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CLEAN AIR PROGRAM: DESIGN GUIDELINES FOR BUS TRANSIT SYSTEMS USING HYDROGEN AS AN ALTERNATIVE FUEL

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13. ABSTRACT (Maximum 200 words)

Alternative fuels such as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), and alcohol fuels (methanol and ethanol) are already being used in commercial vehicles and transit buses in revenue service. Hydrogen, which has better air quality characteristics as a vehicle fuel, is being used in research demonstration projects in fuel cell powered buses, as well as in internal combustion engines in automobiles and small trucks. At present, there are no facility guidelines to assist transit agencies (and others) contemplating the use of hydrogen as an alternative fuel. This document addresses the various issues involved.

Hydrogen fuel properties, potential hazards, fuel requirements for specified levels of bus service, applicable codes and standards, ventilation, and electrical classification are indicated in this document. These guidelines also present various facility and bus design issues that need to be considered by a transit agency to ensure safe operations when using hydrogen as an alternative fuel. Fueling facility, garaging facility, maintenance facility requirements and safety practices are discussed. Critical fuel-related safety issues in the design of the related systems on the bus are also identified. A system safety assessment and hazard resolution process is also presented. This approach may be used to select design strategies which are economical, yet ensure a specified level of safety.

This report conforms to the format of a series of monographs being published by the U.S. DOT/FTA on the safe use of alternative fuels. Documents similar in content to this one have been published for CNG, LPG, LNG, and methanol/ethanol by the U.S. DOT/FTA.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	= 2.5 centimeters (cm)
1 foot (ft)	= 30 centimeters (cm)
1 yard (yd)	= 0.9 meter (m)
1 mile (mi)	= 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	= 28 grams (gm)
1 pound (lb)	= 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	= 5 milliliters (ml)
1 tablespoon (tbsp)	= 15 milliliters (ml)
1 fluid ounce (fl oz)	= 30 milliliters (ml)
1 cup (c)	= 0.24 liter (l)
1 pint (pt)	= 0.47 liter (l)
1 quart (qt)	= 0.96 liter (l)
1 gallon (gal)	= 3.8 liters (l)
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	= 0.04 inch (in)
1 centimeter (cm)	= 0.4 inch (in)
1 meter (m)	= 3.3 feet (ft)
1 meter (m)	= 1.1 yards (yd)
1 kilometer (k)	= 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	= 1 hectare (he) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	= 0.036 ounce (oz)
1 kilogram (kg)	= 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)	= 1.1 short tons

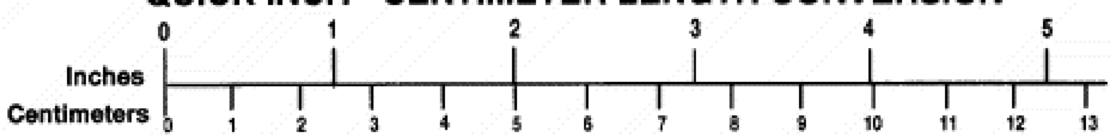
VOLUME (APPROXIMATE)

1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 liter (l)	= 2.1 pints (pt)
1 liter (l)	= 1.06 quarts (qt)
1 liter (l)	= 0.26 gallon (gal)
1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Chapter 1
Introduction

A large number of transit buses in revenue service in the United States are using alternative fuels (alternative to gasoline and diesel). At the end of 1997, over 2,300 transit buses in service were using Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG), Liquefied Natural Gas (LNG), and alcohol fuels (methanol and ethanol). CNG is by far the fuel of choice; over 1500 buses (i.e., about 65% of the alternative fuel bus fleet) use CNG. The use of hydrogen as an alternative bus fuel began in early 1998 with Chicago Transit Authority placing three hydrogen-powered buses in revenue service. The hydrogen in these buses is maintained in a compressed state and is used to power a fuel cell which in turn generates electricity to drive the wheel motors.

One of the key issues in the use of alternative fuels in transit buses is safety. Over the past two years, the Federal Transit Administration (FTA) has published a series of guideline documents for the safe design and operation of transit facilities in which buses powered by alternative fuels are stored or maintained. So far the alternative fuels covered by these design guidelines include CNG, LPG, LNG, or alcohol fuels. The FTA recognized the need to address the safety of hydrogen use as an alternative fuel in transit vehicles, and therefore initiated the work reported in this document.

This report addresses some of the issues related to the use of hydrogen as a transit vehicle fuel. The format of the report is similar to the format followed in each of the previous FTA publications related to the use of alternative fuels (CNG, LPG, LNG, and alcohol fuels) in bus transit systems[1] Each report in this series describes, for the subject fuel, the important fuel properties; guidelines for the design and operation of bus fueling, storage, and maintenance facilities; and issues of personnel training and emergency preparedness.

1.1 BACKGROUND

The Clean Air Act Amendments of 1990 mandate the reduction in tailpipe emissions of air pollutants from mobile sources including heavy duty vehicles or engines. In addition, the National Energy Policy Act of 1992 set a national goal to replace the use of up to 30% of petroleum fuel with alternative fuels by the year 2010 and mandates the use of alternative fuels in the nation's federal, state, and fuel provider fleets at a rate not less than the promulgated phase-in rate. In addition, several states have promulgated statutes encouraging or requiring the use of alternative fueled vehicles by fleet operators.

[1] See the citation to these documents authored by Raj, Hathaway and Kangas, 1995 & 1996 in the section on References.

The increasing use of alternative fuels in the nation's transit bus fleet is a consequence of the above statutes and by the FTA's Alternative Fuels Initiative (AFI) initiated in 1988. The AFI includes field testing, demonstration and assistance in revenue service placement of buses powered by CNG, LNG, LPG, alcohol fuels, and hydrogen fuel cells.

Each of these alternative fuels has unique physical and chemical properties which differ from those of traditional diesel fuels in common use in transit bus fleets operating in the U.S. Transit agencies have decades of knowledge and experience on the use, handling and storage of diesel fuels. However, the use of these alternative fuels in buses is relatively new. The unique properties of the fuels affect usage, storage, handling and response to emergencies.

A number of transit agencies are already operating fleets of alternative fuel buses. However, the transition has been somewhat difficult because of the absence of adequate guidelines to address the issues involved in the design of facilities and vehicles to ensure a safe and smooth transition. The industry as a whole is learning from the experience of some of the pioneers in the transit industry who have successfully converted to operating alternative fuel buses. There is, however, an urgent need to provide guidance to other transit systems that are either contemplating transitions or are initiating the process in the near future. This document is intended to provide some guidance to these transit agencies in their efforts to make the transition to alternative fuel safe and efficient.

1.2 PURPOSE AND SCOPE

The purpose of this document is to: discuss the various safety issues related to the use of hydrogen; provide guidance and information on safe practices followed in the industrial gas and chemical industries (which produce, store, transport, and use hydrogen in a number of industrial processes); discuss applicable regulations, codes and standards (both national and regional, if any); and, in general, discuss issues to be considered when converting an existing diesel facility, or building a new facility, to service hydrogen fueled vehicles.

The scope of this document is limited to discussing issues related to bus facilities, e.g., bus fueling, storage, and maintenance facilities. The overall safety of a hydrogen use facility depends not only on safety systems designed into the fixed facilities but also on the safety systems included in the bus design and the knowledge and training of personnel. Therefore, this document also addresses bus fuel systems and personnel training issues.

In Chapter 2, issues and practices related to the use of hydrogen as an alternative fuel are considered. The topics discussed include:

- Relevant hydrogen properties
- Approaches to storing hydrogen on board the vehicle
- Design issues related to
    - Fueling facility
    - Vehicle storage/parking facility
    - Repair/maintenance facility
    - Bus fuel system and safety features
- Personnel training and operational procedures
- Emergency preparedness and other special issues

An approach to performing a system safety analysis using the methods conforming to Military Standard (MIL Std) 882(3 is described in Chapter 3. The system safety process is applicable when guidance on a specific design approach is not available or when a unique design issue warrants the use of detailed hazard analysis. The hazard resolution process requires giving full consideration to all elements of the alternative fuels system, including the vehicle. In addition, this assessment procedure may be beneficial when a transit authority initially begins operation with a small number of alternative fuel vehicles.

This document is intended to be a reference guideline document on facility design issues and SHOULD NOT be considered as a specification manual or a substitute for existing local, state or national codes and regulations. In addition, the reader should consider the following issues when reading this document.

- Every facility that is either being modified or constructed anew should be in compliance with all local, state and national codes and regulations.

- The information provided in this guidebook is by no means exhaustive on the subject of facility design or personnel training or any other associated issues. The transit system should consult with knowledgeable engineers, consultants, fuel supplier, design architectural & engineering (A&E) firm(s) and the staff of the local authority having jurisdiction to design the facility consistent with local codes, regulations, and local
- conditions.

- This document references sections of national codes or regulations. Such references to particular sections of the standards or the regulations are NOT intended to convey the impression that only those sections apply. It is, however, intended to get the reader started or even directed to the appropriate sections in the standards or the codes. It is recommended that the entire provisions of a currently adopted code or standard be reviewed thoroughly.

1.3 DOCUMENT ORGANIZATION

This document is organized into three chapters, and each chapter number is represented by a numeral. Verbatim quotations from regulations or technical standards are italicized. Other information related to report organization include the following.

Glossary. A Glossary is provided at the end of the document in which the definitions of several terms used are indicated. When a term defined in the glossary is used in the text, it is highlighted (bolded and italicized) for clarity. All acronyms when first used are expanded in the text. Also, a list of acronyms is provided at the end of this document.

Graphic Symbols or Icons. Informational icons are used to draw a reader' s attention to some important aspect of the discussion. Where a statute, regulation or standard is being cited verbatim, the source of the work is acknowledged with an appropriate icon. The section numbers indicated in these citations refer to the section number in the original code or standard. The other type of icon used is intended to provide additional information or raise a cautionary flag to the reader. A list of icons and their definitions is provided at the end of this document. Very important communications to the readers are enclosed in boxes.

Units. All units of measure identified in this document are in Standard International units (meters, kilograms, seconds, Kelvin, etc.). Values in conventional British units are provided in parenthesis. Where verbatim citations are provided, the units used in the codes or standards are cited without any change.

Footnote. In many cases, footnotes are included to expand the information content of a sentence. One can read this document without reading the footnotes and not lose any important information.

Acronyms. References to regulations or standards are made by providing the acronym for the regulation/standard followed by the relevant section number. All references to the National Fire Protection Association (NFPA) standards are to their latest published editions. These may not necessarily be the version adopted by the local or state regulatory authorities. Readers are encouraged to identify the current adopted vintage of the standards in their community. The information provided in this document can then be used to refer to the appropriate chapters/sections in the currently adopted standards to obtain current requirements. It is cautioned, however, that because of the differences in editions, some requirements may vary from those discussed in this document. However, the requirements of currently adopted standards take precedence.

1.4 LIST OF STATUTES, REGULATIONS AND STANDARDS

Listed below are several statutes, regulations, codes, and standards that are relevant to the use of alternative fuel in buses. Not all of these have been cited or referenced in the text to follow. They are included as sources of additional information.

1.4.1 *Statutes*

- Clean Air Act Amendments, 1990, Title U[, "Provisions Relating to Mobile Sources," PL 101-549.

- Energy Policy Act of 1992 (EPACT), Public Law 102-486.

- Alternative Motor Fuels Act of 1988 (AMFA), Public Law 100-494.

1.4.2 *Regulations*

- Code of Federal Regulations, 29 CFR, Subpart H, Section 1910. 103: "Hydrogen".

1.4.3 *Standards*

The following NFPA standards can be obtained from the National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy MA 02269-9101 or by calling 1-800-344-3555.

- NFPA 50A -- Standard for Gaseous Hydrogen Systems at Consumer Sites (1994 Edition).

- NFPA 50B -- Standard for Liquefied Hydrogen Systems at Consumer Sites (1994 Edition).

- NFPA 54 -- National Fuel Gas Code. This code is a safety code that shall apply to the installation of fuel gas piping systems, fuel gas utilization equipment, and related accessories.

- NFPA 70 -- National Electric Code. The purpose of this code is the practical safeguarding of persons and property from the hazards arising from the use of electricity.

- NFPA 88A -- Standard for Parking Structures. This standard covers the construction and protection of, as well as the control of hazards in, open, enclosed, basement, and underground parking structures. This standard does not apply to one- and two-family dwellings.

- NFPA 88B -- Standard for Repair Garages. This standard covers the construction and protection of, as well as the control of hazards in, garages used for major repair and maintenance of motorized vehicles and any sales and servicing facilities associated therewith.

- NFPA 497A - Recommended Practice for Classification of Class I Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas. This recommended practice applies to locations where flammable gases or vapors, flammable liquids or combustible liquids are processed or handled and where their release to the atmosphere may result in their ignition by electrical systems or equipment.

The primary standards that apply specifically to hydrogen systems are NFPA 50A and NFPA 50B. These industry consensus standards stipulate the requirements for the design of hydrogen systems (including containers, pressure relief devices, equipment assembly, marking, etc.), location of hydrogen storage areas, operation and maintenance, fire protection and other safety requirements. No specific standards exist for vehicular hydrogen fueling systems, requirements for operation of vehicles, specification for the vehicle storage and maintenance buildings.

The focus of the Occupational Safety and Health Administration (OSHA) regulations in 29 CFR, g 1910. 103 is primarily the safety of the worker in a plant that stores or uses hydrogen. Substantial parts of these regulations are adaptations of the various requirements in NFPA 50A and NFPA 50B. In this document, the various requirements from NFPA Standards are referred to and the exact language from the relevant sections is cited where necessary.

Chapter 2
Issues & Practices Related to Hydrogen

2.1 GENERAL FUEL PROPERTIES

Hydrogen (H_2) is a gas at normal temperature and pressure. It is the lightest of all elements and is one of the molecular constituents of water. The importance of hydrogen as a vehicle fuel arises from the fact that it is combustible and that the products of combustion contain principally water vapor and only trace oxides of nitrogen. The absence of oxides of carbon (carbon monoxide and carbon dioxide) and particulate matter (soot) in the tailpipe emissions from a hydrogen burning engine make it very attractive for use in internal combustion engines powering road vehicles.

Hydrogen is used as a transportation fuel in three different forms, namely, gaseous hydrogen stored in tanks at elevated pressure, liquid hydrogen held in cryogenic dewars, and chemically bound in metal hydrides. Discussed below are the properties of hydrogen and issues of safety in each form of the hydrogen fuel for vehicular use.

Table 2- 1 provides some important data on the properties of hydrogen. For purposes of comparison, corresponding properties of methane and gasoline vapors are also indicated.

2.1.1 *Properties of Gaseous Hydrogen*

Flammability. Hydrogen has the widest range of flammable concentrations in air among all common gaseous fuels. This range is between the lower limit of 4% to an upper limit of 75% by volume. Because of this wide range, a given volume of hydrogen release will present a large flammable volume, thus increasing the probability of ignition. However, other properties such as high buoyancy and high diffusivity in air tend to reduce the duration over which a large volume of the gas-air mixture is in the flammable concentration range, resulting in a decrease in the ignition potential with time.

