

TECHNICAL CODE

HYDROGEN STORAGE AND SAFETY WITH FUEL CELL AS POWER GENERATOR FOR INFORMATION, COMMUNICATIONS AND TECHNOLOGY INFRASTRUCTURE

Developed by



Registered by



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Committee representation

This technical code was developed by the Hydrogen Safety Sub Working Group under the Green Information and Communications Technology, Environment and Climate Change Working Group of the Malaysian Technical Standards Forum Bhd (MTSFB) which consists of representatives from the following organisations:

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Foreword

This technical code for Hydrogen Storage and Safety with Fuel Cell as Power Generator for Information, Communications and Technology Infrastructure (‘this Technical Code’) was developed pursuant to Section 185 of the Act 588 by the Malaysian Technical Standards Forum Bhd (‘MTSFB’) via its Hydrogen Safety Sub Working Group under the Green Information and Communications Technology, Environment and Climate Change Working Group.

This Technical Code shall continue to be valid and effective until reviewed or cancelled.

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HYDROGEN STORAGE AND SAFETY WITH FUEL CELL AS POWER GENERATOR FOR INFORMATION, COMMUNICATIONS AND TECHNOLOGY INFRASTRUCTURE

0. Introduction

This Technical Code details the storage and safety issues for hydrogen used as fuel for a fuel cell (of type Proton Exchange Membrane (PEM) fuel cell/polymer electrolyte fuel cell) to supply the power for Information, Communications and Technology (ICT) infrastructure in Malaysia. This Technical Code is to assist the ICT industries that carry out their decarbonisation exercises by utilising hydrogen-powered fuel cells as power supply.

Hydrogen is a naturally occurring gas that is amazingly light. The hydrogen atom is so simple and small, it is hard to believe that hydrogen is the most important and abundant substance in the universe. Hydrogen is colourless, odourless, tasteless, flammable gaseous substance.

Hydrogen can be stored physically as a compressed gas or as a cryogenic liquid. As a liquid, storage of hydrogen requires extremely low temperatures because its boiling point at 1 atmosphere pressure is - 253 °C. However, the liquid hydrogen storage is commonly used for bulk hydrogen storage. Hydrogen can be stored using six different methods which are grouped in two forms as follows:

- a) Physical-based
 - i) high-pressure gas cylinders and pressure vessels;
 - ii) liquid hydrogen in cryogenic tanks (at 21.2 K and ambient pressure);
- b) Material-based
 - i) adsorbed hydrogen on materials with a large specific surface area (at $T < 100$ K);
 - ii) absorbed on interstitial sites in a host metal (at ambient pressure and temperature);
 - iii) chemically bonded in covalent and ionic compounds (at ambient pressure); or
 - iv) through oxidation of reactive metals, e.g., Li, Na, Mg, Al, Zn with water.

1. Scope

This Technical Code specifies requirements for handling, labelling and storage of hydrogen from the time it is received by the owner which includes safety for on-site hydrogen storage. Hydrogen is used as fuel for fuel cells that act as backup power supplies to ICT infrastructure which include base stations, data centres, satellite base stations and Internet of Things (IoT) network infrastructure.

This Technical Code will focus only on high-pressure gas cylinders and pressure vessels, which is currently the most common way of storing hydrogen.

Hydrogen production on-site and hydrogen transportation to and from the premises are not covered in this Technical Code.

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2. Normative references

The following normative references are indispensable for the application of this Technical Code. For dated references, only the edition cited applies. For undated references, the latest edition of the normative reference (including any amendments) applies.

Act 139, *Factories and Machinery Act 1967*

P.U. (A) 39/1996, Occupational Safety and Health Act 1994, *Occupational Safety and Health (Control of Industrial Major Accident Hazards) Regulations 1996*

P.U. (A) 310., Occupational Safety and Health Act 1994, *Occupational Safety and Health (Classification, Labelling and Safety Data Sheet of Hazardous Chemicals) Regulations 2013*

Department of Occupational Safety and Health, *Guidelines for Hazard Identification, Risk Assessment and Risk Control (HIRARC)*

Department of Occupational Safety and Health, *Industry Code of Practice on Chemicals Classification and Hazard Communication 2014*

MS IEC 60364, *Standards for Residential Wiring*

MS IEC 60364-7-712, *Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems*

IEC 62282-3-100, *Fuel cell technologies - Part 3-100: Stationary fuel cell power systems - Safety*

ISO/TR 15916, *Basic considerations for the safety of hydrogen systems*

National Fire Protection Agency, *NFPA 2: Hydrogen Technologies Code 2016*

3. Abbreviations

For the purposes of this Technical Code, the following abbreviation apply.

AIT	Autoignition Temperature
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CGA	Compressed Gas Association
CO	Carbon Monoxide
CSA	Canadian Standards Association
DDT	Deflagration to Detonation Transition
DOSH	Department of Occupational Safety and Health
EN	European Standards
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IoT	Internet of Things
ISO	International Organisation for Standardisation
LEL	Lower Explosive Level

LFL	Lower Flammability Limits
MEIM	Most Easily Ignitable Mixture
MSDS	Material Safety Data Sheet
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NOx	Nitrogen Oxides
NTP	Normal Temperature and Pressure
O&M	Operations and Maintenance
PEM	Proton Exchange Membrane
SAE	Society of Automotive Engineers International
UEL	Upper Explosive Limits
UFL	Upper Flammability Limits
WPS	Welding Procedures Specification
WQR	Welding Quality Report

4. Terms and definitions

For the purpose of this Technical Code, the following terms and definitions apply.

4.1 Accessible

Area can be accessed which under below operating conditions:

- a) access can be gained without the use of a tool;
- b) the means of access is deliberately provided to the end user; and
- c) the end user is instructed to enter regardless of whether or not a tool is needed to gain access.

4.2 Autoignition

Ignition that does not require external ignition energy because the thermal energy of the molecules alone is enough to overcome the activation threshold for combustion initiation.

4.3 Autoignition Temperature (AIT)

Lowest temperature at which autoignition occurs; 500 °C - 585 °C for hydrogen.

4.4 Bodily injury

Any injury listed in the Second Schedule in Section 3, *Factories and Machinery Act 1967*.

4.5 Buoyancy

Vertical force exerted on a body of less dense gas by the surrounding heavier static gas, typically air.

4.6 Combustible materials

Item capable of combustion even though flame-proofed, fire-retardant treated, or plastered.

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4.7 Combustion

Reaction process by which a flammable substance is oxidised, producing hot product gases, heat, radiation and possibly pressure waves.

4.8 Component

Any part of a complete item or system.

4.9 Confined space

Space not normally occupied by personnel. It may contain or produce “dangerous air contamination” due to lack of adequate ventilation from limited or restricted openings for entry and exit and may not be safe for entry.

4.10 Confinement

Physical restriction, sufficient to influence the combustion process or to facilitate the accumulation of hydrogen.

4.11 Control area

A building or portion of a building or outdoor area, within which hazardous materials are allowed to be stored, dispensed, used, or handled, in quantities not exceeding the maximum allowable quantities.

4.12 Deflagration

Combustion process in which a flame or chemical reaction moves through a flammable mixture at a rate less than the speed of sound in the unburned mixture.

4.13 Deflagration wave

A deflagration wave is a subsonic process where the pressure change across the flame is negligible. Deflagration waves propagate by the diffusion of heat and chemical radicals in front of the wave to ignite the mixture.

4.14 Deluge system

Water spray system that is used to keep equipment, especially hydrogen storage vessels, cool in the event of a fire.

4.15 Detonation

Shock stabilised combustion process resulting in a combustion phenomenon propagating faster than the speed of sound.

4.16 Detonation limits

Maximum and minimum concentrations of a gas, vapour, mist, spray or dust, in air or oxygen, for stable detonation to occur.

4.17 Diffusion

Flux of a fluid through another fluid or material due to concentration gradient.

4.18 Effluent

Products of combustion plus the excess air being discharged from gas utilisation equipment.

4.19 Electrical equipment

General term including material, fittings, devices appliances, fixtures, apparatus and the like used as part of, or in connection with and electrical installation.

4.20 Emergency

Unintended circumstance, bearing clear and present danger to personnel or property, which requires an immediate response.

4.21 Emergency shutdown

Control system actions for safety shutdown, based on process parameters, taken to stop the fuel cell power system and all its reactions immediately to avoid equipment damage and/or personnel hazards.

