European Train the Trainer Programme for Responders

Lecture 6

Harm criteria for people and property

LEVEL II

Crew Commander

The information contained in this lecture is targeted at the level of Crew Commander.

This topic is also available at level I, III and IV.

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

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Summary

This lecture provides responders with valuable information on the impact of hydrogen leaks, fires and explosions on the health and environment of humans. It also considers the damage to structures and equipment caused by hydrogen fires and overpressure events. It is mainly focused on thermal and overpressure effects on people, natural and built environments. The knowledge of harm and damage criteria is very important in evaluating accident scene status and in making correct decisions with regards to intervention practices. Although it is not a purpose of this lecture to give Responders absolute threshold values, they should be aware of acceptance criteria for the members of the public, operators, users of a FCH facility and themselves. This lecture also introduces Responders to the labelling system. Some requirements to personal protective equipment are also addressed.

Keywords

Hydrogen accident, thermal radiation, overpressure, harm criteria, personal protective equipment

Table of contents

1. Target audience

The information contained in this lecture is targeted at the level of Crew Commander. Lectures are also available at levels I, III and IV: Fire fighter, incident commander and specialist officer.

The role description, competence level and learning expectations assumed at crew commander level are described below.

1.1 Roll description: Crew commander

Crew commanders are responsible for the tactical deployment of teams of firefighters who, under specific direction based on SOP and acquired on scene information, will initiate and lead team operation undertaking defined tasks aimed at achieving desired outcomes like search and rescue, fire extinguishment and containment, extrications and recovery.

1.2 Competence level: Crew commander

A tactical decision making capability based on knowledge, skills and experience with behaviour to support judgemental decision making in fast moving circumstances. Underpinned by operational learning and the ability to interpret and if required modify SOP, use previously acquired information and information obtained at the incident the crew commander is expected to create and lead tactical operations having assessed the emergency, identified priorities and requested any required additional assistance.

1.3 Prior learning: Crew commander

EQF 4 Factual and theoretical knowledge in broad contexts within a field of work or study. A range of cognitive and practical skills required to generate solutions to specific problems in a field of work or study. Exercise self-management within the guidelines of work or study contexts that are usually predictable, but are subject to change; supervise the routine work of others, taking some responsibility for the evaluation and improvement of work or study activities.

2. Introduction and objectives

The primary concern of hydrogen safety is the protection of life and property. Thus, it is important to establish the criteria for operators, users, members of the public, as well as for Responders, who may be affected by the consequences of an incident or accident on a FCH system or infrastructure. The acceptance criteria for customers and personnel involved in the operation, inspection and maintenance of FCH facilities and infrastructure will be similar, whilst for the general public, who happened to be in a vicinity of an incident/accident, the approach should be more conservative. According to British Standard BS 7974 (2004) fire fighters are considered as a separate category of those affected. They are not present at FCH facility when incident/accident occurred and often arrive to the scene when conditions are the most hazardous and they must carry out their professional duties. They are vulnerable to the possible collapse of the buildings/structures and the consequences of the blast wave. Also, because they are equipped with special personal protective equipment (PPE) they can withstand higher levels of thermal radiation and temperatures as well as asphyxiating and toxic atmospheres. In addition, the location of a person within the FCH infrastructure at the time of an incident/accident is very important. Indeed, the effects of hydrogen incident/accident can be immediate and will impact people differently, depending on their proximity to the source of harm. People located indoors are more likely to be affected by the blast wave compared to those positioned outdoors.

It is beyond the scope of the HyResponder project to provide harmonized harm criteria or threshold values to characterise the potential impacts of hazardous phenomena. Any interested stakeholders should utilise the standards applicable to their own country.

By the end of this lecture Responders will be able to:

- Describe main health hazards associated with the unignited releases, physical explosion (compressed vessel rupture), fires, deflagrations and detonations of gaseous and liquefied hydrogen;
- Define harmful effects related to unignited hydrogen releases in confined spaces:
    - the noise level;
    - effect of hydrogen temperature;
    - effect of overpressure in case of pressure peaking phenomenon.
- Define the harmful effects of hydrogen combustion on humans:
    - effect of combustion atmosphere temperature;
    - exposure to radiant heat flux;
    - effect of overpressure.
- Appreciate the principles and implementation of framework of harm criteria for people and environment, damage criteria for structures and equipment:
    - air temperature;
    - thermal dose;

  - heat flux;
  - overpressure, etc.
- Specify dangerous and Lethal Dose, 50% (LD50) thermal dose levels;
- Distinguish between direct and indirect harmful effects of overpressure on humans;
- Relate in particular the damages to structures, equipment, and environment caused by hydrogen fires/blast waves to the levels of radiant heat flux and overpressure;
- Recognise labelling systems for gaseous and liquefied hydrogen storage on hydrogen and fuel cell applications;
- List the items of personal protective equipment that should be used not only by First Responders but also by the personnel working at a FCH facility;
- Outline the impact of hydrogen on the environment.