Table 2-1
Comparison of the Properties of Hydrogen, Methane, and Gasoline
(at ambient conditions unless noted otherwise)

Property	Hydrogen			Methane			Gasoline	
	SI Units	British Units		SI Units	Briti$h Units		SI Units	British Units
Normal State at 289 K (60 "F) and Ambient Pressure	Gas			Gas			Liquid	
Boiling Point at Atmospheric Pressure	20.3 K	423.5 F		112 K	258"F		N/A	N/A
Liquid Density at Normal Boiling Point (NBP)	70.8 kg/m^3	4.41b/ft^3		422.6kg/m^3	26.41b/ft^3		700 kg/m^3	43.7 lb/ft^3
Vapor Density at NBP	1.34 kg/m^3	0.0836 lb/ft^3		1.82 kg/m^3	0.114 lb/ft^3		4.5 kg/m^3	0.28 lb/ft^3
VaporDensityat293 K and at following pressures:	kg/m^3	lb/ft^3	R_v/R_a (Note 2)	kg/m^3	lb/ft^3	R_v/R_a (Note 2)	kg/m^3	lb/ft^3
0.1 MPa (0 psig) Atmospheric(1)	0.0838	0.0052	0.07	0.651	0.041	0.556	4.4	0.275
13.9 MPa (2000 psig)	10.58	0.660	8.82	111.2	6.94	92.70	N/A	N/A
25.0 MPa (3600 psig)	17.81	1.112	14.84	189.0	11.8	157.5	N/A	N/A
34.0 MPa (5000 psig)	23.43	1.463	19.53	230.0	14.4	191.7	N/A	N/A

Table 2-1
(Continued)

Property	Hydrogen		Methane		Gasoline	
	SI Units	British Units	SI Units	Briti$h Units	SI Units	British Units
Limits of Flammability in Air	Volume Concentrations		Volume Concentrations		Volume Concentrations	
• Lower Flammability Limit	4.0%		5.3%		1.0%	
• Upper Flammability Limit	75.0%		15.0%		7.6%	
Limits of Detonability in Air						
• Lower Detonability Limit	18.3%		6.3%		1.1%	
• Upper Detonability Limit	59.0%		13.5%		3.3%	
Stoichiometric (Volume) Composition in Air	29.53 %		9.48 %		1.76 %	
Minimum Ignition Energy	0.02 mJ	--	0.29 mJ	--	0.24 mJ	--
Autoignition Temperature	858 K	1,084 ^oF	813 K	1,003 ^oF	501-744 K	442-879 ^oF
Max. Flame Temperature[(3)]	1,800 K	2,780 ^oF	1,495 K	2,230 ^oF	1,520 K	2,275 ^oF
Heat of Combustion						
• Lower Heat	120 MJ/kg	51,600 Btu/lb	50 MJ/kg	21,500 Btu/lb	44.5 MJ/kg (118 MJ/gal)	17,40 Btu/lb (104,200 Btu/gal)
•						
• Higher Heat	142 MJ/kg	61,050 Btu/kg	55.5 MJ/kg	23,900 Btu/kg	48 MJ/kg (127.2 MJ/gal)	20,650 Btu/lb (120,625 Btu/gal)
Molecular Diffusivity (Gas in Air)	6.1×10^{-5} m^2/s	0.236 ft^2/hr	1.6 x 10-5 m2/s	0.062 ft^2/hr	5 x 10-6 m2/s	0.019 ft^2/hr

Sources: *Herd (1976), McCarty(l975), ASHRAE (1969)*

Notes (1) The condition of 293 K temperature & one atmosphere pressure referred to as Standard Temperature & Pressure (STP)

(2) R_v/R_a, represents the ratio of density of vapor and density of air at Standard conditions

(3) Measured diffusion flame temperatures (Burgess & Hertzberg, 1974)

Ignitability. A flammable concentration of hydrogen-air mixture can be ignited either by a spark or by heating the mixture to its ***autoignition temperature***. The minimum spark energy required for ignition of hydrogen in air is about an order of magnitude (i.e., by about a factor of 10) less than that for methane or gasoline vapor. However, in absolute terms, the ignition energy for all three gases is low so that exposure to weak sparks, hot surfaces, or flames (matches) is sufficient to ignite them. A static electricity spark produced by the human body (in dry conditions) is sufficient to ignite hydrogen.

Hydrogen has a higher ***autoignition temperature*** compared to that of gasoline (see Table 2-1). However, the low ignition energy characteristic makes it more readily ignitable. The hot air-jet ignition temperature for hydrogen is 943 K (compared to 1,493 K for methane and 1,313 K for gasoline). Hence, hydrogen can easily get ignited by ajet of hot combustion products emitted from an adjacent enclosure.

Burning Velocity. The value for this property (also called the "**laminar flame velocity**") is high for hydrogen (2.7 to 3.3 m/s at STP) compared to that of methane (0.37 to 0.45 m/s) or gasoline (0.37 to 0.43 m/s). The burning velocity influences the severity of explosion and, together with the flame quenching distance (6.4×10^{-4} m for hydrogen, 2×10^{-3} m for both methane and gasoline), determines the design of flame arrestors to prevent flame flashback into a hydrogen tank.

Explosion/Detonation. Hydrogen has a wide concentration range in air over which it is detonable. In long tubes and tunnels, an ignition of hydrogen-air mixture in the detonable range will result in an initial "deflagration" flame which will transition to a "detonation" front after a certain induction" length. The induction distance is least for hydrogen compared to the induction lengths in methane-air or gasoline-air mixtures. The detonation velocity in a hydrogen-air mixture can be as high as 1.5 km/s to 2.2 km/s. The energy of' explosion of hydrogen, expressed in kg of TNT per kg of fuel is 24, compared to 11 for methane and 10 for gasoline. <u>Hence, on an equal mass basis, hydrogen explosions will be more destructive than those from gasoline</u>.

Characteristics of Leaks and Dispersion. The relatively small molecular diameter of hydrogen (1.58 A~, compared to those of all other gaseous fuels, makes fuel lines and fuel systems more susceptible to a hydrogen leak (Hansel et al., 1993). The occurrence of hydrogen leaks from properly mated metal-to-metal seals (flared or compression joints) in a hydrogen line is remote. However, non-metal seals, such as gaskets, packings, and pipe thread compounds, present a high probability for leaks. While catastrophic failure of metal joints is highly unlikely, large sudden failures in non-metal seals can occur due to the embrittlement of the materials.

If the leak rate is small due to the hydrogen passing through tortuous paths in the seals, mixing of the released hydrogen with air is determined by buoyancy and molecular diffusion in the absence of air currents. Hydrogen has very high buoyancy (its gas density is only 7% that of air). Because both the diffusivity and buoyancy are high, release of hydrogen at a small leak rate results in its rapid mixing with air. In the case of a large leak rate (e.g., from large failure of a gasket), the exiting jet of hydrogen will be turbulent and result in very rapid mixing with air. Hansel et al., calculate that a turbulent hydrogen jet will be diluted to near air concentrations within a distance of 500-1,000 jet hole diameter. Therefore, if the jet is ignited, the flame length will be less than about 500 diameters from the hole (e.g., for a 1 mm diameter leak, the flame length will be less than 0.5 m).

Hydrogen Flame Properties. A hydrogen flame (or fire) is nearly invisible even though the flame temperature is higher than that of hydrocarbon fires. This is because of the absence of soot in a hydrogen fire. The presence of a hydrogen fire can be inferred, however, from the air density stratification along and above the flame ("mirage" effect). The near invisibility of hydrogen flame poses serious hazards to personnel in an industrial setting. A small leak from a gasket in a pipeline may have been ignited by static electricity but will be invisible to a casual inspection of the pipeline, and it is possible to get burned by the "torch fire."

Hydrogen Embrittlement. Constant exposure of certain types of ferritic steel s to hydrogen results in the embrittlement of the metals. Such embrittlement can cause cracks in pipes, welds, and metal gaskets. The sensitivity of embrittlement of a metal depends upon, in addition to the material characteristics, the purity of hydrogen, the metal stress and plastic deformation, temperature, pressure, and the periodicity in pressure variations, among other items (Ringland, 1994). Stainless steel has a better embrittlement resistance property than ordinary steels. Pure aluminum and most of the aluminum alloys are considered to have better resistance to embrittlement than that of stainless steel, provided the gas is dry (Ringland, 1994). Therefore, when considering the material for critical (hydrogen) systems, it is very important to evaluate the susceptibility of the metal to embrittlement when exposed to hydrogen.

2.1.2 *Properties of Liquid Hydrogen*

Hydrogen liquefies at 20.3 K (-423.5 ^{o}F) at atmospheric pressure. The density of the liquid is 70.8 kg/m^3 which is only 7% of the density of water. A cubic meter volume of liquid hydrogen contains 70.8 kg of hydrogen, whereas a cubic meter of water contains 111 kg of hydrogen. That is, water packs more mass of hydrogen per unit volume because of the tight molecular structure compared to the mass of hydrogen in the same volume of liquid hydrogen at its boiling temperature.

Since the temperature of liquid hydrogen (LH_2) is very low, spills of LH_2 onto any surface (say, the ground) results in very rapid boil off and generation of gaseous hydrogen. This gas is dispersed in air quickly (because of its initial near-neutral buoyancy) in a turbulent wind. Hydrogen gas becomes lighter than air (buoyant) once its temperature exceeds about 20 K. If an LH_2, pool is ignited, it bums very rapidly (at 3 to 6 cm/min compared to 0.3 to 1.2 cm/min for liquid methane, and 0.2 to 0.9 cm/min for gasoline pools).

Pipelines carrying LH, should be adequately insulated, otherwise internal boiling will occur, and the liquid flow will become a two-phase flow leading to pump failures. Also, if a ***LH_2*** pipeline is exposed to air, because of the low temperature, air condenses (liquefaction temperature for oxygen is 90 K and that for nitrogen is 77 K). Any leak of hydrogen in an area of high oxygen concentration (e.g., the condensation of air) can lead to a very hazardous situation with a potential for explosion.

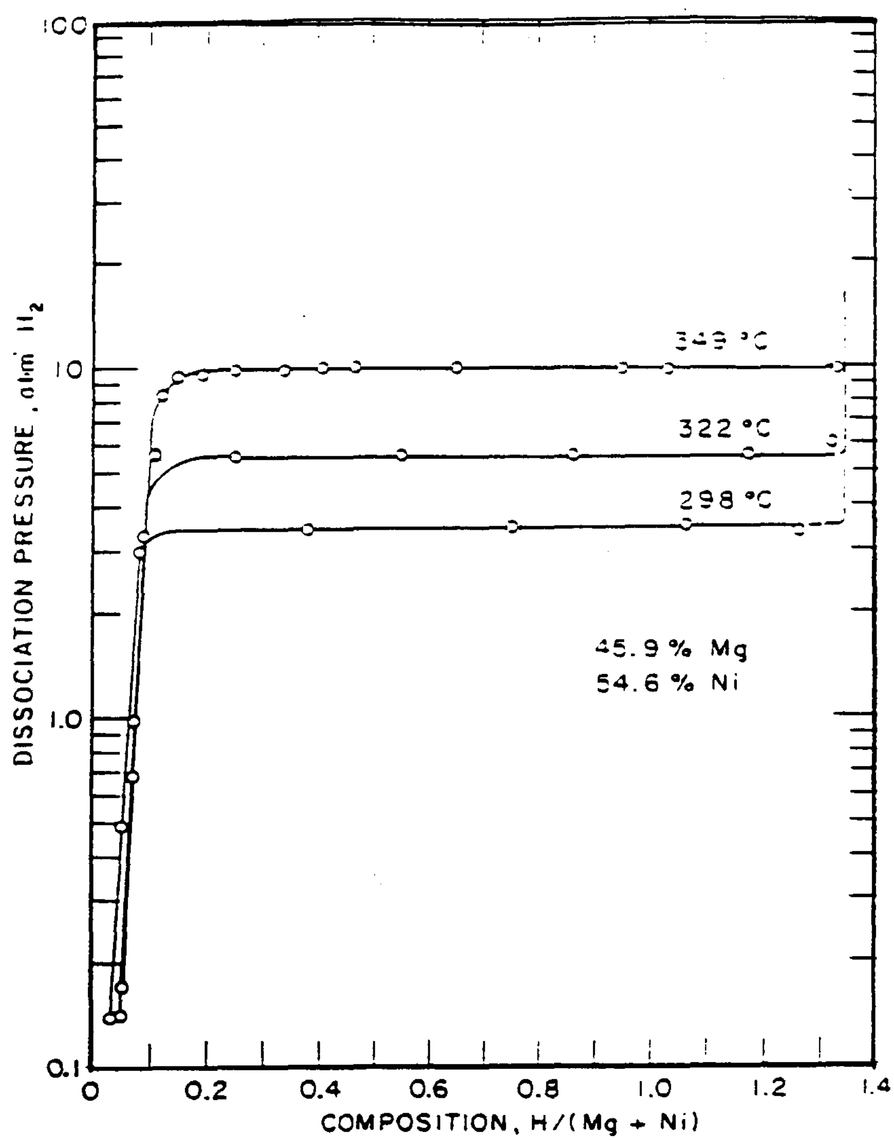
2.1.3 *Chemically-Bound Hydrogen in Metal Hydrides*

One of the methods of storing hydrogen for use in ground transport vehicles is in the form of metal hydrides. Certain metals, such as magnesium, nickel, iron, titanium, and certain metal alloys (iron-titanium, lanthanum-nickel-aluminum, etc.) combine with hydrogen under conditions of high pressure (15 to 20 atmospheres) and relatively moderate temperature (330 to 600 K) to form metal hydrides (Hueng, 1997; Waide et al., 1975). The metal hydrides dissociate and release hydrogen when the pressure is reduced or the temperature is increased. Figure 2-1 shows the typical variation of the amount of hydrogen chemically bound as a function of pressure and temperature. The hydrogen "holding" property of metal hydrides depends on the type of the hydride and other conditions.

Table 2-2 illustrates the properties of typical hydrides. As seen from this table, the mass of hydrogen held in the hydrides is between 1C/o and 2% by weight of the base material. A high value of 7.3% by weight absorbed hydrogen is indicated in the case of magnesium hydride. The temperature at which hydrogen desorption occurs is relatively low.

In general, the total weight of the hydride together with the hydrogen absorbed is relatively large even for moderate hydrogen mass. For example, a gallon of gasoline is equivalent (in heat energy) to 1 kg of hydrogen. Therefore, to store 20 kg of hydrogen (equivalent of 20 gallons of gasoline) in hydride form will require 275 kg of magnesium hydride (MgH_2) at 7.3% hydrogen absorption efficiency. The weight of "fuel" and the hydride will be 295 kg (about 650 Ibs). If other hydrides are used, the total weight will be substantially higher.

Hydrogen gas is generated by heating the hydride bed with the waste heat (from an engine or a fuel cell) which initiates a dissociation reaction at slightly above the ambient temperature. The dissociation of MgH_2 with the release of hydrogen results in the absorption of heat from the outside at a rate of about 37 MJ/kg (15,900 Btu/lb) of hydrogen released.



