions

The most widely recognized hazard in handling hydrogen is that of unwanted combustion. Characteristics of flammability and combustion include

- lean and rich flammability limits
- minimum ignition energy
- flame temperature.

Hydrogen-air mixtures, when compared to similar fuels, have a wide flammability range and a low minimum ignition energy. This is a disadvantage for the fuel.

There are also advantages to these characteristics. When a fuel ignites, the emissivity influences the total flux of heat radiated. Hydrogen's low emissivity reduces the heat transferred by radiation to objects near the flame, thus reducing the risks of secondary ignitions and burns. The average emissivity of a flame is a more significant factor than flame temperature when considering thermal radiation damage from fires. Hydrogen flames radiate less heat than do natural gas, propane, gasoline, and kerosene, although the flame temperatures of hydrogen and the other common fuels are comparable.

Because of their higher lean limits of flammability, both hydrogen and natural gas are less likely than gasoline or propane to ignite in the case of a small leak discharging into a closed area with a nearby ignition source. However, in the unlikely event of leaking hydrogen accumulating above the lean limit of flammability without ignition, hydrogen would be more likely than other common fuels to ignite because it is more likely to reach a distant ignition source due to its wider flammability range and its lower ignition energy.

With respect to explosions, the maximum burning velocity of hydrogen-air mixtures is about eight times greater than those for natural gas-air and propane-air mixtures. The high burning velocity of hydrogen is an indication of its high explosive potential and the difficulty of confining or arresting hydrogen flames and explosions—especially in closed environments. In confined areas, hydrogen storage and use pose the hazards of both combustion and explosion—as well as the transition of a combustion event into an explosion. Both processes depend upon the flame velocity, the conditions of confinement, and other factors necessary to accelerate flame velocity. The hazards of combustion and explosion of hydrogen in confined areas can be addressed with proper design, engineering, and operation. Outdoors, an explosion (i.e., a direct detonation) is not likely, except in the rare case of a large hydrogen accumulation and a high-energy ignition source (such as a lightning strike or a chemical explosion). However, a hydrogen cloud is highly unlikely to occur because hydrogen (unlike other conventional fuels) dissipates rapidly in unconfined areas.

2.3 Special Properties of Liquid Hydrogen

Many existing and emerging applications of hydrogen involve use of hydrogen in the gaseous form. However, important applications use hydrogen as a liquid. All of the safety considerations and hazards related to gaseous hydrogen also apply for liquid hydrogen because of the ease with which it evaporates. Properties of liquid hydrogen of particular concern with respect to design and safe use include

- *low boiling point* – Liquid hydrogen (at atmospheric pressure) evaporates at -423°F (-253 C).
- *ice formation* (i.e., internal condensation) – Because of its low temperature, vents and valves in storage vessels might become blocked by accumulations of ice formed from moisture in the air.
- *condensation of air* (i.e., external condensation) – Again, because of its low temperature, uninsulated lines containing liquid hydrogen can be cold enough to cause air on the outside of the pipe to liquefy.
- *continuous evaporation* – The continuous evaporation (i.e., boiling) of liquid hydrogen in a vessel generates gaseous hydrogen that must be vented safely to prevent pressure buildup.
- *higher density* – The slightly higher density of the saturated liquid hydrogen vapor might cause a hydrogen cloud to flow horizontally or vertically upon release if a liquid hydrogen leak were to occur.

Source: *The Hydrogen Handbook for Building Code and Fire Safety Officials -- Current and Innovative Uses of Hydrogen As an Energy Resource* and *Properties of Hydrogen Compared to Other Fuels*, August 2001.