4.22 Explosion

Self-sustained combustion of a gas mixture releasing heat and hot combustion products when the rate of reaction in a reacting mixture increases with time until either the fuel or oxidiser is consumed or nearly so.

4.23 Facility

Group of buildings or equipment used for specific operations at one geographic location.

4.24 Fail-safe

Ability to sustain a failure without causing loss of equipment, injury to personnel, or loss of operating time.

4.25 Fire

Sustained burning of a fuel jet as manifested by any or all of the following such as light, flame, heat and smoke.

4.26 Fire triangle

Visual concept showing the requirements for combustion depicting a fuel, an oxidiser and an ignition source as the three sides of a triangle, where combustion cannot occur if any one side is not present.

4.27 Flame

Zone of combustion of a gas or vapour from which light and heat are emitted.

4.28 Flame front

Region of burning or chemical reaction (typically from fractions to several millimetres across) that separates burned and unburned regions.

4.29 Flammable gases

Flammable gas means a gas or gas mixture having a flammable range with air at 20 °C and a standard pressure of 101.3 kPa.

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4.30 Flammability

Degree to which a material is ignitable in an oxidising atmosphere.

4.31 Flammability limits

Lower Flammability Limits (LFL) and Upper Flammability Limits (UFL) concentration thresholds of fuel gas in a flammable mixture at a given temperature and pressure that will sustain propagation of a combustion wave.

4.32 Fuel cell

Electrochemical device that converts the chemical energy of a fuel and an oxidant, both externally supplied, to electrical energy (direct current power) heat and other reaction products.

4.33 Fuel cell power system

Generator system that uses a fuel cell module(s) to generate electric power and heat.

4.34 Gases

Substances whose vapour pressure exceed 300 kPa (absolute) at 50 °C or substances which are completely gaseous at standard atmospheric pressure (101.3 kPa) at 20 °C.

4.35 Gas cylinder

A steel cylinder or bottle used for the storage and transport of compressed, dissolved or liquefied gases.

4.36 Gas Storage Area

Any area used for the storage of gas in a gas-holder having a storage capacity of not less than one hundred and forty cubic metres (or 11.68 kg at 21 °C and 1 atm).

4.37 Hazard

A source or a situation with a potential for harm in terms of human injury or ill health, damage to property, damage to the environment or a combination of these.

4.38 Hazardous substance

Any substance which is within any of the criteria laid down in Schedule 1 or any substance listed in Part 1 of Schedule 2 of Part I (3), *Occupational Safety and Health (Control of Industrial Major Accident Hazards) Regulations 1996*.

4.39 Hydrogen embrittlement

Deleterious changes in the ductility properties of a metal that exposure to hydrogen can produce.

4.40 Ignite

To cause to burn or to catch fire.

4.41 Igniter

Device which utilises electrical energy to ignite gas at a pilot burner or main burner.

4.42 Ignition energy

Energy required to initiate a flame in a flammable mixture; function of the mixture concentration.

4.43 Indoor installation

The location where a hydrogen storage system is sited, whether as a unit or built as an assembly, which is completely surrounded and enclosed by walls, a roof and a floor.

4.44 Inspector

This includes Chief Inspector, Deputy Chief Inspector and a Senior Inspector appointed under the *Act Factories and Machinery Act 1967*.

4.45 Laminar flow

Fluid particles moving along smooth paths in thin layers with one-layer gliding smoothly over an adjacent layer (only a molecular interchange of momentum).

4.46 Local authorities

Rural and town board and local, city, municipal, district and town councils, or other similar local authority established by any written law and includes an authority in charge of a federal territory established by any written law.

4.47 Machinery

Includes steam boilers, unfired pressure vessels, fired pressure vessels, pipelines, prime movers, gas cylinders, gas holders, hoisting machines and tackle, transmission machinery, driven machinery, materials handling equipment, amusement device or any other similar machinery and any equipment for the casting, cutting, welding or electro-deposition of materials and for the spraying by means of compressed gas or air of materials or other materials, but does not include:

- a) any machinery used for the propulsion of vehicles other than steam boilers or steam engines;
- b) any machinery driven by manual power other than hoisting machines;
- c) any machinery used solely for private and domestic purposes; or
- d) office machines.

4.48 Major accident

An occurrence including, in particular, a major emission, fire or explosion resulting from uncontrolled development in the course of an industrial activity which leads to serious danger to persons, whether immediate or delayed or inside or outside and installation, or to the environment and involving one or more hazardous substances.

4.49 Major hazard installation

An industrial activity which produces, processes, handles, uses, disposes of or stores, whether permanently or temporarily, one or more hazardous substances or a category or categories of hazardous substances in a quantity or quantities which is or are equal to or exceed the threshold quantity, or an industrial activity which is so determined by the Director General of the Department of Occupational Safety and Health (DOSH) in accordance with Sub-regulation 7(2), *Occupational Safety and Health (Control of Industrial Major Accident Hazards) Regulations 1996*.

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4.50 Manufacturer

A person who designs, manufactures, imports or supplies any plant for use at work, or formulates, manufactures, imports or supplies any substance for use at work.

4.51 Materials handling equipment

Any power-driven equipment for handling materials and includes forklift, conveyor, stacker, excavator, tractor, dumper or bulldozer but does not include hoisting machine.

4.52 Most Easily Ignitable Mixture (MEIM)

Mixture of a fuel gas and an oxidiser which has the lowest ignition energy as function of the concentration.

4.53 Normal Temperature and Pressure (NTP)

Normal Temperature and Pressure (NTP) of air are usually ~ 20 °C (293.15 K, 68 °F) and 1 atmosphere (101.325 kN/m², 101.325 kPa, 14.7 psia, 0 psig, 29.92 in Hg, 407 in H₂O, 760 torr). Density is at 1.204 kg/m³ (0.075 pounds per cubic foot).

4.54 Occupier

A person who occupies or uses any premises as a place of work.

4.55 Operator

Any person employed on any service involving the management or operation of, or attendance on, any machinery.

4.56 Outdoor installation

The location where a hydrogen storage system is sited, whether as a unit or built as an assembly, which is not located inside a building or that has only partial weather protection (maximum coverage of a roof and up to 25 % enclosing walls).

4.57 Owner

The person for the time being receiving the rents or profits of the premises or machinery in connection with which the word is used, whether on his own account or as an agent or trustee for any other person or who would so receive the same if the premises or machinery were leased.

4.58 Permeation

Flow of a fluid (gas) through another (usually solid) material by diffusion without a defect or opening of the latter.

4.59 Pipeline

The physical facilities or any part of the physical facilities through which dangerous substances which may cause fire, explosion or adverse health effects to any person (other than petroleum or petroleum products) in the form of liquid or vapour or any combination of liquid or vapour are transported and includes pipes, pumps, compressors, meters, regulators and fabricated assemblies.

4.60 Place of work

Premises where persons work or premises used for the storage of plant or substance.

4.61 Plant

Includes any machinery, equipment, appliance, implement or tool, any component thereof and anything fitted, connected or appurtenant thereto

4.62 Polymer electrolyte fuel cell/Proton Exchange Membrane (PEM) fuel cell

Fuel cell that employs a solid positive ion exchange membrane as the electrolyte.

4.63 Premises

Any site, land, building or part of any building, vehicle, vessel or aircraft. It includes any installation on land, offshore or other installation whether on the bed or floating on any water and any tent or movable structure.

4.64 Pressure regulator

Device that is used in a system to regulate the pressure to a set value.

4.65 Prime mover

Every engine, motor or other appliance which provides mechanical energy derived from air, steam, water, wind, electricity, the combustion of fuel or other source.

4.66 Purge

Process used to remove impurities.

4.67 Quench

Terminate a chemical reaction or the propagation of a flame.

4.68 Risk

A combination of the likelihood of an occurrence of a hazardous event with specified period or in specified circumstances and the severity of injury or damage to the health of people, property, environment or any combination of these caused by the event.

4.69 Shock wave

Large-amplitude compression wave in which there is a rapid and great change in density, pressure and particle velocity.

4.70 Specific gravity

Ratio of the weight or mass of a given volume of a substance to that of an equal volume of another substance (air for gases, water for liquids and solids) used as a standard, both measured under the same conditions.

4.71 Stoichiometric mixture

Mixture of reactants in a chemical reaction that optimises production of the reaction products.

4.72 Stress

Internal force per unit of area developed within a body when the body is subjected to a system of external forces, or a non-uniform temperature change.