Source- *Waide et al, 1975*

Figure 2-1

Pressure Composition Isotherm Mg_2Ni_2H, System

Table 2-2

Comparison of the Characteristics of Metal Hydrides

Property	Lanthanum-Nickel-Aluminum	Magnesium-Nickel Hydride	Iron-Titanium Hydride
Material Formula	$Lm_{1\ 06},Ni_{4\ 96}Al_{0\ 06}$	Mg_2NiH_2	$FeTiH_{1\ 6}$
Absorption Pressure	18.5 Atm	7 Atm	15 Atm
Desorption Pressure	13.5 Atm	NA	7 Atm
Absorption/Desorption Temperature	333 K (140 ^{o}F)	333 K (140 ^{o}F)	313 K (140 ^{o}F)
Hydrogen Capacity at 313 K and 20 Atmospheres Pressure	1.27 % by weight	7.3 % by weight	1.5 % by weight
Bulk Density of Hydride	2962 kg/m^3	897 kg/m^3	2400 kg/m^3
Weight of Hydride to store 15 kg of hydrogen	1250 kg	206 kg	1000 kg
Data Reference	Heung (1997)	Waide et al. (1974)	Waide et al. (1974)

2.1.4 *Hydrogen Storage on Vehicles*

As indicated earlier, there are three practical methods for storing hydrogen in "***fuel tanks***" on board transit and other road vehicles. These methods are discussed below.

Compressed Hydrogen Gas (*CHG*). This mode of storage is very similar to the current practice of storing ***CNG*** in pressure vessels. ***CNG*** is stored in lightweight composite material cylinders at pressures up to 28 MPa (4,000 psig). It is, however, important to evaluate the compatibility of the storage vessel material with hydrogen before it can be used as a pressure vessel. Also, because of the consequences of leaks from tanks and because the valve stem represents the weakest part of the storage system, generally, the valve assembly in the tank is protected by a metal sleeve. The tanks are provided with ***Pressure Relief Devices (PRDs).*** Also, the pressure regulator(s) used in the fuel line are provided with a heat source to prevent icing caused by the low temperature due to gas expansion.

Liquefied Hydrogen Storage (*LH_2*). Hydrogen liquid at its normal boiling point (20.3 K) is stored at or close to ambient pressure in a vacuum jacketed (double walled) container suitable for vehicle use. Notwithstanding the vacuum jacket and the thermal insulation for the primary storage tank, heat will leak in and increase the tank pressure. These vessels are typically called dewers. Current best technology can limit the heat leak to a boiloff of about 1.8% of the tank inventory per day (Hansel et al., 1993). The tank pressure will have to be relieved by venting the excess boiloff hydrogen. Relief valves are therefore provided on these tanks. Large vessels, such as tanker truck tanks transporting ***LH_2*** have, in addition to a vacuumjacket, a liquid nitrogenjacket to further reduce heat leak into ***LH_2***.

Metal Hydride Storage. A typical hydrogen storage system in metal hydrides consists of solid (powdered) metal hydride in a "tank." The tank is heated by the engine exhaust gases (or by the engine coolant depending on the design). A schematic representation of a hydride storage system for vehicular use is shown in Figure 2-2. The hydride tank operates between I to 2 atmosphere (absolute) pressure. The starter hydrogen may be provided by a separate ***CHG*** tank or from an ***LH_2*** tank (Billings, 1975). The use of metal hydride has been demonstrated recently in a hybrid-electric bus of 10 m length (Heung, 1997). Hydrogen generated by heating the metal hydride is used in a conventional 70 kW internal combustion engine. The electricity generated by the engine-generator power plant is used to recharge electric batteries on the bus. Figure 2-3 shows schematically the metal hydride storage vessel used on the bus.

2.1.5 *Fuel Economy and Diesel Equivalence*

The heat of combustion of hydrogen, on a mass basis, is about 2.8 times the heat of combustion of common hydrocarbon fuels (gasoline, diesel, etc.). Therefore, for a given load duty, measured in energy units, the mass of hydrogen required is only about one-third the mass of hydrocarbon fuel needed. However, the volume of the hydrogen "***fuel tank***" depends on the type of storage of hydrogen on board a vehicle. Table 2-3 shows the diesel equivalent volumes for different hydrogen storage strategies.

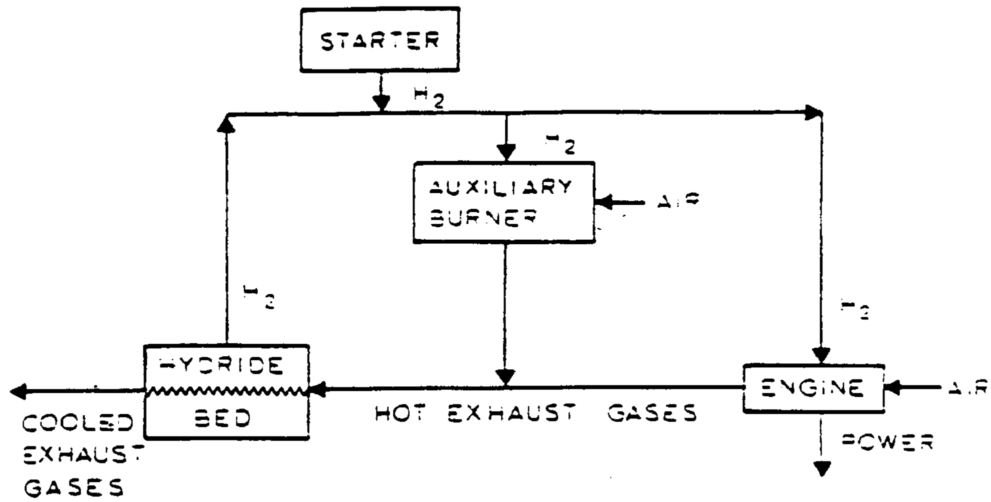
Table 2-3 shows that if the hydrogen is stored as a compressed gas at 25 MPa (3,600 psig), then, on an energy equivalent basis, about 16 times the normal diesel tank volume is needed to store the compressed hydrogen on board the vehicle. That is, for a bus with a 500 liter (125 gallon) diesel tank, about 2, 1 10 gallon volume of compressed hydrogen storage tank volume is required. Of course, this assumes that the hydrogen engine and the diesel engine have the same overall efficiency. Higher engine efficiencies are expected to result from the use of hydrogen fuel. Hence, the overall tank volume required for storing an equivalent amount of hydrogen in a compressed state may be somewhat less than 2, 110 gallons, though still large.

The use of liquid (cryogenic) hydrogen in a vehicle will require about 4.2 times increase in liquid storage volume compared to diesel. That is, a 500 liter (125 gallon) diesel tank will have to be replaced by a cryogenic tank volume of about 2,100 liters (550 gallons). However, the weight of the fuel will be reduced by a factor of approximately 2.8. That is, a 500 liter (125 gallon) diesel with 400 kg of diesel will be replaced by about 150 kg of liquid hydrogen.

The use of metal hydrides presents a severe weight penalty; every kilogram of diesel is replaced by about 4.5 kg of metal hydride to obtain the same hydrogen/diesel energy equivalence. For example, a 500 liter (125 gallon) diesel tank with a fuel weight of 400 kg will have to be replaced by a metal hydride tank containing 1,900 kg (i.e., 1.9 tons) of "fuel."

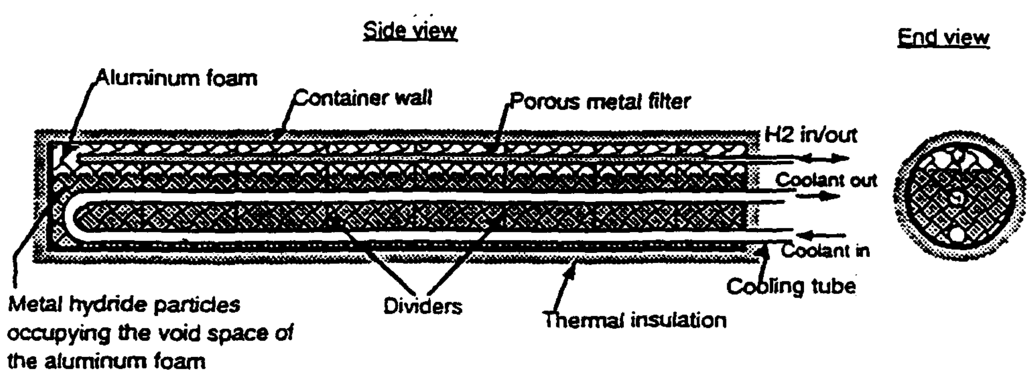
2.1.6 *Hydrogen Fuel Quality*

The quality of hydrogen required depends on the type of vehicular power plant in which it is used. For example, if hydrogen is used in an internal combustion engine, a purity level of 95% (called "fuel Type 1") may be sufficient. There are, at present, no specific hydrogen fuel standards for use in an internal combustion engine. If hydrogen is used in fuel cells, a very high purity is necessary in order to avoid "poisoning" the cells. Hydrogen used in a fuel cell has to be essentially free of CO and CO,. as these have detrimental effects on the electrolytic cells. Table 2-4 shows the gas specification required for a hydrogen-oxygen fuel cell.



Source: Powers and Cummings, 1975

Figure 2-2
Flowsheet of a Typical Hydride Storage System for Use in Vehicles



Source: Heung (1997)

Figure 2-3
Schematic of a Metal Hydride Storage Vessel Used on a Bus

Table 2-3

Diesel Equivalent Values

1. LOWER HEATING VALUES				
Fuel	**SI Units**		**Conventional Units**	
	Value	**Units**	**Value**	**Units**
Diesel #1	35,120	MJ/m^3	126,000	Btu/gal
	42,800	kJ/kg	18,400	Btu/lb
Hydrogen (H,)	10	MJ/m^3 (std)	268	Btu/SCF
	120	MJ/kg	51,600	Btu/lb
Compressed Natural Gas (***CNG***)	36.15	MJ/m^3 (std)	970	Btu/SCF
	50	MJ/kg	21,500	Btu/lb

2. DIESEL #1 EQUIVALENT FOR HYDROGEN*				
Parameter	**SI Units**		**Conventional Units**	
	Value	**Units**	**Value**	**Units**
Hydrogen	0.36	kg/kg	0.36	lb/lb
Gaseous Hydrogen at STP**	3,120	liter/liter	417.20	SCF/gal
Compressed Gaseous Hydrogen[†] at 293K and:				
13.9 MPa (2,000 psig)	27.37	liter/liter	3.66	ft^3/gal
25 MPa (3,600 psig)	16.05	liter/liter	2.15	ft^3/gal
Liquid Hydrogen[††] at NBP	4.13	liter/liter	4.13	gal/gal
Typical Metal Hydride[‡] (MgH_2)	4.37	liter/liter	4.37	gal/gal
	3.80	kg/liter	31.70	lb/gal
	4.47	kg/kg	4.47	lb/lb

Table 2-3

(continued)

3. HYDROGEN FUEL CAPACITY IN A STANDARD BUS (ENERGY EQUIVALENT BASIS)				
Parameter	**SI Units**		**Conventional Units**	
	Value	**Units**	**Value**	**Units**
500 liters (~ 125 gallons) of diesel is equivalent to:				
Compressed Hydrogen Gas at 25 MPa (3,600 psig)	8.03 146.4	m^3 kg	2110 323	gal lbs
Liquified Hydrogen	2.07 146.4	m^3 kg	547 323	gal lbs
Metal Hydride	2.2 1900	m^3 kg	582 4190	gal lbs

* Interpret the numbers in the table as the given number of units of hydrogen (in the specified state) per unit of diesel. For example, 0.36 means 0.36 kg of hydrogen per kg of diesel. Similarly, 3120 implies 3120 liters of gaseous hydrogen at STP is equivalent to 1 liter of diesel liquid on the basis of equivalent energy.

** Density of gaseous hydrogen at STP = 0.083764 kg/m^3

† Hydrogen gas density at 13.9 MPa and 293 K = 10.6 kg/m^3 and at 25 MPa = 17.8 kg/m^3

†† ***LH_2*** density = 70.8 kg/m^3

‡ Solid density of MgH, = 1,450 kg/m^3; hydride void fraction = 40%; nominal hydride density = 870 kg/m3. At fully chemical bound condition 1 kg of hydride holds 0.077 kg of hydrogen. Density of diesel assumed to be 850 kg/m^3.

DVE = Diesel Volume Equivalent. Volume of fuel which, under specified conditions, contains the lower heating value energy content of a unit volume of diesel.

Hydrogen gas generated from the boiloff of liquid hydrogen is expected to be 99.999 % H_2 Hydrogen generated by stripping ammonia or natural gas may contain slightly higher concentrations (at a few parts per million level) of CO and CO, and other trace impurities. Hydrogen gas generated from metal hydrides should be filtered to remove solid hydride particles ("dust") that may be entrained in the gas stream. Table 2-5 shows the concentration of various species in industrial hydrogen (Hansel, 1996). The quality of hydrogen from any of the above three types of storage is high enough for use in internal combustion engines.

Moisture content in hydrogen gas may have deleterious effects on the container (fuel tank and associated plumbing) metal. It is known that moisture is one of the contributing factors for hydrogen embrittlement of metals (Ringland, 1994) due to its effect on the acceleration of the formation of fatigue cracks.

CAUTION

A transit system desiring to use hydrogen as an alternative fuel should discuss with its fuel supplier the issues related to fuel quality and its effects on the intended use (internal combustion engines or the fuel cell). Fuel quality specifications, commensurate with use should be developed.

2.2 FUELING FACILITIES

The physical and operational requirements of hydrogen refueling facilities are discussed in this section. Since hydrogen refueling can involve either a compressed gas or a cryogenic liquid, depending on the type of hydrogen storage on the vehicle, both systems are discussed below.

As of early 1998, only one hydrogen transit refueling facility is operating in the U.S., at one of the bus facilities of the Chicago Transit Authority. In this demonstration project liquid hydrogen is stored at the facility. The liquid hydrogen is compressed to a high pressure (4000 psig) and evaporated, producing high pressure hydrogen gas for fueling the buses. Temporary fueling facilities or bus operations involving consumption of relatively small volumes of hydrogen can use compressed hydrogen refueling using tube trailers (containing cylinders of high pressure gaseous hydrogen). There are industrial size hydrogen transfer stations (both compressed gas and cryogenic liquid) for filling tube trailers or LH_2 tank trucks.

Table 2-4

Hydrogen Fuel Concentration Specifications for Use in a Fuel Cell

Species	Concentration in Volume Units
Hydrogen	> 99.995%
Helium	< 39 ppm
Water + Nitrogen + Hydrocarbons	< 9 ppm
Oxygen + Argon	< 1 ppm
$CO + CO_2$	< 1 ppm
Total Other Impurities	< 50 ppm
Particulate Matter	< 350 solid particles/m^3

Source: Ballard Power Systems (1996)

Table 2-5

Volume Concentrations of Hydrogen and Trace impurities in Hydrogen Fuel

Species	Symbols	Liquified Hydrogen	Gaseous Hydrogen		
			Industrial Grade	Ultra High Purity Grade	Research Use Grade
Hydrogen	H_2	> 99.999%	> 99.95%	> 99.995%	> 99.9995%
Oxygen	O_2	< 2 ppm	< 5 ppm	< 5 ppm	< 1 ppm
Nitrogen	N_2	< 5 ppm	< 400 ppm	< 5 ppm	< 5 ppm
Methane	CH_4	< 4 ppm	< 10 ppm	< 0.5 ppm*	< 0.2 ppm
Carbon Monoxide	CO	< 1 ppm	< 10 ppm**	--	< 0.1 ppm
Carbon Dioxide	CO_2	< 1 ppm		--	< 0.5 ppm
Moisture	H_2O	< 3.5 ppm	< 3.5 ppm	< 3.5 ppm	< 2 ppm

Source: Hansel (1996)

* Total Hydrocarbons
** CO and CO_2 combined

The widely used industry standard for designing industrial systems for gaseous hydrogen storage and/or transfer is in NFPA 50A. Similarly, NFPA 50B describes the standard for liquefied hydrogen systems. The materials presented in this section are based on NFPA 50A and NFPA 50B standards. Information from other sources on safe industrial practices is also presented. Gaseous hydrogen refueling and liquefied hydrogen refueling are discussed in separate subsections.