3.0 Glossary

adsorption	The adhesion of the molecules of gases, dissolved substances, or liquids in more or less concentrated form, to the surface of solids or liquids with which they are in contact. Commercial adsorbent materials have enormous internal surfaces.
air	The mixture of oxygen, nitrogen and other gases which, with varying amounts of water vapor, forms the atmosphere of the earth.
alkaline fuel cell (AFC)	A type of hydrogen/oxygen fuel cell in which the electrolyte is concentrated potassium hydroxide (KOH), and hydroxide ions (OH^-) are transported from the cathode to the anode. Temperature of operation can vary from <120°C to approximately 250°C depending upon electrolyte concentration.
alternating current (ac)	A type of current that flows from positive to negative and from negative to positive in the same conductor.
alternative fuel	An alternative to gasoline or diesel fuel that is not produced in a conventional way from crude oil, for example compressed natural gas (CNG), liquefied petroleum gas(LPG), liquefied natural gas (LNG), ethanol, methanol and hydrogen.
anode	The electrode at which oxidation (a loss of electrons) takes place. For fuel cells, the anode is electrically negative; for the opposite reaction of electrolysis, the anode is electrically positive.
atmospheric pressure	The force exerted by the movement of air in the atmosphere, usually measured in units of force per area. For fuel cells, atmospheric pressure is usually used to describe a system where the only pressure acting on the system is from the atmoshpere; no external pressure is applied.
atom	The smallest physical unit of a chemical element that can still retain all the physical and chemical properties of that element. Atoms combine to form molecules, and they themselves contain several kinds of smaller particles. An atom has a dense central core (the nucleus) consisting of positively charged particles (protons) and uncharged particles (neutrons). Negatively charged particles (electrons) are scattered in a relatively large space around this nucleus and move about it in orbital patterns at extremely high speeds. An atom contains the same number of protons as electrons and thus is electrically neutral (uncharged) and stable under most conditions.
British Thermal Unit (Btu)	The mean British Thermal Unit is 1/180 of the heat required to raise the temperature of one pound (1lb) of water from 32°F to 212°F at a constant atmospheric pressure. It is about equal to the quantity of heat required to raise one pound (1 lb.) of water 1°F.
carbon (c)	An atom and primary constituent of hydrocarbon fuels. Carbon is routinely left as a black deposit left on engine parts such as pistons, rings, and valves by the combustion of fuel.

carbon dioxide (CO_2)	Carbon dixoide is a colorless, odorless, noncombustible gas that is slightly more than 1.5 times as dense as air and becomes a solid (dry ice) below –78.5ºC. It is present in the atmosphere as a result of the decay of organic material and the respiration of living organisms, and it represents about 0.033% of the air. Carbon dioxide is produced by the burning of wood, coal, coke, oil, natural gas, or other fuels containing carbon, by the action of an acid on a carbonate, or naturally from springs and wells. Carbon dioxide is a greenhouse gas and is a major contributor to the greenhouse effect.
carbon monoxide (CO)	A pollutant from engine exhaust that is a colorless, odorless, tasteless, poisonous gas that results from incomplete combustion of carbon with oxygen.
catalyst	A chemical substance that increases the rate of a reaction without being consumed; after the reaction it can potentially be recovered from the reaction mixture chemically unchanged. The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature. In a fuel cell, the catalyst facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the membrane in the fuel cell.
catalyst poisoning	The process of impurities binding to a fuel cell's catalyst, lowering the catalyst's ability to facilitate the desired chemical reaction. See also FUEL CELL POISONING.
cathode	The electrode at which reduction (a gain of electrons) occurs. In a fuel cell, the cathode has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.
Celsius	Metric temperature scale and unit of temperature (ºC). Named for Swedish astronomer Anders Celsius (1701-1744) although the thermometer first advocated by him in 1743 had 100º as the freezing point of water, and 0º as the boiling point, the reverse of the modern Celsius scale. Also called the Centigrade scale (Latin for "hundred degrees").
combustion	Burning, fire produced by the proper combination of fuel, heat, and oxygen. In the engine, the rapid burning of the air-fuel mixture that occurs in the combustion chamber.
compressed hydrogen gas (CHG)	Compressed hydrogen gas is hydrogen compressed to a high-pressure and stored at ambient temperature.
compressed natural gas (CNG)	Mixtures of hydrocarbon gases and vapors, consisting principally of methane in gaseous form that has been compressed for use as a vehicular fuel. (National Fire Protection Association (NFPA) 52)
compressor	A device used for increasing the pressure and density of gas. Also see TURBOCHARGER.
density	The amount of mass in a unit volume. Density varies with temperature and pressure.
dispersion	The spatial property of being scattered about over an area or volume
electrode	A conductor through which electrons enter or leave an electrolyte. Batteries and fuel cells have a negative electrode (the anode) and a positive electrode (the cathode).
electrolysis	The process where an electric current is passed through an electrolytic solution or other appropriate medium, causing a chemical reaction. The process of driving a redox reaction in