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4.73 System

Assembly of components in which hydrogen is delivered, stored, or used, which can include components such as storage vessels, piping, valves, pressure-relief devices, pumps, vacuum subsystems, expansion joints and gauges. A system can refer to a new premise, a new facility at any premises, or a new installation at a facility.

4.74 Thermal radiation

Electromagnetic radiation emanating from a material as a consequence of its temperature.

4.75 Threshold quantity

A given hazardous substance or a category or categories which is or are equal to the amount set out in Schedule 2, *Occupational Safety and Health (Control of Industrial Major Accident Hazards) Regulations 1996*. For fuel cell, hydrogen normally used/stored at minimum volume, not exceeding threshold value of major hazards.

4.76 Turbulence

Flow condition in which radial components or eddies exist together with the fluid motion.

4.77 Unfired pressure vessel

Any enclosed vessel under pressure greater than atmospheric pressure by any gas or mixture or combination of gases and includes any vessel under pressure of steam external to the steam boiler and any vessel which is under pressure of a liquid or gas or both and any vessel subject internally to a pressure less than atmospheric pressure but does not include gas cylinders.

4.78 Use area

A location inside or outside of a building or structure where the material placed into use is situated.

4.79 Vent system

Flue gas vent and vent connector if used, assembled to form a continuous open passageway from the flue collar of gas utilisation equipment to the outside atmosphere for the purpose of removing vent gases.

4.80 Viscosity

Resistance of a fluid to shear motion (its internal friction).

5. Safety requirements and protective measures

Safety requirements for industrial uses of hydrogen are relatively well established. Hydrogen shall be handled on-site by trained personnel, to ensure the safety requirements are well followed.

In case of a person exposed to a risk of bodily injury, preventive action shall be taken to eliminate the risk. Fire extinguisher shall be provided and maintained in every gas storage. Emergency exit also shall be accessible in case of any emergency cases.

The provisions relating to safety shall follow the Act 139, *Factories and Machinery Act 1967* and Act 514, *Occupational Safety and Health Act 1994*.

5.1 Hydrogen gaseous

5.1.1 Hydrogen properties

Gaseous hydrogen should be stored on-site and should be compressed to very high pressures to increase the storage density. The hydrogen gas has considerable potential (stored) energy. The strong pressure effects can be generated by the release of this energy even without a subsequent combustion.

Hydrogen is not generally considered a pollutant. It is classified as a hazardous material based on its flammability properties as in Annex A. The hydrogen characteristics are described in Table 1.

Table 1. Hydrogen characteristics

No.	Characteristic	Value	Description
1.	Buoyancy capability	0.0696	It can rise and accumulate in high spots that have ignition sources if confined.
2.	Flammable	4 % - 75 %	It has low ignition energy, 0.02 mJ.
3.	Vaporise	-	It does not reach the ground in liquid form due to very low boiling point of - 253 °C.
4.	Storage at high pressure	-	a) To achieve enough mass for practical use due to its very low density. b) To create a large portion of the risk associated with hydrogen usage.

5.1.2 Hazards identified

The personnel shall consider the hazards classification in Table 2 during handling the hydrogen which include:

Table 2. Classification and type of hazards

No	Classification	Hazard	Description
1.	Primary	Flammability	Refer Annex A.
		Combustion	
		Deflagration	
		Detonation	
		Ignition	
2.	Others	Small molecule size and low viscosity	Able to permeate through materials.
		Interactions with other materials	Risk to cause embrittlement of certain metals*.
		Storage	Rise of gas pressure.
		Environmental effects	Nitrogen Oxides (NOx) can be created when air-breathing systems combust hydrogen at high temperatures.

*NOTE: Hydrogen embrittlement tests can be conducted according to the standards recommended in Annex B.

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Exposing to hydrogen may affect human health which include (but not limited to):

- a) Cold burns caused by direct contact with cold gas or metallic parts cooled by cold gas can lead to numbness, a whitish colouring of the skin and to frost bite. Prolonged exposure of the entire body can result in hypothermia.
- b) High temperature burns caused by direct contact with combusting hydrogen or hot post flame gases from combustion of hydrogen. The flame temperature of a stoichiometric hydrogen or air mixture is ~ 2 300 K.
- c) Asphyxiation caused by oxygen depletion, especially in confined areas. Even though smoke inhalation is less serious due to water vapour being the sole combustion product, secondary fires can produce smoke or other combustion products that present a health hazard.

5.2 Storage facilities

5.2.1 Physical environment conditions

The suitable physical environment conditions of the fuel cell power system shall be specified by the occupier. The recommended requirements for the technical safety of the hydrogen gas storage facilities are described in Table 3.

Table 3. Recommended requirements for the technical safety of the hydrogen gas storage facilities

Technical safety	Description
Accessible location with suitable distances between hydrogen storages and working or public areas.	<p>To provide an appropriate measure of mitigation:</p> <ol style="list-style-type: none"> a) the recommended separation distances, i.e. for a given pressure range, should be greater when a larger quantity of hydrogen involved; b) the systems to be located above ground, but not beneath electric power lines or close to flammable liquid or other flammable gas piping; c) the systems to be located on ground higher than flammable liquid storage or liquid oxygen storage; and d) suitable protective means (such as diking, diversion curbs, or grading) to be employed if necessary, to locate the systems on ground that is lower than adjacent flammable liquid storage or liquid oxygen storage.
Exclusion areas around the hydrogen storage.	<p>To control an area of appropriate size:</p> <ol style="list-style-type: none"> a) access to the area should be limited to only necessary authorised personnel; b) visible and appropriate signs and warnings of the potential hazard should be posted within the areas; and c) appropriate fencing to control entry to critical locations should be built.

Table 3. Recommended requirements for the technical safety of the hydrogen gas storage facilities *(continued)*

Technical safety	Description
Barricades (e.g. earth mounds or blast mats).	To protect nearby facilities: a) in the case of shrapnel or fragments from an explosion at a hydrogen facility, or vice versa; b) care should be taken to avoid premixing leading to enhanced detonation effects associated with confinement.
Buildings or rooms where hydrogen storage facility is located.	To minimise the hydrogen hazards, the buildings or rooms: a) should be designed using non-combustible building materials, including for the construction of protective walls or roofs; b) must have adequate ventilation, including for the enclosing sides that adjoin each other; c) appropriate hydrogen detectors should be installed; and d) should have typical inherent safety features include fail-safe design, automatic and passive safety operation, caution devices and warning devices. e) should prohibit usage of cell phones.

5.2.2 Indoor requirements

All hazards which can affect health or safety associated with work in a confined space shall be identified and the regulations pertaining the confined space shall be followed. Electrical equipment shall conform to electrical codes in any area classified as hazardous (where elevated hydrogen gas concentrations can exist). If there is a likelihood of fire or explosion in a confined space, the owner shall ensure that no source of ignition is introduced to the space, whether introduced from within or outside the space.

Hydrogen storage inside a building shall not be near to oxidants or another combustible materials storage. Under some circumstances, small quantities of hydrogen should be stored indoor, i.e. in a room or building. However, it is recommended to locate all bulk gaseous hydrogen systems outdoors or in specially designed structures.

The recommended safety measures for indoor installation of hydrogen storage facilities are stipulated in Table 4.

Table 4. Recommended safety measures for indoor installation of hydrogen storage facilities

Recommendation	Description
Storage capacity	Total storage capacity of an indoor hydrogen system should be limited as much as possible and should not exceed 7 kg of hydrogen (at 25 °C and 1.013 bar) without additional engineering safety analysis.

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Table 4. Recommended safety measures for indoor installation of hydrogen storage facilities
(continued)

Recommendation	Description
Gas concentration	<ul style="list-style-type: none"> a) The concentration of hydrogen in the atmosphere of the space should be below 10 000 ppm (25 % of its Lower Explosive Level (LEL)). b) If the concentration in the atmosphere of the space is equal to or greater than 10 000 ppm, the electrical input shall be cut off and ventilation shall start. Any employee is removed immediately from the space.
Ventilation	<ul style="list-style-type: none"> a) All vents should be piped to the exterior of the building and shall be installed in accordance with local regulations. b) Indoor storage and use areas and storage buildings shall be provided with mechanical exhaust ventilation or fixed natural ventilation, i.e. where natural ventilation is shown to be acceptable for gaseous hydrogen. c) Adequate ventilation must be provided, particularly near roof areas where hydrogen might collect and forced ventilation may be necessary in some applications. d) Explosion vents may not be required where small quantities of hydrogen are involved. e) Mechanical exhaust or fixed natural ventilation should be at a rate of not less than 1 scf/min/ft² (0.3048 Nm³/min/m²) of floor area over the area of storage or use. f) The fuel cell power system exhaust to atmosphere, under normal steady-state operating conditions, shall not contain concentrations of carbon monoxide in excess of 0.03 % by volume in an air-free sample of the effluents, which is a sample that has its effluent carbon monoxide (CO) concentration mathematically corrected as though there was zero percent excess air.
Monitoring	<ul style="list-style-type: none"> a) The atmosphere in areas where hydrogen gas may collect should be monitored with portable or continuous flammable gas air monitors calibrated for hydrogen. b) Where large quantities of hydrogen can be released indoors, provide an explosion-venting surface or vents, taking care to vent a pressure wave to areas where people or other equipment will not become involved.