A transit agency contemplating using hydrogen-powered buses should first evaluate the type of fueling station to be used. This choice will be based on the type of H, storage used on the bus. A liquefied hydrogen refueling station will be necessary, if the bus "runs" on LH,. If the bus has CHG storage, there are two or three options depending on the number of buses operated, purity of hydrogen needed, nearness to hydrogen pipeline,[2] etc. Figure 2-4 shows possible decision tree approaches to selecting the type of hydrogen refueling station in a transit bus system.[3]

2.2.1 *Compressed Hydrogen Gas (CHG) Fueling Facility*

A compressed hydrogen facility may be supplied with gaseous hydrogen from on site tube trailers ("a temporary facility") or a pipeline or by the vaporization of Liquefied Hydrogen(LH,) from a storage tank and compression of the vapors. Tube trailer based hydrogen supply may be sufficient if the transit system is servicing fewer than 5 buses (see Figure 2-4). In the case of a temporary storage facility (principally tube trailers), an auxiliary compressor and a gas dispensing station will be needed in addition to the hydrogen from the tube trailers. In the case of a larger dispensing facility, hydrogen gas is obtained from either a gas pipeline or by evaporating liquid hydrogen. This gas is then compressed on site with a compressor and supplied to the dispensing station (similar to the process in most CNG dispensing stations). One other design involves the compression of liquid hydrogen and then evaporating the compressed liquid to generate the high pressure gas.[4]

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[2] Hydrogen pipelines service several major U.S. cities, namely, Houson, Los Angeles, New Orleans, and San Francisco (Hansel, 1996).

[3] The decision critical number of 5 buses in the fleet is somewhat arbitrary. It is based on the fact that a jumbo tube trailer can carry about 4,000 m^3 std (140,000 SCF) of hydrogen at 15.2 MPa (2,200 psig). A 40 ft bus operating in a CBD uses an average of 75 liters (20 gallons) of diesel per day. This is equivalent to 234 m^3 of STP hydrogen (8,300 SCF). Therefore, a tube trailer holds enough hydrogen to fuel each of 5 buses for 3 days.

[4] In the Chicago Transit Authority's hydrogen fill station at the Pulaski garage, LH, is first compressed and then evaporated in the natural convection heating evaporators to produce hydrogen at 4500 psig. This station can deliver compressed hydrogen at the rate of 565 m^3 (20,000 SCF) in 15 minutes sufficient to fill the H, tanks in a standard 40 ft bus.

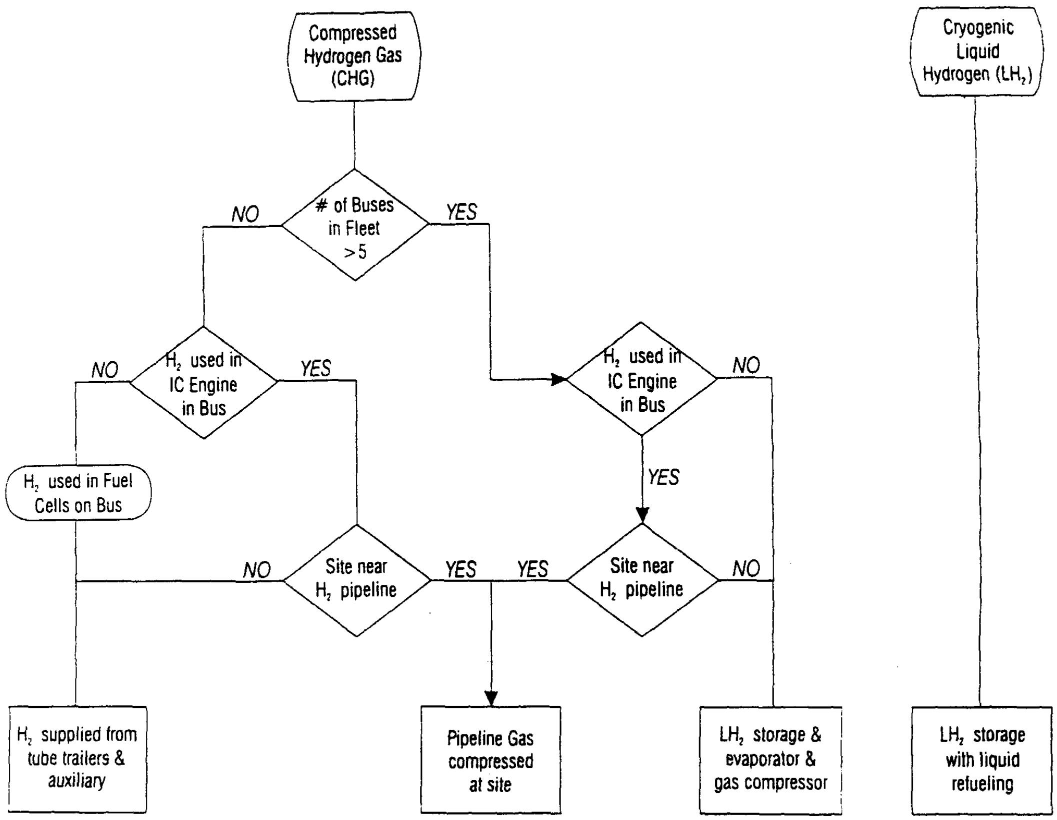

Figure 2-4

Decision Tree for Selecting the Type of Hydrogen Refueling Station

Normally, the dispenser in a CHG dispensing station should be rated to fill a bus tank up to a pressure of 25 MPa (3,600 psig). The rate of discharge of the gas from the dispenser will depend on whether a slow fill or a fast fill facility is being designed. Normal fast fill times range from 5 to 15 minutes for a 40 ft bus.

2.2.1.1 General Siting Requirements. In general, ***CHG*** refueling facilities are to be located outdoors or in separate special buildings (NFPA 50A, §3-2). The location is dependent on the size of the operation. NFPA 50A Table 3-2.2 indicates the minimum separation distances to be provided between gaseous hydrogen systems and other equipment and buildings. These criteria should be followed. The following requirements for the location of different sizes of hydrogen systems are excerpted from NFPA 50A.

2.2.1.2 Electrical Equipment. All electrical equipment and machinery that have a potential for exposure to hydrogen should conform to NFPA 70, National Electrical Code requirements. In addition, NFPA 50A, §4-1.2 stipulates that all equipment within 4.6 m (15 ft) of hydrogen equipment should be classified Class I, Division 2. In addition, the guidelines and recommended practices indicated in the American Petroleum Institute's Publications 500 and 505 should be reviewed. These guidelines refer to the design and operation of electrical machinery and equipment operating in environments where the potential for the occurrence of flammable vapor mixtures with air exists.

NFPA®

3-2.1 *The location of a system, as determined by the maximum total contained volume of hydrogen, shall be in the order of preference as indicated by Roman numerals in Table 3-2.1.*

Table 3-2.1

Name of Location	***Size of Hydrogen System***		
	Less than 3,000 SCF (85 m^3)	***3,000 SCF (85 m^3) to 15,000 SCF (425 m^3)***	***In Excess of 15,000 SCF (425 m^3)***
Outdoors	*I*	*I*	*I*
In a separate building	*II*	*II*	*II*
In a special room	*III*	*III*	*Not Permitted*
inside buildings not in a special room and exposed to other occupancies	*IV*	*Not Permitted*	*Not Permitted*

There are no specific guidelines in NFPA 50A for electrical classification of the hydrogen dispenser area. However, because of similarities between ***CHG*** and ***CNG*** the requirements for ***CNG*** dispenser should, at a minimum, be made applicable. Figure 2-5 shows, schematically, the electrical classification that should be used around a hydrogen dispenser.

2.2.1.3 Ventilation and Heating. In a completely outdoor fueling station, there will be no need for heating or additional ventilation. If the fueling station is located indoors in a separate building, ventilation should be provided with exhaust to the outdoor environment (NFPA 50A, §4-2.2).[5] The vent area should be at least 1 m^2 per 300 m^3 of building volume (i.e., 1 ft^2/1,000 ft^3). Also, open flames, electrical equipment, or heating equipment (including open flame heaters) that can act as ignition sources should be prohibited from use in this building (§4-2.4). Heating should be provided through hot water, steam, or other indirect methods. Other requirements in NFPA 50A related to locating hydrogen fueling system indoors in separate buildings should be strictly followed.

The design requirements for hydrogen ***containers*** indicated in §2-1 and for ***pressure relief devices*** and piping, tubing, and fittings in §2-2 and §2-3 of NFPA 50A should be followed.

2.2.1.4 Detection Instruments. NFPA 50A does not indicate specific requirements for detecting hydrogen leaks and fire detection. It is, however, prudent to install hydrogen leak detection instruments. Instruments to detect the leak of hydrogen gas from the fueling system or the presence of hydrogen gas in the atmosphere in the fueling area should be provided. The presence of hydrogen in the atmosphere can be detected with flammable gas detectors. If provided, these detectors should be installed over the dispenser area and on the underside of the ceiling of a weather protection canopy provided over the dispenser (since hydrogen gas released is lighter than air it will tend to rise and accumulate under the canopy). Hydrogen leaks can be detected remotely by ultraviolet or infrared frequency based sensors. The field of view of these sensors should be such that they can "see" the gas leaks from the fueling side of the bus or from the roof mounted tanks. If the released hydrogen ignites, these sensors will detect the fire rapidly. Note that a hydrogen fire is undetectable in the visible range, i.e., it cannot be "seen" by a human being.

2.2.1.5 Other Important Design Considerations. Consideration should be given to implementing all of the following design items. There are no current standards or guidelines specific to each of the requirements indicated below; however, many are used as a matter of routine in hydrogen and other flammable gas industries leg., CNG). Therefore, it is prudent to implement these in the design of a hydrogen fueling station.

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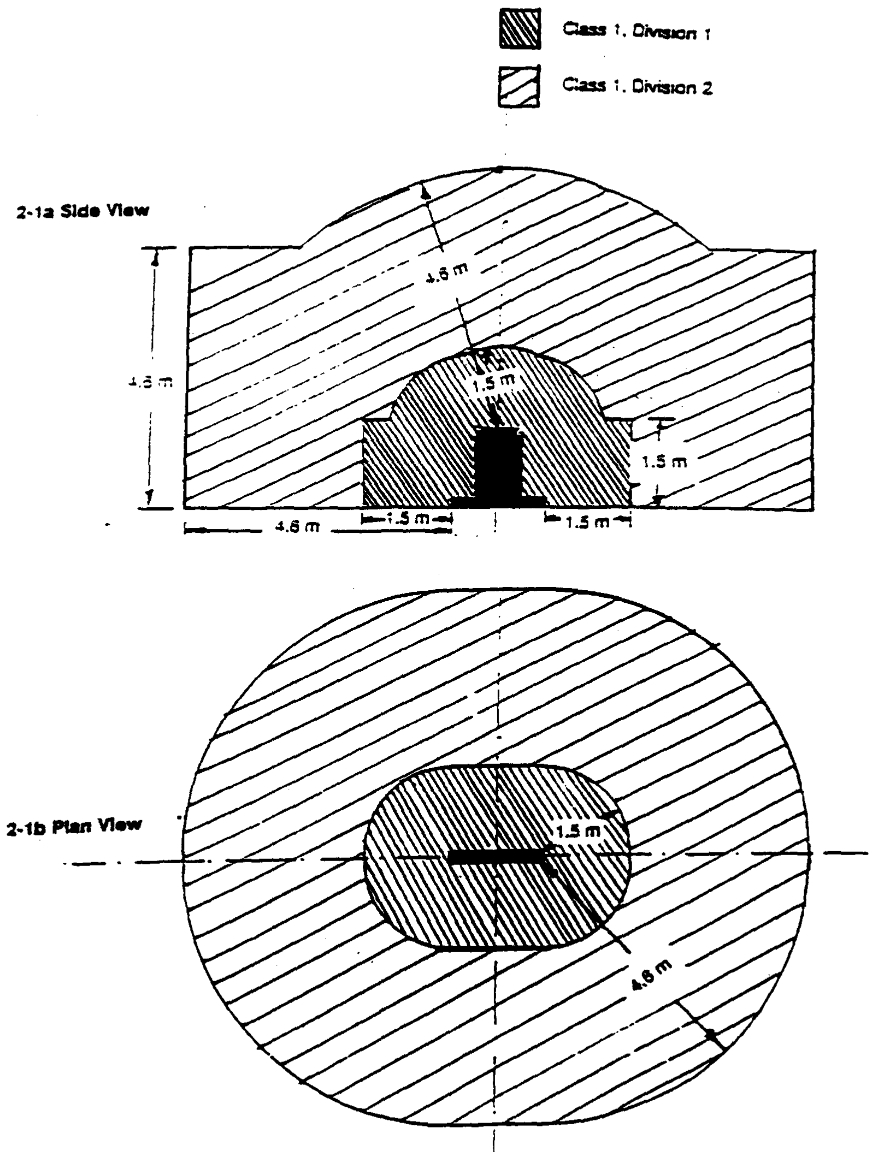
[5] A detached building is used exclusively to house a hydrogen system (see definitions in NFPA 50A).



Note: *These figures are drawn based on the author's interpretation of the information in Figure A-4-12 in NFPA 52 and the dimensions specified in the NFPA 52, Section 4-12 for different classified regions.*

Figure 2-·5

Classified Areas In and Around Dispensers

1. The design of the fueling system (hoses, lines, and nozzle) should be such that no air leaks into the bus tank. The consequence of a failure of this "air free fueling" protection can be disastrous.

2. The bus being refueled, the dispensing hose, and the dispenser station should be electrically grounded to prevent static electrical discharge during a refueling operation.

3. A lightning arrestor should be provided in a fueling facility. Correct sizing of the cable and its footing in the earth are required to ensure proper grounding.

4. The fueling lines should be designed to ensure that under no circumstances will the external air enter the ***fuel tank***. The fuel dispenser should incorporate a feature that prevents fuel transfer to the bus if the bus fuel tank pressure is less than 200 kPa (`14.7 psig). Low tank pressure may indicate that the tanks contain air (e.g., tanks are new or are in use and the relief device leaked all of the hydrogen out of the tanks and air diffused back into the tanks). The presence of air in a hydrogen tank poses extreme danger.

5. A proper venting system has to be designed to vent hydrogen from (pressurized) storage and from a bus in the case of an emergency. The vent height should be such that the hydrogen released will not be sucked into adjoining buildings, air intakes, or other facilities. Also, the vent should be located far from any ignition source.

6. If compressed hydrogen is generated by evaporating liquid hydrogen and compressing the gas generated, care should be taken in the design to ensure that exposed LH_2 pipes are protected against accidental tripping and contact by operators, maintenance personnel and others in the fueling facility.