	the reverse direction by passage of an electric current through the reaction mixture.
electrolyte	A substance that conducts charged ions from one electrode to the other inside a fuel cell.
emission standards	Regulatory standards that govern the amount of a given pollutant that can be discharged into the air from a given source.
energy	The quantity of work a system or substance is capable of doing, usually measured in British thermal units (Btu) or Joules (J).
Fahrenheit	Temperature scale and unit of temperature (ºF). Named for German physicist Gabriel Daniel Fahrenheit (1686-1736) who was the first to use mercury as a thermometric fluid in 1714.
flammability limits	The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). Between the two limits is the flammable range in which the gas and air are in the right proportions to burn when ignited. Below the lower flammability limit there is not enough fuel to burn. Above the higher flammability limit there is not enough air to support combustion.
flashpoint	The lowest temperature under very specific conditions at which a substance will begin to burn.
flexible fuel vehicle	A vehicle that can operate on a wide range of fuels blends (e.g., blends of gasoline and alcohol) that can be put in the same fuel tank.
fuel	A material used to create heat or power through chemical conversion in processes such as burning or electrochemistry.
fuel cell	A device that uses hydrogen and oxygen to create electricity through an electrochemical process.
fuel cell poisoning	The lowering of a fuel cell's efficiency due to impurities in the fuel binding to the catalyst.
fuel cell stack	Individual fuel cells connected in series. Fuel cells are stacked to increase electrical current.
fuel processor	Device used to extract the hydrogen from fuels, such as natural gas, propane, gasoline, methanol, and ethanol, for use in fuel cells.
gas	Fuel gas, such as natural gas, undiluted liquefied petroleum gases (vapor phase only), liquefied petroleum gas-air mixtures, or mixtures of these gases. Liquefied Petroleum Gases (LPG) as used in this standard, shall mean and include any material which is composed predominantly of any of the following hydrocarbons, or mixtures of them: propane, propylene, butanes (normal butane or isobutane) and butylenes. LP Gas-Air Mixture - Liquefied petroleum gases distributed at relatively low pressures and normal atmospheric temperatures which have been diluted with air to produce desired heating value and utilization characteristics. Natural Gas - Mixtures of hydrocarbon gases and vapors consisting principally of methane (CH_4) in gaseous form.
gas diffusion	Mixing of two gases caused by random molecular motions. Gases diffuse very quickly; liquids diffuse much more slowly, and solids diffuse at very slow (but often measurable) rates. Molecular collisions make diffusion slower in liquids and solids.
hydrocarbon (HC)	An organic compound containing only carbon and hydrogen, usually derived from fossil fuels such as petroleum, natural gas, and coal: an agent in the formation of photochemical smog.
hydrogen (H_2)	The simplest and lightest element in the universe, which exists as a gas except at low