5.2.3 Outdoor requirements

The hydrogen storage and related systems in the facilities which are located outdoors shall comply with this Technical Code, in addition to local, state, or federal regulations that address the requirements of building or local zoning. Permits shall be obtained in accordance with the requirements of the jurisdiction in which the facility operates. The recommended safety measures for outdoor installation of hydrogen storage facilities are as stipulated in Table 5 below:

Table 5. Recommended safety measures for outdoor installation of hydrogen storage facilities

Recommendation	Description
Sources of hazards	<ul style="list-style-type: none"> a) Open flames and high-temperature devices shall not be used in a manner that creates a hazardous condition. b) Smoking shall be prohibited in the following locations: <ul style="list-style-type: none"> i) within 25 ft (7.6 m) of outdoor hydrogen storage or areas, dispensing areas, or open areas; and ii) in rooms or areas where gaseous hydrogen is stored, dispensed, or used in open systems. c) Energy-consuming equipment with the potential to serve as a source of ignition shall be listed or approved for use with gaseous hydrogen.
Weather protection structure or shaded environment for storage or use	<ul style="list-style-type: none"> a) For other than explosive materials and hazardous materials presenting a detonation hazard, weather protection structure shall be permitted to be used for sheltering hydrogen in outdoor storage or use areas without requiring these areas to be classified as indoor storage. b) Hydrogen storage that have not been designed for use under elevated temperature conditions shall not be exposed to direct sunlight outdoors where ambient temperatures exceed 125 °F (52 °C).

5.2.4 Equipment and processes

Insulation materials such as wood, paper and some fabrics will typically form a conductive layer that can prevent static build-up by absorbing water from the air in environments where the relative humidity is greater than 50 %.

Other requirements for building materials include the following:

- a) materials used in hydrogen environments should be evaluated for their ability to discharge static electricity; and
- b) materials should be non-combustible.

The following equipment shall be suitable for hydrogen service and for the pressures and temperatures involved:

- a) piping, tubing and fittings;
- b) joints in piping and tubing, gaskets and thread sealants;
- c) equipment assembly, including valves, gauges, regulators and other accessories; and
- d) cabinets or housings containing hydrogen control or operating equipment.

Auxiliary measures that provide essential support for primary functions should include the following:

- a) separate hydrogen storage and oxidiser storage;
- b) fluid delivery lines to connect hydrogen and oxidiser storage systems to the fuel cell power system;
- c) flow controls;

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- d) pressure relief systems that are incorporated into the design of the above-mentioned components;
- e) detection component; and
- f) guard posts or other means shall be provided to protect the hydrogen storage and connected piping, valves and fittings, as well as storage areas from vehicular damage.

Caution should be taken towards the following hazards:

- a) a reduction of temperature or hydrogen embrittlement during operation may cause a drastic decrease in the ductility of materials in a hydrogen system.
- b) material failure can cause the release of hydrogen either internally, e.g. through a valve seat, or externally, e.g. through a seal, into the system.
- c) the presence of confining surfaces and obstacles such as pipes, containers and enclosure walls can also, significantly elevate the flame speed and increase it to hundreds of metres per second.

5.2.5 Containers

The hydrogen storage shall be designed for a maximum working pressure, with the minimum wall thickness dictated by the metal's tensile strength.

Three types of materials typically used for design and manufacturing of hydrogen storage are:

- a) metals (aluminium or steel);
- b) polymers (high-density polyethylene or polyamide); and
- c) carbon fibres.

A hydrogen system commonly involves a considerable number of components that are crucial for the safety of the system and they include:

- a) valves;
- b) pressure relief devices;
- c) pressure regulators;
- d) check valves;
- e) filters;
- f) instrumentation; and
- g) pumps

The different storage types at high pressure are cylinders of steel or composite. The storage types are as follows:

- a) Type I
 - i) Metal tank (steel/aluminium).
 - ii) Approximate maximum pressure, aluminium 175 bars (17.5 MPa; 2 540 psi), steel 200 bars (20 MPa; 2 900 psi).

- b) Type II
 - i) load-bearing metal liner hoop wrapped with resin-impregnated continuous filament.
 - ii) Metal tank (aluminium) with filament windings like glass fiber/aramid or carbon fiber around the metal cylinder.
 - iii) Approximate maximum pressure, aluminium/glass 263 bars (26.3 MPa; 3 810 psi), steel/carbon or aramide 299 bars (29.9 MPa; 4340 psi).
- c) Type III
 - i) Tanks made from composite material, fiberglass/aramid or carbon fiber with a metal liner (aluminium or steel).
 - ii) Approximate maximum pressure, aluminium/glass 305 bars (30.5 MPa; 4 420 psi), aluminium/aramid 438 bars (43.8 MPa; 6 350 psi), aluminium/carbon 700 bars (70 MPa; 10 000 psi).
- d) Type IV
 - i) Composite tanks such of carbon fiber with a polymer liner.
 - ii) Approximate maximum pressure 700 bars (70 MPa; 10 000 psi).

The recommended requirements for the hydrogen storage containers are listed in Table 6 below:

Table 6. Recommended requirements for the hydrogen storage containers

Recommendation	Description
Materials	<ul style="list-style-type: none"> a) Components in the hydrogen system should be made of materials that are compatible with the operating conditions, such as temperature and pressure and with each other if more than one material is involved. b) The most advanced lightweight storage system for the case of compressed gas consists of a container, which is actually an advanced composite material using a non-load-bearing metallic (Type III) or plastic (Type IV) liner axial and hoop wrapped with resin-impregnated continuous filaments. c) Cylinders for stationary applications are mostly of Type I made wholly of steel (typically out of austenitic stainless steel, e.g. AISI 316 and AISI 304), to reduce material and manufacturing costs. d) For composite pressure vessels, a test is given in BS EN 12245 (up to 3 000 litres), ISO 1119-3 (up to 450 litres) and ISO 11515. The minimum fire test time should be 10 minutes without any relief valves (after reaching 590 °C within 5 minutes). Composite cylinders should be approved using a standard that has a safety factor of minimum 3.0.

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Table 6. Recommended requirements for the hydrogen storage containers *(continued)*

Recommendation	Description
Pressure limit	<p>a) For larger storage capacity with maximum operating pressure of 50 bar and 2.8 m in diameter are available in a range of lengths from 7.3 m to 19 m, with capacities from 1 300 m³ to 4 500 m³.</p> <p>b) In a release of hydrogen where the pressure > 0.2 MPa (2 atm), the issuing jet will be a result of a choked flow, where the molecular diffusion and buoyancy effects of hydrogen will be dominated by the fluid dynamics.</p>
Containers	<p>a) The storage systems are compressed gas cylinders with the range of 10 bar to 350 bar.</p> <p>b) The design, function and applied construction materials of storage containers and their components should reflect the type of service.</p> <p>c) High pressure containers commonly built from aluminium, steel, or compound materials are used to contain hydrogen at pressures up to 40 - 70 MPa. Gaseous hydrogen storage and associated piping must be electrically bonded and grounded.</p> <p>d) Hydrogen storage with capacities of about 2 000 m³, compressed to about 185 bar (mostly spherical containers) have been the state-of-the-art for many years.</p>

Caution should be taken towards the following hazards:

- a) Metals should neither allow hydrogen permeation nor be subjected to hydrogen embrittlement, especially if they are to undergo an extensive pressure/temperature cycling during their lifetime.
- b) Material failures, responsible for 3 % of the mishaps, include the failure of materials and components as a result of stresses that had been considered within the design limits.
- c) During storage, impurities may be introduced into the hydrogen gas and this can adversely affect the fuel cells that consume it as fuel.
- d) The anti-static requirements apply to all possible devices, equipment, or tools that can cause potential static discharge and create a source of ignition.
- e) The design of an effective fire protection system should consider the implementation of both active and passive fire protection measures.
- f) Manufacturer should provide the fatigue and stress rupture loads information (maximum allowable pressure) and the occupier shall evaluate this annually to decide end of life for the cylinder. The fatigue needs to be decided based on the actual cycles. The total number of pressure cycles gives the life for the cylinder and it always have to be below maximum allowable pressure.