7. The designs of the fuel dispensing control panel and other instrument panels should be based on sound human engineering principles. That is, the display panels should be bright and the display lettering should be visible and readable by a person standing close to a bus and fueling the bus. The keyboard on the control panel should be large so as to be useable by a person wearing thick winter gloves. The dispensing area should be brightly lit so that all parts of the facility are visible under the worst weather and/or nightitme conditions.

The following guidelines applicable in the design of a ***CNG*** fueling station should also be considered as being applicable to a ***CHG*** dispensing station.

8. The lines from the pressurized storage container(s) or ***compressor*** to the dispenser should be equipped with both automatic fast closing valves and manual valves at the storage end and at the dispenser end. If the fueling area is indoors, then each compressed gas pipeline entering the building should be equipped with a manual isolation valve. (Refer to NFPA 52, §4-11.3, §4-11.5, and §4-11.10.)

9. NFPA 52 requires that dispensers have a breakaway connection on each hose to limit the breakaway force to 660 N (150 Ibs) in the event of vehicle drive away. A manual isolation valve should be provided immediately upstream of this breakaway and a bleed off device should be located between the breakaway and the manual valve. (Refer to NFPA 52, §4-11.7, §4-11.8, and §4-11.11).

10. NFPA 52 §4-11.4 alludes to excess flow valves, but does not require the provision of these valves. If local or state codes require their use, it should be noted that current technology indicates that they are impractical, particularly with the large flow rates typical of transit compressed gas fuel stations. In the absence of these valves, the dispenser should be equipped with electronic shutdown for excess flow and should be designed to limit the total fill of any one vehicle to the maximum amount of fuel that the vehicle would use. In the event either of these conditions (excess flow rate or fueling continuing even when the bus tanks are full) occurs, it is desirable to immediately and automatically shut down fueling at all other islands in the area (all fuels) and shut down the ***compressors***. Sounding a remote alarm should also be considered.

11. The requirements for the materials of the dispensing hose and their testing are specified in NFPA 52 §4-9.3 and §4-10, respectively. It is, however, prudent to use a hose manufactured of manmade material and braids of stainless steel. All hoses must be electrically conductive. Hoses must be designed for ***CHG*** use and must be certified by the manufacturer as such. The hose ends should be installed by the original hose manufacturer, who should pressure test the hose to 1.5 times the rated pressure. Hoses should be equipped with a manufacturer tag indicating the serial number of the hose, the test pressure and the test date. This tag should be marked on site with the first date of service.

    Hoses should be discarded after 12 months of use--for hose with carbon steel braid, after six months of use or immediately after any mechanical abuse, such as a breakaway incident.

    Hoses should be equipped with retractors or counterweights to ensure that fueling connections do not fall to the ground.

12. The fueling connector should be equipped with a sealed vent back connection which is connected by hose to a pipe to convey this vent back gas to a safe area away from the fueling operation. This hose must decouple so as not to interfere with the breakaway on the main dispenser hose. (Refer to §4-14.7 of NFPA 52.)

13. The dispenser is required by NFPA 52 to include a temperature compensation system, (Refer to §4-14. 1, §4-14.2, and §4-14.3.)

    This system is generally electronically controlled and its function is to adjust the fill pressure to account for variations in ambient temperature as well as the heating effect which is common in vehicle cylinders during a fueling cycle. This system must be carefully designed and calibrated to ensure fills as close as possible to complete while not allowing overfills to occur. If this system includes a safety relief valve, it should be piped to a safe location in a separate line from the fueling connection vent back (See §4-9.2.).

2.2.1.6 Dispensing Area Operations and Procedures. Existing codes do not address, in detail, the operational aspects of the fueling area. NFPA 52 for ***CNG*** specifies some signage requirements as do several of the local codes. It is prudent practice to establish the following procedures, as a minimum, in a hydrogen fueling facility.

1. Smoking or operations producing an open flame or spark (including from jumper cables) or any other source of ignition **must be strictly prohibited** in the fueling area.

2. Clearly visible signs indicating NO SMOKING and IGNITION OFF as well as the location of all Emergency Shutdown Device (ESD) buttons and FIRE pulls must be provided in and around the fueling area.

3. Anyone dispensing fuel must be adequately trained in the proper procedures and emergency procedures. If local regulations require additional training or certification, this should be regarded as the minimum training requirement.

4. Prior to fueling, the bus engine ignition must be shut off. In the case of a fuel cell bus, the hydrogen feed to the fuel cell should be shut off and the parking brake must be set. If a vehicle is parked on an incline or the brakes are not fully locked, the wheels of the bus must be checked. No one should be permitted inside the bus during refueling. The ignition keys should be held by the refueling person.

5. The bus should be electrically grounded before fueling is initiated.

6. An employee evacuation plan should be developed and implemented for use in cases of significant hydrogen release or detection of a hydrogen fire.

7. Performing any type of service or repair to the bus while it is parked in the fueling area (with the exception of normal fluid level and tire pressure inspections and cleaning) should be avoided. No service should be performed if the refueling is intended to last less than 15 minutes.

8. Any bus with a known leak must remain outside, or be moved outside if it is safe to do so, .until the bus can be defueled and the leak isolated. A bus that is leaking fuel should never be fueled. Such a bus should be taken to a remote outdoor location and roped-off for a distance of at least 8 m (25 ft) from any portion of the bus.

   Handheld flammability monitors may need to be used to detect the leak location and the direction of movement of the hydrogen plume. Depending on the size of the leak, a large rope-off distance may be enforced. There should be no personnel, equipment, electric/telephone wires, structures, overpasses, and the like above the parked bus. Warning signs should be posted in highly visible locations alerting individuals that hydrogen is leaking. Also, warning signs should prohibit smoking, operation of nearby equipment and other potential ignition sources. The keys to the bus should be removed and placed in a secure location. Decisions should be made regarding leaving bus windows and doors open for ventilation, depending on the location of the gas leak.

9 Employees should be trained to activate the ESD as the first line of action in the event of a gas leak or any other incident. The area should then be evacuated.

10. Prior to ***defueling*** a bus, electrical ground must be established between the bus, the ***defueling*** stack, and the earth. ***Defueling*** must take place at controlled rates, and a technician must remain with the bus to ensure the proper operation of the ***defueling*** equipment.

11. Refueling a bus during a threat of lightning storms should be prohibited.

12. In the case of potential vehicular traffic in the vicinity of the fueling facility, appropriate measures should be implemented including procedures to restrict the movement of other vehicles and erecting physical barriers (such as a Jersey barrier, chain link fence, gates, etc.) between a hydrogen bus being fueled and other traffic. This will prevent accidental collisions between a hydrogen bus being fueled and other vehicles.

2.2.1.7 Safety Control Systems. It should be noted that the current practice in the hydrogen industry is to perform hydrogen transfer operations only outdoors. (The industrial gas and chemical industry recommends that all hydrogen transfers be made outdoors). However, if a hydrogen refueling station is located within a separate building, it is prudent practice to institute the following procedures and alarm systems to enhance safety in the fueling area.

1. Provide a combustible gas detection system in the building and integrate it with other building control systems. Upon detecting combustible gas at 20% LFL (Stage 1 alarm), doors connecting the fueling area to the outside should be opened, any inside partitions should be closed, the ventilation rate should be increased to a higher level, an audible and visual alarm should be activated, all fueling operations (all fuels) and ***compressors*** should be shut down and a remote alarm should be sent to an on-site dispatcher.

2. Sound an alarm (Stage 2 alarm) when the gas detector senses 50% LFL. The entire facility should be put on alarm and all but safety personnel should be evacuated. The local fire department should be called by the dispatcher, or by a direct, automatic, central station connection.

3. Activate a centralized ***ESD*** system at the ***CHG*** station which upon activation will terminate dispensing, close all automatic valves on the storage lines and shut down all compressors, and isolate the gas service upstream of the ***gas dryer***. This system must befall-safe and must require a manual reset. (Refer to §4-1 1.6 and §4-4.3.7 of NFPA 52.)

   ESD buttons should be provided at each dispenser and at all exits from the fueling area. An ESD button and a signal of ESD activation should be located in the transit agency dispatcher's office.

2.2.1.8 Maintenance of Safety Equipment. Regular maintenance of instruments and equipment should be performed. This maintenance, as a minimum, should include:

1. Testing and calibration of combustible gas detection and fire systems at manufacturer specified intervals.

2. Regular testing and calibration of ***gas dispenser*** temperature compensation systems.

3. Testing and calibration of ***gas dispenser*** excess flow detection and fill shutdown system and verification of ***CHG*** emergency shutdowns performed at regular, specified, intervals.

4. Inspection of ***CHG*** bus piping systems and components, including ***Pressure Relief Devices (PRDs,*** at regular intervals.

Facilities should also undergo a fire prevention inspection. This inspection should include all devices which are commonly inspected in transit garages, such as:

- All sprinkler valve assemblies (monthly inspection).

- Yard hydrants and hoses, inside hoses and portable fire extinguishers (monthly inspection). Electrical equipment and storage of flammable liquids should be checked monthly.

- Housekeeping, as well as cutting and welding, smoking regulations, sprinkler alarms and doors at cut-off walls (monthly inspection).

- Operational capability and readiness of systems to verify triggering, interlocks, and automatic controls (threshold should be checked with a simulated gas release event).

Weekly inspections should include:

- General condition of automatic sprinkler heads

- Dry pipe valves

- Water supplies

- Locked valve shutoffs

In addition to the above, the electrical systems controlling ventilation should be checked monthly. A calibration of flammable gas detectors and other remote hydrogen sensors (infrared and ultraviolet) should be done on a six-month interval or per the manufacturer's recommendations, whichever is more frequent. The fire sensors should be inspected regularly and any time there is a suspicion of malfunction.

2.2.1.9 Defueling Connections Design. There may arise circumstances in which the hydrogen inventory on the bus will have to be removed. These circumstances may include a small leak in the fuel system or components, scheduled maintenance of the fuel system or components, or other emergencies. The transit facility must have a well thought out plan of action to defuel a hydrogen bus and develop the facility and bus fuel system designs accordingly. The following approaches should be considered.

1 . Downloading the fuel through a certified hose from the bus to be defueled to empty tanks of another hydrogen bus of the same type. Of course, no additional defueling is possible when the tank pressures in each bus equalize.

2. Connecting the tank of the bus to be defueled to the suction side of a compressor (if present) and using the inventory to refuel other buses. Caution must be exercised so that low pressure (risk of air intrusion) is not created in the bus that is undergoing defueling. An air leak into a hydrogen tank will pose an extreme danger.

3. Designing an atmospheric vent stack system located far from ignition sources and buildings to which the bus containing a residual gas in a tank can be connected and hydrogen gas released safely into the atmosphere. The height of the vent stack should be greater than the height of any building within a radius of 30 m (100 ft).

All of the above *defueling* strategies require proper design of the bus fuel system so that proper and safe *defueling* connectors are provided on the system.

2.2.2 *Liquid Hydrogen Fueling Facility*

A liquefied hydrogen LH_2 fueling facility consists of a LH_2 storage (tank), LH_2 vaporizer (if only to generate enough vapor to pressurize the tank to initiate liquid flow into a bus tank), a dispensing unit, and all associated piping, tubing, and valves. The liquid hydrogen storage tank on a bus may operate between O. 1 MPa (O psig) and 1.1 MPa (150 psig). The LH_2 dispensing system is designed to have a vapor return line to the main LH_2 tank.

The principal difference between a compressed hydrogen gas fueling station and LH_2 station is that, in the former, the hydrogen being pumped into the bus is at ambient temperature (albeit at high pressure), whereas in the latter, the hydrogen is a liquid at a very low temperature of 20.3 K (-423.5 ^{o}F). Because the liquid stored is cryogenic, special requirements both in materials of construction as well as in procedures need to be followed. However, most of the requirements for hydrogen detection instrumentation and fire safety, as well as classification of electrical equipment discussed in Section 2.2 for a CHG fueling station, also apply to a LH_2 fueling station.

Standards which are specifically applicable to vehicular LH_2 refueling stations do not exist. However, NFPA 50B standard for LH_2 systems at consumer sites has a number of design requirements which can be considered applicable, as a minimum, to an LH_2 refueling station, also. This document, therefore, indicates a number of these requirements.

2.2.2.1 General Requirements. The LH_2 storage tank should be constructed of materials that are compatible with liquefied hydrogen and should always be located outdoors in a well ventilated area. The specific design requirements for *containers, pressure relief devices,* piping, tubing, and fittings, are indicated in NFPA 50B, Chapter 2. These standard requirements should be followed. Specifically, the following requirements on the discharge from pressure relief devices and location of piping should be noted.

2-4.3 Pressure relief devices shall be arranged to discharge unobstructed to the outdoors and in such a manner as to prevent impingement of escaping liquid or gas NFPA"   upon the container, adjacent structures, or personnel. See 3-1.5 for venting of pressure relief devices in special locations.

2-5.4 Means shall be provided to minimize exposure of personnel to piping operating at low temperatures and to prevent air condensate from contacting piping, structural members, and surfaces not suitable for cryogenic temperatures. insulation shall be of noncombustible material and shall be designed to have a vapor-tight seal in the outer covering to prevent the condensation of air and subsequent oxygen enrichment within the insulation. The insulation material and outside shield also shall be of adequate design to prevent attrition of the insulation due to normal operating conditions.

2-5.5 Uninsulated piping and equipment that operate at liquefied hydrogen temperature shall not be installed above asphalt surfaces or other combustible materials in order to prevent contact of liquid air with such materials. Drip pans shall be permitted to be installed under unInsulated piping and equipment to retain and vaporize condensed liquid air.

The following table from NFPA 58 indicates the allowable location of LH_2 containers. (The Roman numerals indicate the order of preference.)

Table 3-2.1 Maximum Total Quantity of Liquefied Hydrogen Storage Permitted

Nature of Location	Size of Hydrogen Storage (Capacity in Gallons)			
	39.63 to 50	51 to 300	301 to 600	In excess of 600
Outdoors	I	I	I	I
In a seperate building	II	II	II	Not Permitted
In a special room	III	III	Not Permitted	Not Permitted
Inside buildings not in a special room and exposed to other occupancies	IV	Not Permitted	Not Permitted	Not Permitted

The restrictions on the location of $\boldsymbol{LH_2}$ storage containers based on the volume of storage are indicated in NFPA 50B, §3-2. Also indicated in NFPA 50B §3-2.2 are the minimum distances from $\boldsymbol{LH_2}$ system to different types of exposure (see Table 3-2.2 in NFPA 50B). For example, the nearest location of flammable or combustible fluids should be at least 33 m (-100 ft) away from any of the components of the $\boldsymbol{LH_2}$ system, including the tank.

2.2.2.2 Electrical Equipment. NFPA 50B does not specify special requirements for electrical equipment used in LH, service other than to stipulate that the requirements of Article 501 of NFPA 70 be met (02-9, NFPA 50B). However, in keeping with the requirements for the dispensing units of other similar flammable gases (CNG, LPG, etc.) it is prudent to design the electrical equipment in and around dispensing units for LH, service to conform, as a minimum, to the requirements discussed in Section 2.2.1.2 of this document. These requirements are schematically illustrated in Figure 2-5 of this document.