	cryogenic temperatures. Hydrogen gas is colorless, odorless and highly flammable gas when mixed with oxygen over a wide range of concentrations. Hydrogen forms water when combusted, or when otherwise joined with air, as within a fuel cell.
hydrogen-rich fuel	A fuel that contains a significant amount of hydrogen, such as gasoline, diesel fuel, methanol (CH_3OH), ethanol (CH_3CH_2OH), natural gas, and coal.
kilogram (kg)	Metric unit of weight or mass, equal to approximately 2.2 lb. Related units are the milligram (mg) at 1000 per kg, and the metric tonne at 1000 kg.
kilowatt (kw)	A unit of power equal to about 1.34 hp, or 1000 watts. The watt is named for James Watt, Scottish engineer (1736-1819), a pioneer in steam engine design.
liquefied hydrogen (LH_2)	Hydrogen in liquid form. Hydrogen can exist in a liquid state, but only at extremely cold temperatures. Liquid hydrogen typically has to be stored at -253 ºC (-423 ºF) . The temperature requirements for liquid hydrogen storage necessitate expending energy to compress and chill the hydrogen into its liquid state. The cooling and compressing process requires energy, resulting in a net loss of about 30% of the energy that the liquid hydrogen is storing. The storage tanks are insulated, to preserve temperature, and reinforced to store the liquid hydrogen under pressure.
liquefied natural gas (LNG)	Natural gas in liquid form. Natural gas is a liquid at -162 ºC (-259 ºF) at ambient pressure.
liquefied petroleum gas (LPG)	Any material that is composed predominantly of any of the following hydrocarbons or mixtures of hydrocarbons: propane, propylene, normal butane, isobutylene and butylenes.
meter (m)	Basic metric unit of length equal to 3.28 feet, 1.09 yards or 39.37 inches. Related units are the decimeter (dm) at 10 per meter, the centimeter (cm) at 100 per meter, the millimeter (mm) at 1000 per meter and the kilometer (km) at 1000 meters.
methane (CH_4)	See NATURAL GAS.
methanol (CH_3OH)	Methyl alcohol is the simplest of the alcohols. It has been used, together with some of the higher alcohols, as a high-octane gasoline component and is a useful automotive fuel in its own right.
natural gas	A naturally occurring gaseous mixture of simple hydrocarbon components (primarily methane) used as a fuel.
nitrogen (N_2)	A colorless, tasteless, odorless gas that constitutes 78% of the atmosphere by volume and is a part of all living tissues.
oxygen (O_2)	A colorless, tasteless, odorless, gaseous element that makes up about 21% of air. Oxygen is capable of combining rapidly with ALL elements (except inert gases) in the oxidation process called burning (combustion). Oxygen combines very slowly with many metals in the oxidation process called rusting.
phosphoric acid fuel cell (PAFC)	A type of fuel cell in which the electrolyte consists of concentrated phosphoric acid (H_3PO_4) and protons (H+) are transported from the anode to the cathode. The operating temperature range is generally 160-220°C.
polymer electrolyte membrane (PEM)	A solid membrane, similar in consistency to thick plastic wrap, used as an electrolyte in fuel cells. The membrane allows positively charged ions to pass through it, but blocks electrons. See also POLYMER ELECTROLYTE MEMBRANE FUEL CELL.
polymer electrolyte membrane fuel cell	A type of acid-based fuel cell in which the transport of protons (H+) from the anode to the cathode is through a solid, aqueous membrane impregnated with an appropriate acid. The

(PEMFC or PEFC)	electrolyte is a called a polymer electrolyte membrane (PEM). The fuel cells typically run at low temperatures (<100°C).
propane (C_3H_8)	See LPG. REFORMATE
	Hydrocarbon fuel that has been processed into hydrogen and other products for use in fuel cells.
reformer	Device used to extract the hydrogen from fuels, such as natural gas, propane, gasoline, methanol, and ethanol, for use in fuel cells.
reforming	A chemical process that reacts hydrogen-containing fuels in the presence of steam, oxygen, or both into a hydrogen-rich gas stream.
reformulated gasoline	Gasoline that is blended so that, on average, it significantly reduces volatile organic compounds and air toxics emissions relative to conventional gasolines.
solid oxide fuel cell (SOFC)	A type of fuel cell in which the electrolyte is a solid, nonporous metal oxide, typically zirconium oxide (ZrO_2) doped with Y_2O_3, and O_2- is transported from the cathode to the anode. Any carbon monoxide (CO) in the reformate gas is oxidized to carbon dioxide (CO_2) at the anode. Temperatures of operation are typically 800-1,000°C.
stack	See FUEL CELL STACK.
steam reforming	The process for reacting a hydrocarbon fuel, such as natural gas, in the presence of steam to form hydrogen as a product. This is a common method of bulk hydrogen generation.
technology validation	Confirming that technical targets for a given technology have been met.
temperature	A measure of thermal content. See also AMBIENT TEMPERATURE.
water (H_2O)	A colorless, transparent, odorless, tasteless liquid compound of hydrogen and oxygen. The liquid form of steam and ice. Fresh water at atmospheric pressure is used as a standard for describing the relative density of liquids, the standard for liquid capacity, and the standard for fluid flow. The melting and boiling points of water are the basis for the Celsius temperature system. Water is the only byproduct of the combination of hydrogen and oxygen, and is produced during the burning of any hydrocarbon. Water is the only substance that expands on freezing as well as by heating, and has a maximum density at 4ºC.

Source: *DOE's Hydrogen, Fuel Cells and Infrastructure Technologies Program's Glossary of Terms.*
http://www.eere.energy.gov/hydrogenandfuelcells/glossary.html.