5.2.6 Safety relief systems

The safety relief systems shall be designed to protect the hydrogen systems in accordance to the Act 139, *Factories and Machinery Act 1967* (i.e. set to limit the pressure so that it does not exceed the authorised safe working pressure assigned to the system that they are protecting by 10 % of such safe working pressure). Sufficient protective measures need to be taken to prevent the risk of having the gas flow from a high-pressure volume to a low-pressure side. The relief devices should be sized for

adequate flow capacity for the most extreme conditions that could be encountered. The O-ring for the pressure relief valve should use a suitable material which can handle pressure cycles.

As the relief systems rely on sensing the build-up pressure, they cannot sense the approaching detonation waves that move faster than the speed of sound and thus cannot react in time to protect the hydrogen systems from the rapid pressure rise. However, the relief systems such as rupture disks and relief panels can respond to combustion phenomena that progresses slower than the speed of sound (i.e. deflagrations).

5.2.7 Piping system

Any pipeline and related parts, such as tubing and fittings, used for transporting dangerous substances which may cause fire, explosion or adverse health effects to any person (other than petroleum or petroleum products) which is used in connection with and for the purposes of the gas storage area, shall be deemed to be part of the place of work.

Prior to acceptance and initial operation, all piping installations shall be inspected and pressure tested in accordance with local regulations. Inspection and testing of piping systems shall not be required to remove a system from service.

Prior to cleaning or purging, piping systems shall be inspected and tested to determine that the installation, including the materials of construction and method of fabrication, comply with the requirements of the design standards used and the intended application for which the system was designed. The recommended specification for hydrogen pipeline is specified in Table 7.

Table 7. Recommended hydrogen pipeline specification

Recommendation	Description
Personnel	The pipeline should be installed by qualified personnel who produces relevant work method and test report, as well as material selection to ensure satisfactory pipeline work.
Jointing	<ul style="list-style-type: none"> a) A welding personnel first produces a Welding Procedures Specification (WPS) that details the work methods of the welding/joint works. b) Upon completion, the personnel produce a Welding Quality Report (WQR) that outlines the work quality (e.g., check for cracks on piping). c) Pipeline pressure test is carried out. d) The results are recorded and reported as necessary.
High-pressure (1 000 bar)	All fittings and materials installed on this pipeline shall be tested/guaranteed by the manufacturer. The guarantees would be dependent on the manufacturer.

5.2.8 Operation and Maintenance (O&M)

The occupancy of a building or structure, or portion thereof, where hydrogen is stored or used shall be classified in accordance with the adopted building code. Maintenance, inspection and calibration shall be conducted by trained personnel, i.e. a qualified representative of the equipment owner. Scheduled maintenance activities shall be formally documented and records should be maintained.

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The maintenance shall include:

- a) inspection for physical damage;
- b) leak tightness;
- c) ground system integrity;
- d) vent system operation;
- e) equipment identification;
- f) warning signs;
- g) operator information and training records;
- h) scheduled maintenance and retest records;
- i) alarm operation; and
- j) other safety-related features.

The hydrogen facility or system should consider a fire protection subsystem. Small fires should be extinguished by:

- a) dry-chemical extinguishers;
- b) carbon-dioxide extinguishers;
- c) nitrogen; and
- d) steam.

An extinguisher is not capable of stopping a hydrogen source from burning. The source of hydrogen needs to be closed. A water-based system may cool down the piping and related system to prevent further leaks.

Fire protection measures for hydrogen system shall include the following:

- a) dry-chemical extinguishing system;
- b) sprinkler system;
- c) deluge system; and
- d) process shutdown system (automatic and/or manual).

When an emergency shutdown system is required, activation of the emergency shutdown system shall shut down operation of all compressors serving a single gas installation.

5.2.9 Contingency planning

Adequate lighting shall be provided for night-time transfer operations where appropriate. Adequate water supply should be available to keep surrounding equipment cool in the event of a hydrogen fire.

The local fire department should be advised of the nature of the products handled and made aware of the appropriate methods for combating hydrogen fires. The most effective way to prevent a hydrogen

fire from spreading is to let it burn until the hydrogen is consumed or until the flow of gas can be shut off. However, if the fire is extinguished without stopping the flow of gas, an explosive mixture may form, creating a more serious hazard than the fire itself should reignition occur.

The owner shall prescribe the provision and maintenance of suitable and adequate personal protective clothing and appliances to reduce the possible consequences of a hazard, which include but not limited to the following items:

- a) fire-retardant clothing;
- b) goggles;
- c) gloves;
- d) leggings;
- e) safety helmets; and
- f) anti-static safety shoe.

It is applicable to any place of work personnel when they are exposed to a wet or dusty process, to noise, to heat or to any poisonous, corrosive or other injurious substance.

The nature of work determines what kind of protection the personnel should use which include below conditions:

- a) exposure to cryogenic temperatures;
- b) flame temperatures;
- c) thermal radiation from a hydrogen flame; and
- d) oxygen-deficient atmospheres of hydrogen or inert purge gases such as nitrogen and helium.

5.2.9.1 Emergency procedures training

The emergency procedures training in handling any abnormal events are required. Examples of emergency procedures training are as follows:

- a) hydrogen leak;
- b) hydrogen fire, deflagration, detonation;
- c) excessive pressure;
- d) contamination of the hydrogen (with an oxidiser or an inert gas);
- e) line rupture;
- f) premixed combustible cloud migration;
- g) electrical fire; and
- h) failure of critical equipment.

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5.2.9.2 Emergency procedures requirements

The requirements for the emergency procedures should address but not limited to the following items.

- a) Emergency alarm system to alert personnel.
- b) Emergency escape procedures and escape-rout assignments.
- c) Procedures to be followed by employees who remain to operate critical systems before they evacuate.
- d) Procedures to account for all personnel after an emergency evacuation has been completed.
- e) Rescue and medical duties for those employees who are to perform them.
- f) Actions to be taken by the initial response personnel.
- g) Appropriate medical response.
- h) Requesting outside assistance.

6. Hazard identification

Hazards can be divided into three main groups:

- a) health hazards;
- b) safety hazards; and
- c) environmental hazards.

Hazard identification activities shall be carried out to highlight the critical operations of tasks. Those tasks posing significant risks to the health and safety of employees and highlighting those hazards pertaining to certain equipment due to energy sources, working conditions or activities performed. Methods in identifying the group of hazards shall refer to the *Guidelines for Hazard Identification, Risk Assessment and Risk Control (HIRARC)*.

7. Type of tests

Inspection and testing of the equipment and facilities shall be conducted at least annually in accordance with local regulations by a qualified representative of the service provider. Scheduled retest activities shall be formally documented and records shall be maintained.

7.1 Hydrogen leakage tests

The system shall be leak tested and be leak-free prior to admitting hydrogen. Periodic leak tests should be performed and any leaks that are found should be repaired immediately.

Hydrogen burns with an almost invisible blue flame. If a hydrogen leak is suspected in any part of a system, a hydrogen flame can be detected by cautiously approaching with an outstretched broom, lifting it up and down.

Where gaseous hydrogen detection systems are installed, they shall be designed, installed, tested, inspected, calibrated and maintained in accordance with the manufacturer's requirements and equipment listing requirements.

7.2 Earth protection tests

Earthing methods and tests shall be conducted to minimise the risk of static discharge and the potential for lightning strikes in outdoor environments in accordance to MS IEC 60364 or MS IEC 60364-7-712.

8. Marking, labelling and packaging

For marking, labelling and packaging requirements of hydrogen storage, the manufacturer shall comply with the following regulations:

- a) Occupational Safety and Health Act 1994, *Occupational Safety and Health (Classification, Labelling and Safety Data Sheet of Hazardous Chemicals) Regulations 2013* (for example, refer Annex C); and
- b) *Industry Code of Practice on Chemicals Classification and Hazard Communication 2014*.

A permanent placard labelled “Hydrogen - Flammable Gas - No Smoking - No Open Flames” shall be placed at the hydrogen storage location.