NFPA 50B, however, requires the following classification where $\boldsymbol{LH_2}$ connections and disconnections are made regularly.

Table 2-9 Electrical Area Classification

Location	*Division*	*Extent of Classified Area*
Points where connections are regularly made and disconnected	1	Within 3ft(l m) of connection
	2	Between3 ft (l m) and 25 ft (7.6 m) of connection

Electrical grounding of $\boldsymbol{LH_2}$ systems should be implemented. The requirements in NFPA 50B are as follows.

2-10 Bonding and Grounding. The liquefied hydrogen container and associated piping shall be electrically bonded and grounded.

2.2.2.3 Other Requirements. All other requirements discussed in the various subsections of Section 2. 1 under Ventilation and Heating, Detectors and Instruments, Other Design Requirements, and Operations for a compressed hydrogen refueling station should be assumed to be equally applicable to an $\boldsymbol{LH_2}$ refueling station also. In addition, the following should be considered for implementation in an $\boldsymbol{LH_2}$ fueling facility.

1. Cryogenic liquid releases must be avoided. Provisions should be made to channel/direct potential liquid releases away from personnel and structural materials so that the thermal effect of any release is minimized.

2. Fueling personnel should be made to wear eye protection, gloves, and outerwear made of fire resistant clothing, NOMEX® or other garment materials for use with cryogenic materials.

3. Regular maintenance checks should be performed (at specified time intervals) along all LH_2 lines to test for hydrogen leaks. These checks should be performed with a handheld flammable gas (or hydrogen) detector. Every packing, flange, gasket or seal, and threaded connection must be "sniffed" for leaks on a regular basis.

4. A high pressure air or nitrogen supply should be provided at the dispensing unit to clean the ice and frost from the nozzle. Before every refueling operation it should be ensured that the nozzle mating surface is clean and does not have any solid particles (dust, frost, etc.) so that a leak proof seal can be established with the bus fueling receptacle.

5. The liquid flow nozzle, the LH_2 flow lines, and bus fuel lines should be designed carefully to avoid any possibility of air leak into the system. Before each refueling operation, it should be a standard and necessary practice to purge the fill hose at the dispensing unit with nitrogen.

2.3 BUS STORAGE FACILITY

A bus storage facility is a building where buses are parked for long periods of time, i.e., 12 or more hours (dead vehicle storage). Issues relating to design considerations for such buildings for storage of hydrogen fueled buses are discussed in this section. In certain climates, transit buses are stored outdoors. Outdoor parking does not present a significant area of safety concern, and therefore is not discussed in this document.

NFPA 88A standard is applicable to vehicle parking structures. The standard is not intended to be applied to alternative fuel bus parking garages. However, since this is the only standard available, and many of its requirements are equally applicable to a transit bus garage, some of its provisions are indicated below. A transit agency should, however, review NFPA 88A completely and determine which sections may be applicable to its facility. Garages without physical barriers between parking and maintenance of vehicles (not for vehicle dead storage) are discussed in Section 2.4 of this document.

2.3.1 *Design Overview*

The principal design considerations for an indoor bus storage facility should include:

1. Eliminating, to the maximum possible extent, all ignition sources within the bus storage areas.

2. Detecting a hydrogen leak and/or a hydrogen flame at the earliest possible time after its occurrence.

3. Developing strategies to direct hydrogen gas away from potential ignition sources. This could include providing within the storage facility hydrogen capture hoods and parking the buses such that the relief valves on the hydrogen tanks are directly below the hoods.

4. Managing the ventilation rates, by active sensors, to increase air flow and flush the leaked hydrogen out of the building in the shortest possible path and time. It should be noted that hydrogen is very light compared to air (and hence, will tend to rise immediately after release). The ventilation strategy should take advantage of this property .

5. Providing adequate warning devices and alarms for the emergency response personnel to take necessary action.

6. Designing the structural details in such a fashion as to minimize accumulation of hydrogen-air pockets between structural I-beams or purlins (i.e., reduce the possibility of dead air zone occurrence).

7. Providing explosion-proof venting systems for areas where the hydrogen buses will be stored (see requirements in §4-4.3.3 of NPFA 52).

8. Evaluating the classification required for the electrical systems within the immediate vicinity of and roof area above the parked hydrogen buses. The height of the walls (close to the parked hydrogen buses) above which electrical classification will be applied should be discussed with the Architect and Engineering firm employed by the transit system and the authority having jurisdiction. Strong consideration should be given to making the wall and roof areas electrically Class 1, Division 2 compliant where there is a potential for leaked hydrogen to impact.

9. Strong consideration should be given to electrically grounding each hydrogen bus when parked within the storage building.

10. Developing procedures to expeditiously remove from the storage facility a bus leaking hydrogen without imperiling other buses stored.

11. Prohibit the long-term parking of a liquid hydrogen fuel bus indoors because the heat leak into the ***fuel tank*** will increase the tank pressure. When the pressure exceeds the relief valve set pressure, gaseous hydrogen will be discharged. This occurrence should be prevented ***unless*** special relief valve couplings are provided that vent the gas to the outside of the building.

It may be a prudent practice to park hydrogen fuel buses outdoors until sufficient operational data are obtained on the reliability of hydrogen fuel system components. This will ensure that if hydrogen leaks occur, the gas will be dispersed in the atmosphere without any potential for a ***hazard***. If indoor storage of hydrogen fueled buses is necessary due to climate or other considerations, the transit system should evaluate a bus fuel system design in which all CHG tanks on the bus, except one tank, are automatically shut off as soon as the bus enters the garage.[6]

2.3.2 *Operations in an Indoor Storage Facility*

A transit system should implement other (passive) safety practices in hydrogen bus parking garages as a part of routine operations. Associated with these practices should be the training of personnel-including bus operators--to understand the various safety issues and to inculcate a "safety first" attitude in day-to-day operations. These passive safety enhancement procedures should include but not be limited to:

1. Strictly enforcing a rule which requires hydrogen fuel buses to be parked only in the designated lanes or vestibules designed for hydrogen safety within the garage. These lanes should be provided with ceiling mounted flammable gas or hydrogen concentration sensors. (it is assumed here that a garage may be used to park buses using a variety of other fuels, namely, diesel, gasoline, methanol, etc. If the garage is a dedicated hydrogen storage facility, designated parking is not relevant.)

2. Ensuring that no hydrogen bus whi6h has sprung a fuel leak, however small the leak rate may be, is ever allowed to be brought into the garage nor allowed to park in the garage.

3. Strictly prohibiting smoking by anyone anywhere, except in designated smoking areas.

4. Providing a portable handheld hydrogen gas or flammable gas concentration measuring instrument at a convenient and easily accessible location either within or very close to the storage facility. This instrument could be used to detect potential hydrogen leakage from the fuel system of a bus parked in the garage. Any such detection should be followed by the implementation of an appropriate level of response.

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[6] Long Island Bus transit has implemented such a system for CNG- powered buses. Each CNG tank is provided with a solenoid valve which is operated by a radio transmitter/receiver. As the bus enters the garage, a facility-based radio transmitter instructs the solenoid valves to close for all but one tank. This enables the bus to move about within the garage with fuel from the one tank whose valve is not closed.

5. Developing a proper written response plan for various types of hydrogen leak emergencies. These plans should include action items such as turning off all nonclassified electrical systems and other potential ignition sources, increasing ventilation rate, evacuating facility personnel to safe areas, and safe withdrawal of buses parked inside the garage, to respond to different sizes of releases. Additional requirements for an emergency plan are discussed in Section 2.7.

6. Limiting the time the vehicle is running in the storage facility, since larger quantities of gas may be released when the vehicle is in actual operation.

7. Assuring that only minor maintenance (such as checking oil level or tire pressure) is performed in the bus parking area. All other maintenance activities should be performed in a facility specially designed for maintaining hydrogen powered vehicles.

2.4 BUS MAINTENANCE FACILITY

A bus maintenance facility is generally a partial or fully enclosed building within which repairs and routine servicing of buses are performed. In many transit systems, this facility consists of one or more bays consisting of either a lift or a pit over which the bus to be serviced is parked. Also, in transit systems which operate mainly diesel fuel buses and a limited number of alternative fuel buses, the same maintenance facility is used for servicing alternative fuel and diesel buses. In large facilities several buses may be serviced at the same time. Where alternative fuel buses are serviced in existing diesel bus maintenance facilities, a common practice is to designate a section of the facility to service alternative fuel buses only with or without walled partitions between the alternate fuel service bays and diesel service bays; The section of the facility in which alternate fuel buses are serviced is upgraded with the provision of gas sensors, alarms, and special equipment. A shared maintenance facility may not be the best facility configuration when hydrogen fuel buses are to be serviced. It may be a prudent design to have a dedicated maintenance facility for hydrogen fuel buses, especially when fuel system related servicing is to be performed.

The definition of a repair facility can be found in NFPA 88B; only those buildings which comply with the requirements in NFPA 88B are discussed in this section. Garages without physical barriers between parking and maintenance of vehicles (not for vehicle dead storage) are also within the purview of this section.

In general, all requirements for safety in a bus storage area (discussed in the previous section) should be assumed to be applicable to a bus maintenance facility. However, there are exceptions and somewhat more restrictive requirements in a maintenance facility because of the nature of work being performed and the (increased) probability of hydrogen release incidents to occur, especially when the fuel system components are serviced. **Therefore, the reader should review the requirements for the storage facility (Section 2.3 of this document) and assume that all of those design guidelines are a part of this section also.** Only additional requirements for a maintenance facility are indicated in the sections below.

2.4.1 *Design Overview (Bus Maintenance)*

All of the design philosophy indicated in Section 2.3.1 applies to this section and is made a part by reference.

It should be noted that in a repair facility, vehicle engines are often left running during a maintenance activity. Therefore, the potential exists for larger fuel releases in a relatively small volume of space. A maintenance facility is generally smaller than a storage facility. Vehicle design can control the amount of gaseous hydrogen being released from a severed fuel line or from a ***PRD*** release. It may also be possible with the proper vehicle design and/or operational procedures to minimize the duration of gas release and/or the quantity of gas released. In addition, repair facilities should also implement the design considerations indicated in Section 2.3.l,especially the ventilation strategy (item 3) and electrical grounding (item 11).

2.4.2 *Electrical Equipment*

In a maintenance facility there are both fixed and movable electrical machinery that may or may not be classified. These include such items as fans, power tools, lights, radios, and heaters. A transit system should assess the potential for ignition from all electrical equipment used (or proposed to be used) in a maintenance facility and initiate appropriate design or use modifications to reduce or eliminate the ignition potential. The design changes may include:

- Electrically classifying the equipment according to the requirements of NFPA 70.
- Replacing electric spark producing equipment and tools with air-operated machinery/tools or electrically classified equipment.
- Eliminating the use of open flame or hot element electrical heaters whose surface temperature is above 700 K (800 ^{o}F). Heating of the premises should be provided using a hot water/steam system. No surface hotter than 700 K (800 ^{o}F) should be permitted for use in a hydrogen bus facility.

If the maintenance facility has work pits, they should be provided with lights and electrical outlets which are certified Class I, Division 2.

The design modifications of the maintenance facility, especially those modifications related to the electrical classification of the various parts of the facility (such as the ceiling, wall, floor, etc.), should be discussed with the transit system's safety office, engineering staff, A&E firm, insurance carrier, and the local fire department. It is necessary to comply with all regulations and local code requirements .

2.4.3 *Ventilation and Heating*

An indoor maintenance facility for servicing hydrogen-powered vehicles should have ventilation airflow over and above the normal building ventilation required by NFPA 88B or OSHA guidelines (6 air changes per hour) for a repair facility. Ventilation flow should be designed such that any hydrogen leak is exhausted to the outside without dispersing throughout the maintenance shop or accumulating below the ceiling. One way to achieve this is to provide movable hoods at each bus bay which exhaust the air to the outside. The airflow into these hoods should be activated only when work is performed on the hydrogen fuel system and only in the repair bay when the hydrogen bus is parked. The exhaust fans in these "hoods" should be electrically classified as Class 1, Division 1 since they will be operating in an explosive hydrogen environment, should a leak occur.

2.4.4 *Other Safety Systems and Practices*

The following safety practices must be followed unless a risk analysis indicates a higher level of safety can be provided with alternative approach(es).

1. Materials used in the construction of the maintenance facility should be noncombustible.

2. Flammable gas or hydrogen sensor(s) should be provided at strategic location(s) within the maintenance building. These should be connected to the building alarm system.

3. The bus being maintained should be electrically grounded to prevent accidental static electricity-generated sparks.

4. The facility should have a workable emergency response system. The level and type of response should be commensurate with and adequate for the magnitude of the hydrogen release (or other) emergency.

In addition, the following (passive) safety practices should be implemented:

5. Procedures should be implemented to ensure that when service is being performed on bus components and systems not related to hydrogen fuel system (e.g., brakes, steering, wheels, or other such components) the fuel system is not affected, either mechanically (i.e., impacts) or electrically.

6. Consideration should be given to ***defueling*** the bus outside the maintenance facility (except for very nominal pressure in ***fuel tank*** sufficient to move the bus in and out of the maintenance bay) when any part of the hydrogen fuel system on a bus is to be serviced.

7. Detailed instructions should be provided to the staff and ***fail-safe*** procedures implemented to prevent a bus which is leaking hydrogen (at however small a rate) from being moved inside the maintenance building. A bus leaking hydrogen should always be serviced outdoors.

8. Only mechanics who are trained in servicing a hydrogen fuel system should be allowed to perform the maintenance on hydrogen fuel systems. Proper training, along with the availability of proper equipment, should stress the importance of using nitrogen to purge hydrogen from equipment before opening the equipment to air. Training should also emphasize using nitrogen to purge air from equipment before placing hydrogen in the equipment. Helium must be used to purge where LH_2 will be present.

9. Adequate training and instructions should be provided to the mechanics working on the hydrogen fuel system with regard to proper procedures for tightening compression fittings, mating of the same parts after removal, and testing for fuel vapor leaks.

2.5 BUS FUEL SYSTEM

There are a number of issues related to materials compatibility, location of hydrogen tanks, sizing and direction of hydrogen vents, and types of valves used, and other issues, all pertaining to the design of the fuel system on a hydrogen-powered bus. There are common fuel storage tank design issues to both a compressed gaseous hydrogen storage or liquefied hydrogen storage on the bus. However, there are also significant differences. The important design issues are indicated below.

1. All hydrogen fuel lines and hydrogen wetted components should be compatible with hydrogen. Low melting temperature metals, plastics, and elastomers should be avoided, as they could fail in either a fire or in the event of a hydrogen leak.

2. The fuel lines and components should be located exterior to the passenger compartment and should be easily accessible from the outside. Enclosed areas within the bus in which vapors from a fuel leak can accumulate should be avoided to the extent possible.

3. The location of lines/components and the materials to be used on the bus should be evaluated against potential corrosion from salt and exposure to weather elements.

4. Fuel lines should be ductile to withstand impact, vibration, and braking forces.

5. Fuel lines should have a minimum number of joints, as joints represent the weakest part of a fuel system and could lead to leaks from gaskets and threads. However, the designers should also consider the vehicle and fuel system serviceability.