Where “No Smoking” placard is not applicable to the entire premises, the placard shall be placed in rooms or areas where hydrogen is stored, dispensed, or used in open systems. For outdoor storage, dispensing, or open-use areas the placard shall be placed within 25 ft (7.6 m).

9. Technical documentation

Higher management of an organisation should establish organisational policies and procedures by which a program or project involving hydrogen is directed, conducted, controlled, monitored and evaluated. They are also should provide controls, guidance and oversight to ensure proper planning, monitoring, reporting, evaluation and assessment of the program or project is achieved.

The higher management should provide detailed and adequate safety-training and education program. The training and education programs are aimed for the following objectives:

- a) to learn the physical, chemical and hazardous properties of hydrogen;
- b) to follow the accepted standards, guidelines and regulations; and
- c) to handle the proper use of equipment in the specific hydrogen systems pertaining to the applications that they are involved with.

Procedures and checklists documents should be developed, established and approved periodically by appropriate personnel prior to their use operations. The documents developed should cover but not limited to the cleaning, cool-down, operating, purging and storage (especially filling).

For the storage, below additional items should be covered in its procedure and checklist documents.

- a) Hydrogen transfer.
- b) Leak checks.
- c) Modifications.
- d) Repairs

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- e) Maintenance.
- f) Decommissioning.

The documents should include information such as instructions on steps to take during any abnormal events and how to use the personal protective equipment provided. It should be easily accessible for everybody in the specific area where the work is done.

Listed or approved hydrogen equipment shall be in accordance with the listing requirements and manufacturers' instructions. An up-to-date and adequate on-site emergency plan detailing how major accidents are to be dealt with on the premises on which the industrial activity is carried on must be made available. The plan shall include:

- a) name of the person who is responsible for safety on the premises; and
- b) names of those who are authorised to take action pursuant to the plan in the event of an emergency.

On being required by an Inspector, the occupier shall furnish the means necessary for entry, inspection, examination, inquiry, the taking of samples, or otherwise for the exercise of his powers under the Act 139, *Factories and Machinery Act 1967* in relation to that place of work.

9.1 Installation manual

A Notification of Industrial Activity Form shall be submitted to the DOSH to determine whether it is a major or non-major hazard installation.

The manufacturer shall immediately notify the DOSH of any change in any of the particulars furnished in the Notification, such as an increase or a reduction in the maximum quantity of any hazardous substance, by resubmitting the Notification of Industrial Activity Form.

9.2 User's information manual

This Technical Code is not intended to be used as the sole means of compliance for the broad category of hazardous materials. References for the adopted fire prevention code or other referenced codes and standards are required to provide additional information on hazardous materials for users.

The overall safety goal is to reduce the hazards from exposure to or mishap with other hazardous materials. Therefore, one cannot disregard the hazards of these materials and focus solely on the hazards of hydrogen.

9.3 Operations and Maintenance (O&M) manual

The Operations and Maintenance (O&M) manual shall be maintained at the facility in an approved location and should include the following:

- a) clearly state the requirement of the facility operator to ensure that the components of the performance design are in place and operating properly;
- b) describe the commissioning requirements and the interaction of the different systems' interfaces;
- c) communicate to tenants and occupants these limits and their responsibilities as a tenant;
- d) identify all subsystems as well as create inspection and testing regimes and schedules;
- e) be used as a guide for renovations and changes;

- f) be used to document agreements between stakeholders; and
- g) give instruction to the facility operator on restrictions placed on facility operations.

These limitations are based on the engineering assumptions made during the design and analysis. It may include critical fire load, sprinkler design requirements, building use and occupancy and reliability and maintenance of systems.

Annex A
(informative)

Hydrogen classification

A.1 Hydrogen class

Hydrogen gas is classed in the Schedule 1 under Flammable Gases, *Occupational Safety and Health (Control of Industrial Major Accident Hazards) Regulations 1996*, which in the gaseous state at normal pressure and mixed with air become flammable and the boiling point of which at normal pressure is 20 °C or below.

Hydrogen is also classed in Schedule 2 under Group 3 (Highly Reactive Substances) with a threshold quantity of 10 tonnes. Oxygen is classed under the same group but with a threshold quantity of 500 tonnes. The threshold quantity of other flammable substances at site (if any) is 200 tonnes as defined in Schedule 1 (3c).



Figure A.1a. Fixed cylinder bundle



Figure A.1b. Cylinder baskets

Figure A.1. Common hydrogen storage vessels for stationary applications

A.2 Hydrogen properties

Hydrogen is a colourless, odourless, flammable gas. It has the smallest, lightest molecule of any gas (~14 times lighter than air). Inhalation of hydrogen can cause symptoms of acute exposure include nausea, headaches, delirium, disturbed equilibrium, tremors, convulsions and skin and eye irritation, which are not included in the list of notifiable occupational diseases. The summary of hydrogen properties are stipulated in Table A.1 below.

Table A.1. Hydrogen properties

Chemical formula	Gaseous hydrogen
Molecular weight	2.016
Vapor pressure at - 423 °F (- 252.8 °C)	101.283 kPa
Density of the gas at boiling point and 1 atm	1.331 kg/m ³
Specific gravity of the gas at 32 °F and 1 atm (air = 1)	0.0696
Specific volume of the gas at 70 °F (21.1 °C) and 1 atm	11.99 m ³ /kg
Specific gravity of the liquid at boiling point and 1 atm	0.0710
Molecular weight	2.016

Table A.1. Hydrogen properties *(continued)*

Chemical formula	Gaseous hydrogen
Vapor pressure at -423°F (-252.8°C)	101.283 kPa
Density of the gas at boiling point and 1 atm	1.331 kg/m ³
Specific gravity of the gas at 32°F and 1 atm (air=1)	0.0696
Specific volume of the gas at 70°F (21.1°C) and 1 atm	11.99 m ³ /kg
Specific gravity of the liquid at boiling point and 1 atm	0.0710
Density of the liquid at boiling point and 1 atm	67.76 kg/m ³
Boiling point at 14.69 psia (101.283 kPa)	- 252.8 °C
Melting point at 14.69 psia (101.283 kPa)	- 259.2 °C
Critical temperature	- 239.9 °C
Critical pressure	1 296.212 kPa, abs
Critical density	30.12 kg/m ³
Triple point	- 259.3 °C at 7.042 kPa, abs
Latent heat of fusion at triple point	58.09 kJ/kg
Latent heat of vaporisation at boiling point	446.0 kJ/kg
Cp	14.34 kJ/(kg)(°C)
Cv	10.12 kJ/(kg)(°C)
Ratio of specific heats	1.42
Solubility in water vol/vol at 60°F (15.6°C)	0.019

The ignition and combustion properties for air mixtures at 25 °C and 1.013 bar for several common fuels are summarised in Table A.2 below:

Table A.2. Ignition and combustion properties for air mixtures at 25 °C and 1.013 bar for several common fuels

Fuel	Lower flammability limit (% vol. fraction)	Stoichiometric mixture (% vol. fraction)	Upper flammability limit (% vol. fraction)	Minimum ignition energy (mJ)	Autoignition temperature (K)	Laminar burning velocity (m/s)
Hydrogen (H ₂)	4	29.5	77	0.017	858	2.70
Methanol (CH ₃ OH)	6.0	12.3	36.5	0.174	658	0.48
Methane (CH ₄)	5.3	9.5	17.0	0.274	810	0.37
Propane (C ₃ H ₈)	1.7	4.0	10.9	0.240	723	0.47
Gasoline (C ₈ H ₁₈)	1.0	1.9	6.0	0.240	488	0.30

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The energy content for hydrogen and other common fuels which measured by weight and by volume are stipulated in Table A.3 below:

Table A.3. Energy content by weight and by volume for hydrogen and other common fuels

	Hydrogen	Natural gas	Petrol
Energy content per unit mass	2.8 times more than petrol	~1.2 times more than petrol	43 MJ/kg
Energy content per unit volume	4 times less than petrol	1.5 times less than petrol	120 MJ/Gallon

A.3 Descriptions of primary hazards for hydrogen

Hydrogen stored in a gaseous form under high pressure presents several pressure-related hazards. Pressure effects are characteristic and could be hazardous for scenarios involving unignited release in a vented enclosure, initial stage of a jet fire, deflagrations and detonations.

A.3.1 Flammability

The LFL and UFL is considered by many safety professionals to be the same as LEL and Upper Explosive Limits (UEL), respectively. The mixture is considered too “lean” to burn if it is below the LFL level and too “rich” to burn if it is above the UFL level.