6. Fuel line welding should be performed only by certified welders. All fuel line welds should be thoroughly tested.

7. Fueling port on the bus should be at a convenient height for an average height fueler to service the bus with ease. Also, all gauges and electrical grounding connections on the bus should be located at such height as to facilitate easy reading of the electrical connections. Consideration should be given to specifying in the bus design the provision of all gauges, electrical connection ports and the fueling port on the same side.

8. Exhaust system (in case of Internal Combustion [IC] engines) components and fuel system components should be well separated or thermally shielded from each other.

9. The hydrogen storage tanks should be located away from the vehicle perimeter to enhance crash survival potential.

10. Hydrogen storage tanks on vehicles should be properly anchored to the vehicle body to withstand a minimum force of 8 g in any direction.

11. Manual shutoff valves on the storage tanks should be designed so that they are easily accessible from the outside during normal operation of the bus, They should be protected against damage in accidents.

12. Buses using hydrogen should be equipped with hydrogen/flammable vapor sensing instrument(s) within the passenger compartment and in the engine compartment of the bus.

13. A ***defueling*** port should be properly designed and built into the fuel system. This port should be easily accessible during the normal operation of the bus.

14. A system for emergency venting of hydrogen to the atmosphere from a bus should be provided. The vent system should be designed to take advantage of the natural buoyancy of hydrogen at ambient conditions. A vent with a less than 45" angle with the vertical will be beneficial if the design can ensure the absence of dirt and debris accumulation in the vent pipe. The vent stack height should be above the highest point of any structure within 16 m (50 feet) of the vent stack.

15. In the case of liquefied hydrogen storage, because of heat leak, the storage tank pressure will rise continuously. At a preset (safety) pressure, it will be necessary to vent the boil-off hydrogen gas to the atmosphere. Therefore, the LH_2 fuel system should be designed to allow the venting of boil-off in a safe manner.

16. The fuel system design should focus on the tightness of shutoff and resistance to valve packing leaks. Positive shutoff or isolation of the hydrogen is essential. Packless valves should be considered wherever possible.

17. Emergency shutoff valves should be provided on the fuel tanks to attain a "failed-closed" position if a hydrogen leak is detected or if a high g-force is sensed. A minimum of exposed fuel line should exist between the tank and this valve. Also, the valve should be located such that it has a low probability of being damaged in an accident.

2.6 PERSONNEL TRAINING

The safe operation of any bus transit facility which uses hydrogen as an alternative fuel will depend strongly on the level of training given to various personnel throughout the facility as well as on the commitment to safety from management. Servicing a hydrogen system will require specialized training, separate labels on system components, and separate venting and purging systems in the facility. Training should emphasize that hydrogen must be treated differently than natural gas and other conventional liquid fuels. Personnel will have to be trained in hazard awareness, fuel tank and fuel line purging procedures, leak detection, pressure checking, component testing and replacement (Hansel, 1996).

Safety consciousness can only be achieved by providing continuous training for all personnel (including management). Training programs should be developed to include all personnel who will be directly or indirectly involved in the maintenance, operation, fueling or storage of the hydrogen buses. The following individuals (at a minimum) should be provided with formalized training:

- Fuelers
- Bus Operators
- Mechanics
- Supervisors
- Management
- Other Building Occupants

The topics that should be covered in a training program will depend on the skill level and nature of responsibility of the individuals being trained. Table 2-6 shows a matrix of types/topics of training and the category of personnel. The information in this matrix should be used as a guide to determine the minimum training to be provided. In some cases, the type of training to be provided for hydrogen fuel operations will be similar to that which is required for other fuels.

Local fire department, police, hazardous material response teams, and emergency medical service personnel should also receive training on the location of all safety controls, the ***hazards*** associated with hydrogen, and any special information on systems installed. The training should, in particular, emphasize the extreme flammability and explosivity of hydrogen, the near invisibility of hydrogen fires, and the rapid diffusion of hydrogen vapors. Also, the differences between hydrogen and other hydrocarbon fuels and vapors should be emphasized.

Training in all areas identified in Table 2-6 can be accomplished in a variety of ways. In-house training is probably the most cost-effective way to provide training to the employees, provided a training department exists within the organization. If proper in-house technical information is not available, Train-the-Trainer courses are available from government agencies and private training companies. The Federal Transit Administration offers one such course entitled "Instructor's Course in Alternative Fuel Safety" through the Transportation Safety Institute (TSI), Oklahoma City, OK. This type of training can also be used to reinforce in-house trainers' technical training material so that it can be passed on to transit agency employees.

Hydrogen fuel supply companies, insurance companies, and utility companies are also sources for training material. These training courses are generally given at specific locations, but can also be brought to the transit agency.

Recordkeeping is an important part of any training program. In the case of an accident, questions raised may include the competence and qualifications of personnel associated with the alternative fuel bus program, the type and level of training received by each employee, when and where the training was provided and for how long. It is therefore essential to place in each employee's personnel file copies of training records.

Table 2-6

Training Topics for Various Personnel

Training Topics	Fuelers/ Mechanics	Building Occupants	Bus Operators	Emergency Response Personnel	Local Groups	Manage-ment	Utilities
Physical/Chemical Properties of the Fuel	✔	✔	✔	✔		✔	✔
Safe Handling/Fueling Procedures	✔		✔				
Emergency Notification Procedures	✔	✔	✔			✔	
Emergency Evacuation Procedures	✔	✔	✔	✔	✔	✔	
Fire Detection/Suppression Features	✔	✔	✔	✔		✔	✔
Vehicle/Facility Safety Features	✔		✔	✔		✔	
Safe Repair/Maintenance Procedures	✔					✔	
Licenses/Permits Required/Certification	†		†			‡	‡
Fire Prevention	✔	✔	✔			✔	
Emergency Preparedness Drills	✔		✔	✔	✔	✔	✔

† If Applicable ‡ As Required

Maintenance records of equipment failures become very important when trying to isolate and identify equipment problems. Every failure, no matter how small in nature, should be recorded and, if possible, investigated to determine why the failure occurred. If needed, the manufacturer should be called in to offer technical assistance.

Fire drills should be conducted on a regular basis and records kept and made available for inspection by the fire department and/or safety personnel. Deficiencies in the evacuation of a building or any problems with alarm/detection equipment should be documented and forwarded to the appropriate person for corrective action. OSHA regulations require that fire drills be conducted on a regular basis, and these regulations should be followed,

Fire alarm systems as well as fire suppression systems installed in the facility as well as on buses should be inspected on a regular basis and conform to manufacturers' requirements and/or local codes, if any. In addition to the regular inspections, periodic testing of this equipment may also be required. NFPA standards should be consulted to determine exact testing procedures and inspection intervals. Records of these inspections and tests should be kept on the premises. Additional information is included in Section 2.2.1.8 "Maintenance of Safety Equipment" of this document.

Personnel required to receive safety training on the chemical/physical properties of hydrogen should receive basic information to make them aware of the potential dangers associated with a release of the gas. The information contained in Section 2. 1 "General Fuel Properties" of this document should be included in the training.

Fire prevention should be practiced whether or not hydrogen buses are used. Good housekeeping and the proper storage of flammable and combustible materials is essential in order to provide a safe workplace for the employees. When hydrogen buses are utilized, precautions should be taken to ensure that ignition sources are kept away from potential gas pockets. Strict enforcement of "no smoking" policies, electrically grounding vehicles and equipment during hydrogen transfer operations, adequate ventilation, the use of non-sparking tools, and the use of personal protective clothing and safety equipment will greatly contribute to the elimination of potential problems.

Some jurisdictions may require special licenses or certifications from the fire department or the state to maintain hydrogen buses. The transit agency should check local regulations to see whether or not these are required. In addition, fire department permits or licenses to operate the fueling station as well as the bulk storage of hydrogen and/or the hydrogen buses may also be required. Other permits may be the responsibility of the local utility supplying the fuel or the contractor operating the fueling facility. In all cases, proper licenses and permits should be obtained prior to operation.

2.7 EMERGENCY PREPAREDNESS

The establishment of an Emergency Response Action Plan constitutes an important part of a facility's safety management in a facility handling/storing/or dispensing a hazardous/flammable material such as hydrogen. The Emergency Response Action Plan should be a ***written document*** which addresses the following issues.

1. Identification of emergencies (detection and classification).

2. Action times required, their implementation sequence and the time duration within which to initiate different actions.

3. Notification procedures and a notification list which should include both internal (i.e., transit agency) and external (fire service, ambulance, police, et al.) contacts.

4. Evacuation procedures and required training to implement such procedures.

5. Location and type of safety systems (both in the facility and on the bus).

6. Event suppression or management actions which should include personnel rescue, fire suppression strategies, evacuation of personnel, and protection of property not yet affected.

OSHA's Personnel Protection regulations require the employer to have an "Employee Emergency and Fire Prevention Plan" (29 CFR §1910.38). Specifically, 29 CFR §1910.38 requires the inclusion of the following items, as a minimum, in the plan:

OSHA

29 CFR §1910.38 Employee Emergency and Fire Prevention Plan

(i) Emergency escape procedures and emergency escape route assignments;
(ii) Procedures to be followed by employees who remain to operate critical plant operations before they evacuate;
(iii) Procedures to account for all employees after emergency evacuation has been completed;
(iv) Rescue and medical duties for those employees who are to perform them;
(v) The preferred means of reporting fires and other emergencies; and
(vi) Names or regular job titles of persons or departments who can be contacted for further information or explanation of duties under the plan.

The transit system should comply with the provisions of OSHA regulations and incorporate these requirements in its ***system safety*** plan.

Because of the potential impacts of a hydrogen release and ignition incident, it is important that the transit agency work closely with the local emergency response agency to develop ajoint notification and action implementation plan.

Emergency preparedness drills involving the transit agency, fire department, emergency medical services and police should be conducted to test the effectiveness of the emergency action plan. This will help in minimizing unnecessary damage by familiarizing response personnel with the safety equipment installed. In areas where the transit system operates in more than one jurisdiction, drills should be rotated so that all jurisdictions have a chance to participate. Emergency plans should clearly identify what agency is in charge of the incident prior to an actual emergency in order to eliminate unnecessary delays.

These emergency exercises should be followed up with a critique. If problems are identified, additional training may be needed or the emergency action plan may need to be revised.

Transit employees should be familiar with their agency's emergency action plan so they can implement it as soon as an alarm is sounded. This may include manning fire command stations, removing buses from other parts of the facility, or helping in the evacuation of the facility.

Depending on the location of the hydrogen facility, local civic groups, school boards, and local businesses should be made aware of any emergency action plans which could affect them in a major gas release incident.

In addition to providing training to the fire, police, and emergency medical services, the supplier of hydrogen should be included in emergency preparedness.

Chapter 3
Alternative Fuel Facility
System Safety Process

3.1 SAFETY REQUIREMENTS

The purpose of this section is to assist transit agencies in implementing a program to identify and resolve potential safety issues that may occur over the lifetime of the system. Such a program will assist in the development of a proactive safety assessment that allows for the identification and resolution of potential safety issues during the planning, design, construction, and operation of the transit system. This section identifies the important elements of a safety/***hazard*** assessment technique, by which a transit authority can conduct a ***risk*** assessment to address design issues when standards/codes do not provide the necessary definitive guidance or when a transit authority wishes to consider alternative designs.

A ***system safety*** program, discussed in Section 3.2, should be instituted during the system planning/design phase and continue throughout the system construction, renovation, operation and disposition of a facility used for the maintenance, fueling and/or storage of transit vehicles fueled with alternative fuels. The ***system safety*** program should emphasize the prevention of accidents by identifying and resolving ***hazards*** in a systematic manner in accordance with the Hazard Resolution Process elaborated in Section 3.3.4.

3.2 SYSTEM SAFETY PROGRAM

A ***system safety*** program should be implemented to identify and resolve ***hazards***. The transit authority should provide for the development of a System Safety Program Plan (SSPP) to assist in implementing and documenting that program. The SSPP should identify the responsibilities of ail parties for implementing a ***system safety*** program.

The SSPP should:

- Have the objective of providing safety for passengers, employees, general public, and equipment.
- Encompass all system elements and organizations within the transit system.
- Identify the safety roles and responsibilities of all organizational elements, and require accountability.

- Designate one individual with the responsibility for the safety of the system who has clearly defined roles and responsibilities established through a written policy.

- Establish a safety program that contains a ***hazard*** resolution process including the procedures necessary to identify and resolve ***hazards*** throughout the system life cycle.

- Ensure transit authority management's commitment and approval, in the form of a signed policy, for allocation of resources required to maintain a high level of safety.

The individual identified to carry out the safety program should clearly have the authority to insure its implementation and should report directly to top management.

The SSPP should be developed during the planning/design phase of the alternative fuel transit facility and maintained current throughout the facility system life cycle. The SSPP should be prepared in general accordance with the requirements of MIL-STD-882C, Task 102 or equivalent. The SSPP should, as a minimum identify the scope of the ***system safety*** program activities including those discussed previously.

3.3 HAZARD IDENTIFICATION AND RESOLUTION PROCESS

A hazard analysis should be performed on all facility modification and new construction projects. This analysis should be initiated by defining the physical and functional characteristics of the alternative fuel vehicle and facility system to be analyzed. These characteristics should be presented in terms of the people, procedures, facilities, and equipment which are integrated to perform a specific operational task or function within a specified environment.

3.3.1 *System Definition*

The first step in the ***hazard*** resolution process is to define the physical and functional characteristics of the system to be analyzed. These characteristics are presented in terms of the major elements which make up the system: equipment, procedures, people, and environment. A knowledge and understanding of how the individual system elements interface with each other is essential to the ***hazard*** identification effort.

3.3.2 *Hazard Identification*

The second step in the hazard resolution process involves the identification of hazards and the determination of their causes.

There are four basic methods of hazard identification that may be employed to identify hazards. These methods are:

- data from previous accidents (case studies) or operating experience;
- scenario development and judgment of knowledgeable individuals;
- generic ***hazard*** checklists; and
- formal ***hazard*** analysis techniques.

When identifying the safety ***hazards*** present in a system, a major concern is that only a portion of the total number of system ***hazards*** has been identified. Therefore, every effort should be made to identify and catalog the whole universe of potential ***hazards***.

There are several ***hazard*** analysis techniques that should be considered to assist in the evaluation of potential ***hazards*** and to document their resolution. These techniques include a Preliminary Hazard Analysis (PHA), Subsystem Hazard Analysis (SSHA), System Hazard Analysis (SHA) and/or Operational and Support Hazard Analysis (O&SHA). These analyses should be conducted in general accordance with MIL-STD-882C, Tasks 202 (PHA), 204 (SSHA), 205 (SHA) and 206 (O&SHA), or equivalent, respectively.

3.3.3 *Hazard Assessment*

The third step in the hazard resolution process is to assess the identified hazards in terms of the severity or consequence of the hazard and the probability of occurrence of each type of hazard. All hazards that are identified should be assessed in terms of the severity or consequence of the hazard and the probability of occurrence. This should be accomplished in general conformity with the criteria outline in MIL-STD-882C, Paragraphs 4.5 and 4.6 or the equivalent.

3.3.4 *Hazard Resolution*

After the ***hazard*** assessment is completed, ***hazards*** can be resolved by deciding to either assume the risk associated with the ***hazard*** or to eliminate or control the ***hazard***. The ***hazard*** reduction precedence is as follows:

- Design to eliminate or control the ***hazard***.
- Add safety devices.
- Provide warning devices.
- Institute special procedures and training.
- Accept the ***hazard***.
- Eliminate the use of the system/subsystem/equipment that creates an unacceptable ***hazard***.