Flammability can be due to thermal effects, pressure effects and easy ignitability of some mixtures. Flammability limits and ignition energy data are used to quantify effects that produce flame acceleration. Flammability of the hydrogen/air mixture is also a function of flame propagation direction. The buoyancy-induced upward velocity of the hot, burnt gases retards a downward-propagating flame, but promotes an upward-propagating flame.

Before introducing hydrogen into systems that were open to air, the oxygen concentration in the system should be reduced to below the lower flammable concentration (4 %) and well less than 25 % of this value (below 1 % actual), which is well below the minimum oxygen concentration needed for hydrogen ignition. Additional purging will often be needed to meet higher-purity application requirements. The Most Easily Ignitable Mixture (MEIM) for hydrogen can be found in the range between 22 % - 26 %. During fire, hydrogen flames should not be extinguished before the gas supply is interrupted to prevent creating premixed explosive flammable mixtures that can be ignited and cause significant hazardous situation.

Surfaces remove energy from flames and ignition sources, such that if the surfaces are sufficiently close, combustion cannot continue or be initiated. Hydrogen flames entering such regions are arrested and quenched. A stoichiometric mixture of hydrogen and air at NTP is 0.64 mm and decreases with the increase of pressure and temperature. If possible, system components around a flame may be cooled with water to prevent mechanical failure due to decreased strength at elevated temperatures.

A.3.2 Combustion

Combustion is a process that releases heat and the resulting expansion of products may cause a pressure wave to propagate from the source resulting in an explosion. Flammability limits, ignition energy and Autoignition Temperature (AIT) are primary variables used to characterise the circumstances under which combustion can occur.

Combustion occurs in three different physical processes, namely as:

- a) a non-premixed flame;
- b) a premixed flame propagating as a deflagration wave (a subsonic process); and
- c) a premixed flame coupled with a shock wave propagating as a detonation wave (a supersonic process).

For combustion to occur, two additional elements need to be present (i.e. fire triangle): an oxidiser and a source of ignition. Hydrogen has to be mixed with sufficient quantities of an oxidiser to form a flammable mixture. For a mixture of hydrogen with air, where additional nitrogen is present, the stoichiometric ratio mixture is 29.5 % hydrogen. Mixtures of hydrogen and oxidisers near stoichiometry are particularly ignitable.

Ignition without an artificially provided energy source is possible under certain conditions of sudden hydrogen release into an oxidising atmosphere, which could occur at storage pressures as low as 0.2 to 0.3 MPa. Normally, a hydrogen fire should not be extinguished until the hydrogen source has been isolated, because of the danger of ignition of a large combustible premixed cloud that could develop from unburnt hydrogen.

Under wind conditions, it has been verified that with an outdoor hydrogen fuel cell power system subjected to a wind having a nominal velocity of 54 km/h, the anode exhaust gas shall be oxidised in the combustor without excessive delay and the combustor shall not stop its oxidising reaction.

To reduce hydrogen combustion risk, separation of hydrogen from the oxidisers is necessary to prevent the formation of reactive mixtures and the area within 15 ft (4 m) of any hydrogen container should be kept free of dry vegetation and combustible material.

A.3.3 Deflagration

Deflagrations of gaseous hydrogen-air mixtures can produce pressures as much as 8 times the initial pressure, even more in special geometries. For hydrogen/oxidiser mixtures, the visible propagation velocity can be higher than the burning velocity due to the expansion of hot combustion products behind the flame adding a convection velocity to the flame propagation velocity.

In a stationary mixture in the open with no confinement, the flame will propagate with laminar flow at a burning velocity into the unburnt mixture in the order of 2 - 3 m/s, i.e. ~ 10 times faster than for hydrocarbon flames. The maximum propagation velocity of a deflagration wave in a turbulent flow field is limited to the speed of sound in the unburnt gas mixture (975 m/s for a stoichiometric ratio hydrogen/air mixture under NTP). Flow turbulence and various flame front instabilities may accelerate the flame up to Deflagration to Detonation Transition (DDT) level.

Under suitable fluid dynamic conditions, a deflagration wave can accelerate to near the speed of sound and can even transition to a detonation wave DDT, where a fast deflagration wave can create a spherically propagating audible sound wave similar to that created by a detonation wave.

A.3.4 Detonation

A detonation is a supersonic process, which has very significant pressure rise across the front (10 times or more). However, the definition of detonation limits in the literature is still ambiguous and there is no standard measurement procedure yet for this property. Detonation waves propagate by adiabatic shock heating and detonation limits correlate with detonation cell sizes. However, there is currently no standard procedure for the determination of detonation limits.

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The value at which a detonation can occur is a strong function of geometry, fluid dynamics and mixture ratio. The ability of detonation to propagate depends on the mixture concentration, the relationship between the size of the detonation cell, the geometrical boundary conditions and the turbulence level of the reacting fluids.

The reflected pressure waves from detonations that impinge on surfaces typically produce greater peak pressures of 2 - 3 times the incident shock pressure. Detonation of hydrogen-air mixtures can produce pressures as much as 20 times the initial pressure (and even more for very short duration) and with reflection, 50 times the initial pressure. Detonations of non-confined gas clouds have a tendency to occur more easily with increasing cloud size.

A.3.5 Ignition

If a hydrogen leak ignites, the following should be important:

- a) To detect the leak early and to close the source of hydrogen fast (in order to prevent the fire from heating up the equipment and cause more leakages).
- b) To put in place fire walls between the gas storage area and other systems where leak is a risk, which means "the rest" of the equipment, has proven to work very well.
- c) The possibility to "dump" the hydrogen, due to the fire in the system or externally, in a controlled manner.

Powerful ignition sources capable of forming shocks such as high-energy spark discharges and explosives can directly initiate detonation. Ignition energy is typically measured in a standardized apparatus. Ignition varies with the composition of the mixture and becomes infinite at the flammability limits. Other factors that can influence the ignition energy include the spark gap, the initial gas pressure and temperature. Potential igniters for hydrogen/oxidiser mixtures include:

- a) flames;
- b) electrical sparks;
- c) fused wires;
- d) incendiaries;
- e) hot surfaces (including catalysts);
- f) heating;
- g) rapid adiabatic compression; or
- h) shock waves.

The AIT is the minimum temperature required to initiate self-sustained combustion and hydrogen's AIT is 1 040 °F (560 °C). The relatively high AIT makes ignition of a hydrogen/air mixture unlikely from heat alone without an additional ignition source. Over the flammability range (a given pressure and temperature) of hydrogen/air mixtures, the ignition energy varies by almost three orders of magnitude and can be as low as 0.017 mJ for the most easily ignitable mixture.

Annex B
(informative)

Relevant documents/standards for guidance

Table B.1 shows the relevant documents/standards for guidance.

Table B.1 Relevant documents/standards for guidance

Category	Type	Documents/Standards
Hydrogen	MSDS	<i>Hydrogen Gas Material Safety Data Sheet</i>
	ISO	<ul style="list-style-type: none"> a) ISO/TR 15916:2015, <i>Basic considerations for the safety of hydrogen systems</i> b) ISO 14687-1:1999, <i>Hydrogen fuel - Product specification - Part 1: All applications except proton exchange membrane (PEM) fuel cell for road vehicles</i> c) ISO 14687-2:2012, <i>Hydrogen fuel - Product specification - Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles</i> d) ISO 26142:2010, <i>Hydrogen detection apparatus - Stationary applications</i> e) ISO 7539-11:2013, <i>Corrosion of metals and alloys - Stress corrosion testing - Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking</i> f) ISO 15330:1999, <i>Fasteners - Preloading test for the detection of hydrogen embrittlement - Parallel bearing surface method</i>
	IEC	IEC 60079-29:2016, <i>Explosive atmospheres - Part 29-1: Gas detectors - Performance requirements of detectors for flammable gases</i>
	ASTM	<ul style="list-style-type: none"> a) ASTM E681-09, <i>Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)</i> b) ASTM F1624-12(2018), <i>Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique</i>
	NFPA	<ul style="list-style-type: none"> a) NFPA 2, <i>Hydrogen Technologies Code</i> b) NFPA 55, <i>Compressed Gas and Cryogenic Fluids Code</i>
	EN	BS EN 1839, <i>Determination of the explosion limits and the limiting oxygen concentration (LOC) for flammable gases and vapours</i>
Equipment	ISO	<ul style="list-style-type: none"> a) Gaseous hydrogen <ul style="list-style-type: none"> i) ISO 19880, <i>Gaseous hydrogen (all parts)</i> ii) ISO 19881, <i>Gaseous hydrogen - Land vehicle fuel containers</i> iii) ISO FDIS 19884, <i>Gaseous hydrogen - Cylinders and tubes for stationary storage</i> iv) ISO 14912:2003, <i>Gas analysis - Conversion of gas mixture composition data</i> v) ISO 14456:2015, <i>Gas cylinders - Gas properties and associated classification (FTSC) codes</i>