Various means can be employed in reducing the ***risk*** to a level acceptable to management. Resolution strategies or countermeasures in order of preference are:

Design to Eliminate Hazards. This strategy generally applies to the acquisition of new equipment or expansion of existing systems; however, it can also be applied to any change in equipment or individual subsystems. In some cases ***hazards*** are inherent and cannot be eliminated completely through design.

Design for Minimum Hazards. A major safety goal during the system design process is to include safety features that are ***fail-safe*** or have capabilities to handle contingencies through redundancies of critical elements. Complex features that could increase the likelihood of ***hazard*** occurrence should be avoided. Changes may be made to an existing design to control the known ***hazard***.

Safety Devices. Known ***hazards*** which cannot be eliminated or minimized through design may be controlled through the use of appropriate safety devices. This could result in the hazards being reduced to an acceptable ***risk*** level. Safety devices may be a part of the system, subsystem, or equipment.

Warning Devices. Where it is not possible to preclude the existence or occurrence of an identified ***hazard***, visual or audible warning devices may be employed for the timely detection of conditions that precede the actual occurrence of the ***hazard***. Warning signals and their application should be designed to minimize the likelihood of false alarms that could lead to creation of secondary hazardous conditions.

Procedures and Training. Where it is not possible to eliminate or control a ***hazard*** using one of the aforementioned methods, safe procedures and/or emergency procedures should be developed and formally implemented. These procedures should be standardized and used in all test, operational, and maintenance activities. Personnel should receive training in order to carry out these procedures.

Hazard Acceptance/System Disposal. Where it is not possible to reduce a ***hazard*** by any means, a decision must be made to either accept the ***hazard*** or dispose of the system.

Risk assessment estimates (Table 3-1, Table 3-2, and Table 3-3) should be used as the basis in the decision-making process to determine whether individual facility, system or subsystem ***hazards*** should be eliminated, mitigated, or accepted. ***Hazards*** should be resolved through a design process that emphasizes the elimination of the ***hazard***.

3.3.5 Follow-up

The last step in the ***hazard*** resolution process is follow-up. It is necessary to monitor the effectiveness of recommended countermeasures and ensure that new ***hazards*** are not introduced as a result. In addition, whenever changes are made to any of the system elements (equipment, procedures, people, and/or environment), a ***hazard*** analysis should be conducted to identify and resolve any new ***hazards***.

This process should include full documentation of the hazard resolution activities. The effectiveness of the countermeasures should be monitored to determine that no new hazards are introduced. In addition, whenever substantive changes are made to the system, analyses should be conducted to identify and resolve any new hazards.

Table 3-1

Risk Assessment

Frequency	Hazard Category			
	I-Catastrophic	II-Critical	III-Marginal	IV-Negligible
A-Frequent	IA	IIA	IIIA	IVA
B-Probable	IB	IIB	IIIB	IVB
C-Occasional	IC	IIC	IIIC	IVC
D-Remote	ID	IID	IIID	IVD
E-Improbable	IE	IIE	IIIE	IVE

(dark shading)	IA, IIA, IIIA, IB, IIB, IC	Unacceptable
(medium shading)	IIIB, IIC, ID	Undesirable (allowable with agreement from Authority having jurisdiction)
(light shading)	IVA, IVB, IIIC, IID, IE, IIE	Acceptable with notification to the Authority having jurisdiction
(no shading)	IVC, IVD, IIIE, IVE	Acceptable

Table 3-2

Frequency Categories

Frequency	Definition of Term
A-Frequent	***MTBE*** is less than 1,000 operating hours
B-Probable	***MTBE*** is equal or greater than 1,000 operating hours and less than 100,000 operating hours
C-Occasional	***MTBE*** is equal or greater than 100,000 operating hours and less than 1,000,000 operating hours
D-Remote	***MTBE*** is equal or greater than 1,000,000 operating hours and less than 100,000,000 operating hours
E-Improbable	***MTBE*** is greater than 100,000,000 operating hours

MTBE = Mean Time Between Events

Table 3-3

Hazard Categories

Hazard	Definition of Term
I-Catastrophic	Death, system loss, or severe environmental damage
II-Critical	Severe injury, severe occupational illness, major system or environmental damage
Ill-Marginal	Minor injury, minor occupational illness, or minor system or environmental
IV-Negligible	Less than minor injury, occupational illness, or less than minor system or environmental damage

3.4 SAFETY PRINCIPLES

The following safety principles should be observed in the transit system operating alternative fuel vehicles (see Table 3-1, Table 3-2, and Table 3-3 for a definition of undesirable and unacceptable ***hazards***):

1. When the system is operating normally there should be no unacceptable or undesirable ***hazard*** conditions.

2. The system design should require positive actions to be taken in a prescribed manner to either begin system operation or continue system operation.

3. The safety of the system in the normal operating mode should not depend on the correctness of actions or procedures used by operating personnel.

4. There should be no single point failures in the system that can result in an unacceptable or undesirable ***hazard*** condition.

5. If one failure combined with a second failure can cause an unacceptable or undesirable ***hazard*** condition, the first failure should be detected and the system shall achieve a known ***safe state*** before the second failure can occur.

6. Software faults should not cause an unacceptable or undesirable ***hazard*** condition.

7. Unacceptable ***hazards*** should be eliminated by design.

8. Maintenance activities required to preserve specified ***risk*** levels (Table 3-1) involve the elimination of unacceptable or undesirable ***hazard*** conditions during maintenance. These should be prescribed to the individual responsible for *system safety* during the design phase. These maintenance activities should be minimized in both the frequency and in the complexity of their implementation. The personnel qualifications required to adequately implement these activities should also be identified.

3.5 VERIFICATION AND VALIDATION

The design and implementation of all ***safety critical*** hardware and software elements of the system as identified in the ***hazard*** resolution process should be subjected to verification and validation. The objective of this verification and validation activity should be to assure that all safety critical elements have been designed and implemented to achieve safe operation and to verify the level of safety achieved.

The verification and validation process should include:

1. The identification of all factors upon which the assurance of safety depends. Such factors should be directly associated with the design concept used.

2. The identification of all ***safety critical*** functions performed by the system.

3. Analyses demonstrating that all dependent factors are satisfied and that each ***safety critical*** function is implemented in accordance with safety principles. Each facility used for storing, maintaining and/or fueling alternative fuel vehicles should, in addition to the above, exhibit a calculated Mean Time Between Hazardous Events (***MTBHE***) of 100 million system operating hours or greater. ***System safety*** documentation should support this calculation and substantiate the methodology used to arrive at the result.

Glossary

Auto Ignition Temperature The temperature at which a flammable concentration of vapor will ignite in the absence of an external ignition source. (Ignition effected by a hot surface rather than by an open flame or a spark.)

Chemical Formula The chemical composition. Hydrogen, methanol and ethanol are pure substances with a definite formula. Natural gas, commercial propane, gasoline, and diesel fuel have variable compositions.

CNC (Compressed Natural Gas) is defined as natural gas above the gas main supply pressure. The gas main supply pressure can be as low as 5 pounds per square inch and as high as 800 pounds per square inch or more.

CHG (Compressed Hydrogen Gas) is hydrogen gas compressed to a high pressure (20 MPa) and stored at ambient temperature.

Compressors The compressors are generally supplied as packaged, pre-engineered equipment. The compressors increase the pressure of the gas from pipeline conditions (generally 10 psig to 300 psig) to the maximum required fill pressure (generally 3600 psig for 3000 psig buses and 4500 psig for 3600 psig buses).

Container A pressure vessel, generally of cylindrical shape, used to store the compressed natural gas.

Defueling is defined as removing all of the hydrogen inventory from a bus fuel delivery and storage system by allowing contained hydrogen to flow to a lower pressure and then to atmospheric pressure.

Detonation The very rapid burning of vapor resulting in a self-sustaining shock wave, the pressure behind which is several atmospheres. Detonation waves travel at speeds exceeding the speed of sound in air.

Diesel Fuel This is the most common fuel for heavy duty engines and therefore a standard of comparison for other, alternative fuels.

Diesel Volume Equivalent (DVE) The number of standard cubic meters of hydrogen equivalent to a liter of diesel (or, alternatively, number of SCF of hydrogen equivalent to a gallon o-f diesel on an energy equivalent basis).

Fail-Safe A characteristic of a system or its elements whereby any failure or malfunction affecting safety will cause the system to revert to a state that is known to be safe.

Flame Temperature The temperature of a flame burning a stoichiometric mixture of fuel and air (neither fuel nor air is in excess) .

Flammability Limits The range of fuel vapors concentrations in a fuel-air mixture over which burning can occur. 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.

Fuel Storage System One or more containers, including their interconnecting equipment, that are designed, fabricated and approved for use in the mobile containment of hydrogen for bus power.

Fuel Tank A hydrogen container on board the vehicle.

Gas Dispensers The gas dispensers often look and function much like a diesel dispenser, but dispense hydrogen gas or liquid. The dispenser is "smart" enough to control its own fill pressure and the required cycling of valves.

Gas Storage The storage vessels are used to store a volume of gas to reduce the potential of compressor short cycling. On smaller stations this volume of gas may be used to enhance the fill speed through cascading, however on larger stations which includes most transit stations, the storage functions as a buffer and buses are generally filled directly from the compressor.

Hazard An existing or potential condition that can result in an accident.

Heat of Vaporization The amount of heat energy necessary to vaporize one unit mass (say, a kilogram) of liquid fuel. For comparison, the latent heat of vaporization of water is 2550 Id/kg.

High Release Rate Event (HRRE) This is characterized by gas release due to a catastrophic failure in the high pressure tubing connecting the bank of fuel storage cylinders (fuel tanks) or a gas discharge through a pressure relief device (either due to malfunction, a thermal fusible plug failure, or tank overpressure). This type of leak would lead to the release of a large volume of gas which may pose a hazard if released inside a building.

LH_2 (liquefied hydrogen) When hydrogen gas is cooled to 20.3 K at ambient pressure, it becomes a liquid.

Lower Flammable Limit The minimum volume concentration of a combustible vapor in a mixture of vapor and air at normal temperature which can sustain the propagation of a flame in the mixture.

Low Release Rate Event (LRRE) A hydrogen release from a bus is characterized as a "low release rate event" if the gas is emanating from a loose fitting, a valve stem, a crack in the gasket, etc. This type of leak can be expected to dissipate rapidly and pose very limited hazard, either immediately or over an extended period of time. It is assumed that the total volume of gas leaked during the leak event is considerably smaller than the volume of the building into which the leak occurs. The air currents induced by the normal ventilation may be adequate to dissipate the vapors below the flammable limit quickly.

MTBE Mean time between events.

MTBHE Mean time between hazardous events = mean time between the occurrence of critical or catastrophic hazards (Table 3-1).

Natural Gas An alternative fuel, natural gas is the same natural gas burned for heating and cooking. Natural gas varies in composition with location. Natural gas is usually more than 90 percent methane with smaller amounts of other hydrocarbons.

Pressure Relief Device (PRD) A safety device provided in the high pressure gas line very close to the tank to vent excess pressure in the tank in case of tank overpressure. The device is actuated by either overpressure or high tank temperature. The excess pressure in the tank is relieved by venting the contents of the tank to the atmosphere.

Relative Fuel Vapor Density The density of the fuel vapor compared to air. Thus, on this scale, air equals 1.00.

Risk A measure of the severity and likelihood of an accident.

Safe State System state which is deemed acceptable by the hazard resolution process (3.1.2).

Safety Critical A designation placed on a system, subsystem, element, component, device, or function denoting that satisfactory operation of such is mandatory to mitigation of unacceptable and undesirable hazards as defined in Table 3-1.

Saturated Hydrocarbon A chemical molecule containing carbon and hydrogen atoms in a combination represented by C_nH_{2n+2}. Methane, ethane, propane, butane, pentane, hexane, heptane, are examples of a saturated hydrocarbon.

Scheduled Defueling The planned removal of hydrogen from a bus fuel storage system in order to make repairs or modifications to the bus equipment.

Stoichiometric -Air/Fuel Ratio The mass of air that is just enough to burn a unit mass of fuel. A stoichiometric ratio of 34 implies that one kg of fuel requires 34 kg of air for combustion if neither fuel nor air is to be in excess.

System Safety The application of engineering and management principles, criteria, and techniques to optimize all aspects of safety within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle.

Upper Flammable Limit The maximum volume concentration of a combustible vapor in a mixture of vapor and air at normal temperature which can sustain the propagation of a flame in the mixture and which cannot sustain a stable and steady flame front throughout the mixture at higher concentrations.

Vapor Pressure The pressure exerted by the vapors in equilibrium with its liquid at a specific temperature. ASTM D323 Test "Standard Method of Test for Vapor Pressure of Petroleum Products" measures the vapor pressure at a standard temperature of 37.8 ^{o}C (100 ^{o}F) and reports the value as "Reid Vapor Pressure."

Volume Fuel with Same Energy This is the ratio of the volumetric energy content of the fuel to that of gasoline or diesel fuel. Numerically, this is the ratio of the Lower Heating Value (LHV) in MJ/L for the fuel to the lower heating value of gasoline or diesel fuel in MJ/L.

Water Capacity This is numerically the same as the volume of water at 15.6 ^{o}C (60 ^{o}F) required to fill a fuel tank completely.

List of Acronyms

A&E	Architectural and Engineering
ACH	Air Changes per Hour
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CH_2	Compressed Hydrogen
CHG	Compressed Hydrogen Gas
CNG	Compressed Natural Gas
DVE	Diesel Volume Equivalent
ESD	Emergency Shutdown
FTA	Federal Transit Administration of the United States Department of Transportation
LFL	Lower Flammability Limit
LH_2	Liquefied Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MTBE	Mean Time Between Events
MTBHE	Mean Time Between Hazardous Events
NBP	Normal Boiling Point (boiling temperature at atmospheric pressure)
NFPA	National Fire Protection Association
NTP	Normal Temperature and Pressure
O&SHA	Operational and Support Hazard Analysis
OSHA	Occupational Safety and Health Administration of the U.S. Dept. of Labor
PHA	Preliminary Hazard Analysis
PRD	Pressure Relief Device
SCF	Standard Cubic Feet
SHA	Support Hazard Analysis

SSHA	Subsystem Hazard Analysis
SSPP	System Safety Program Plan
STP	Standard Temperature and Pressure (20 "C and 1 bar pressure)
U.S. DOT	United States Department of Transportation
UFL	Upper Flammability Limit

Glossary of Graphic Symbols

CAUTION

Caution

OSHA

Occupational Safety & Health Administration logo

NFPA®

National fire Protection Association logo

Units of Measurement

The units of physical parameters such as mass, length, pressure, temperature, etc., are indicated first in the Standard International (SI) units (kilogram, meter, Pascal, Kelvin, etc.), followed in parenthesis by the values in more conventional British units.

All vapor pressure values indicated in SI units are in absolute pressure units (unless otherwise stated) to be consistent with the thermodynamic convention. In general, when the vapor pressure values are indicated in conventional British units they are in pounds per square inch gage (psig). Therefore, care should be taken to add the atmospheric pressure to the gage pressure when converting to absolute pressure values.

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