Table B.1 Relevant standards for guidance (continued)

Category	Type	Standards
Equipment	ISO	<p>b) Machinery</p> <p>i) ISO 13849-1:2015, <i>Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design</i></p> <p>ii) ISO 2626:1973, <i>Copper - Hydrogen embrittlement test</i></p> <p>iii) ISO 11114-4, <i>Transportable gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 4: Test methods for selecting steels resistant to hydrogen embrittlement</i></p> <p>c) Gas cylinders</p> <p>i) ISO 10286:2015, <i>Gas cylinders - Terminology</i></p> <p>ii) ISO 11625:2007, <i>Gas cylinders - Safe handling</i></p> <p>iii) ISO 10156:2017, <i>Gas cylinders - Gases and gas mixtures - Determination of fire potential and oxidizing ability for the selection of cylinder valve outlets</i></p> <p>iv) ISO 18119:2018, <i>Gas cylinders - Seamless steel and seamless aluminium-alloy gas cylinders and tubes - Periodic inspection and testing</i></p> <p>v) ISO 10460:2018, <i>Gas cylinders - Welded aluminium-alloy, carbon and stainless-steel gas cylinders - Periodic inspection and testing</i></p> <p>vi) ISO 11118:2015, <i>Gas cylinders - Non-refillable metallic gas cylinders - Specification and test methods</i></p> <p>vii) ISO 11119, <i>Refillable composite gas cylinders and tubes - Design, construction and testing (all parts)</i></p> <p>viii) ISO 11623:2015, <i>Gas cylinders - Composite construction - Periodic inspection and testing</i></p> <p>ix) ISO 24431:2016, <i>Gas cylinders - Seamless, welded and composite cylinders for compressed and liquefied gases (excluding acetylene) - Inspection at time of filling</i></p> <p>x) ISO 20475:2018, <i>Gas cylinders - Cylinder bundles - Periodic inspection and testing</i></p> <p>xi) ISO 10961:2010, <i>Gas cylinders - Cylinder bundles - Design, manufacture, testing and inspection</i></p> <p>xii) ISO 11755:2005, <i>Gas cylinders - Cylinder bundles for compressed and liquefied gases (excluding acetylene) - Inspection at time of filling</i></p> <p>d) Valves</p> <p>i) ISO 5145:2017, <i>Gas cylinders - Cylinder valve outlets for gases and gas mixtures - Selection and dimensioning</i></p> <p>ii) ISO 10297:2014, <i>Gas cylinders - Cylinder valves - Specification and type testing</i></p> <p>iii) ISO 22435:2007, <i>Gas cylinders - Cylinder valves with integrated pressure regulators - Specification and type testing</i></p> <p>iv) ISO 13341:2010, <i>Gas cylinders - Fitting of valves to gas cylinders</i></p>

Table B.1 Relevant standards for guidance (continued)

Category	Type	Standards
Equipment	ISO	<ul style="list-style-type: none"> v) ISO 17879:2017, <i>Gas cylinders - Self-closing cylinder valves - Specification and type testing</i> vi) ISO 17871:2015, <i>Gas cylinders - Quick-release cylinder valves - Specification and type testing</i> vii) ISO 11117:2008, <i>Gas cylinders - Valve protection caps and valve guards - Design, construction and tests</i> viii) ISO 14246:2014, <i>Gas cylinders - Cylinder valves - Manufacturing tests and examinations</i> ix) ISO 25760:2009, <i>Gas cylinders - Operational procedures for the safe removal of valves from gas cylinders</i> x) ISO 28219:2017, <i>Packaging - Labelling and direct product marking with linear bar code and two-dimensional symbols</i> xi) ISO 7225:2005, <i>Gas cylinders - Precautionary labels</i> xii) ISO 13769:2018, <i>Gas cylinders - Stamp marking</i> xiii) ISO 32:1977, <i>Gas cylinders for medical use - Marking for identification of content</i>
	ASTM	<ul style="list-style-type: none"> a) Machinery <ul style="list-style-type: none"> i) ASTM G142-98, <i>Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both</i>
	ASME	<ul style="list-style-type: none"> a) Pressure vessels <ul style="list-style-type: none"> i) ASME Boiler and Pressure Vessel (BPV) Code b) Piping <ul style="list-style-type: none"> i) ASME B31.3 and B31.12 Hydrogen Piping and Pipelines
	SAE	<ul style="list-style-type: none"> a) Machinery <ul style="list-style-type: none"> i) USCAR5, <i>Avoidance of Hydrogen Embrittlement of Steel</i>
	IEC	<ul style="list-style-type: none"> a) IEC 61010-2-081, <i>Safety requirements for electrical equipment for measurement, control and laboratory use - Part 2-081: Particular requirements for automatic and semi-automatic laboratory equipment for analysis and other purposes</i> b) IEC 60812, <i>Failure modes and effects analysis (FMEA and FMECA)</i> c) IEC 61025, <i>Fault tree analysis (FTA)</i> d) IEC 61511-1, <i>Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and software requirements</i>
	CGA	<ul style="list-style-type: none"> a) S-1, <i>Pressure Relief Device Standards (all parts)</i> b) G-5.5, <i>Hydrogen Vent Systems</i>
	CSA	ANSI/CSA HGV 4.2-2013, <i>Hoses for Compressed Hydrogen Fuel Stations, Dispensers and Vehicle Fuel Systems</i>
	UL	UL 2075, <i>Standard for Gas and Vapor Detectors and Sensors</i>
	NIST	NIST Handbook 44, <i>Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices</i>

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Table B.1 Relevant standards for guidance *(continued)*

Category	Type	Standards
Fuel cell	ISO	ISO 14687-3:2014, <i>Hydrogen fuel - Product specification - Part 3: Proton exchange membrane (PEM) fuel cell applications for stationary appliances</i>
	IEC	a) IEC 62282-3-100, <i>Fuel cell technologies - Part 3-100: Stationary fuel cell power systems - Safety</i> b) IEC 62282-3-201:2017, <i>Fuel cell technologies - Part 3-201: Stationary fuel cell power systems - Performance test methods for small fuel cell power systems</i>
	NFPA	NFPA 853, <i>Standard for the Installation of Stationary Fuel Cell Power Systems</i>

Annex C
(normative)

Sample of CLASS label

<p>Hydrogen (CAS No. : 1333-74-0)</p> <p>Manufacturer (Pengilang) ABCD Kimia Sdn. Bhd., 1126 Jalan Kg Attap, 50534 Kuala Lumpur. (24 Hr Emergency Tel No : +603-8888 8887)</p> <p>Supplier (Pembekal) WXYZ Kimia Sdn. Bhd., 1127 Jalan Kg Attap, 50534 Kuala Lumpur. (24 Hr Emergency Tel No : +603-8888 8889)</p> <p><u>HAZARD STATEMENTS</u> <u>(PERNYATAAN BAHAYA)</u></p> <ul style="list-style-type: none"> • Extremely flammable gas (Gas paling mudah terbakar) • Contains gas under pressure; may explode if heated. (Mengandungi gas di bawah tekanan; boleh meletup jika dipanaskan) 	<p>DANGER BAHAYA</p> 	<p><u>PRECAUTIONARY STATEMENTS (PERNYATAAN BERJAGA- JAGA)</u></p> <ul style="list-style-type: none"> • Keep away from heat/spark/open flames/hot surface-No smoking. (Jauhkan daripada haba/cucuhan/nyalaan terbuka dan permukaan panas - Dilarang merokok) • Leaking gas fire : Do not extinguish, unless leak can be stopped safely. (Kebakaran gas bocor : Jangan padamkan api, kecuali kebocoran boleh dihentikan dengan selamat) • Eliminate all ignition sources if safe to do so. (Hapuskan semua pencucuhan jika selamat berbuat demikian) • Protect from sunlight. Store in well ventilated place. (Lindungi daripada sinaran cahaya matahari. Simpan di tempat yang dialihudarakan dengan baik)
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Figure C.1. Sample of CLASS placard

Bibliography

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Acknowledgements

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