3. Main definitions

It is important for Responders to be able to evaluate an impact of hydrogen incidents/accidents on life safety and loss control. Several methods are available to define and assess the consequences of an incident/accident depending on its severity, exposure, duration and the target under consideration (i.e. public, occupants, structures, buildings, equipment, etc.). There are some useful definitions used in the current and future lectures.

Acceptance criteria are the terms of reference, against which safe design of a FCH facility/infrastructure is assessed [1].

Incapacitation is a condition, under which humans do not function adequately and unable to escape untenable conditions [2].

Occupants are people present within the boundaries of a FCH facility/infrastructure including personnel involved in its operation and maintenance as well as the customers/visitors [1].

Place of safety is a predetermined place inside or outside an FCH facility/infrastructure, in which persons are not in immediate danger from the effect of hydrogen release, fire or explosion [1].

Public are people present outside the boundaries of an FCH facility/infrastructure.

Sensitive area is the establishment, infrastructure or equipment containing inventories of dangerous substances that can become a source of harm when targeted by a hydrogen incident/accident [1].

Survivability is the maximum exposure that may be received with a negligible statistical probability of fatality/damage and without impairment of an individual's ability to escape [1].

Tenability is the maximum exposure to hazards from a hydrogen incident/accident that can be tolerated without violating safety goals [1].

Threshold is the maximum intensity or dose for a given hazard that corresponds to a specific physiological (for humans) or structural (for structures and equipment) response [1].

4. Health hazards of hydrogen releases

Hydrogen gas is lighter than air and that is why it rises quickly and can be diluted rapidly in air during unwanted releases in an open environment. If accidental release occurs in a confined space/indoors it can harm humans by asphyxiation. In addition, hydrogen releases in the confined spaces pose dangers of explosions. Hydrogen-air mixtures are flammable due to the wide flammability range, from 4 to 75 vol. % of hydrogen. When released in air and in the presence of ignition source hydrogen will combust, producing water and heat. The probability of hydrogen being ignited following its release is very high as it has low minimum ignition energy: even static electricity discharge is sufficient to ignite hydrogen. For responders, using protective clothing to avoid static electricity discharge is not needed because static electricity discharge is sufficient to ignite hydrogen in rare cases. In case of fires, hydrogen flame is almost invisible in daylight and its temperature can reach 2000 ºC. Although hydrogen flame radiates little compared to a hydrocarbon one, there is a risk for Responders to walk into the flame.

4.1 Gaseous hydrogen

Hydrogen gas is odourless, colourless and tasteless gas, undetectable by human senses. The use of odorants (e.g. mercaptans) in storage vessels is not possible as they can poison fuel cells. Hydrogen is not a carcinogenic substance. Hydrogen is not expected to cause mutagenicity[1], teratogenicity[2], embryotoxicity[3] or reproductive toxicity. There is no evidence of adverse effects on skin or eyes exposed to hydrogen atmospheres. However, high pressure hydrogen jets may cut bare skin [3]. Hydrogen cannot be ingested. However, inhaled hydrogen can result in a formation of a flammable mixture within the human's lungs.

Similar to other gases, an increase in hydrogen concentration leads to a reduction of oxygen levels in air, which in turn may lead to *asphyxiation*. Hydrogen is classified as a simple *asphyxiant*; it has no threshold limit value (TLV) [4]. High concentrations of hydrogen in air, in fully/partially confined spaces, lead to formation of *oxygen-deficient atmospheres.* Individuals exposed to/breathing such atmospheres may experience the following symptoms: headaches, dizziness, drowsiness, unconsciousness, nausea, vomiting, depression of all the senses, etc. An affected person may have a blue coloured skin, and under some circumstances, a death may occur. If hydrogen is inhaled and the above symptoms are observed the person should be moved to fresh air; oxygen should be given if breathing is laboured, or artificial respiration should be supplied if the person is not breathing.

The system design should prevent any possibility of asphyxiation of personnel working in confined areas [4]. The system design shall provide for prevention of personnel entering the

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1 The induction of permanent transmissible changes in the amount or structure of the genetic material of cells or organisms.

2 Birth defects via a toxic effect on an embryo or foetus.

3 Toxic effects on the embryo of a substance that crosses the placental barrier.

enclosure unless confined space entry procedures are strictly followed. It is recommended to check the oxygen concentration before entering an incident/accident area (no odour warning available if dangerous concentrations are present) and to wear a self-contained breathing apparatus for First Responders. Hydrogen concentrations must be measured with a suitable detector [5]. This point is worth emphasising, hydrogen appropriate gas monitors must be used.

The maximum value of hydrogen concentration in air for an occupant of an FCH facility will be about 40 vol. % because it corresponds to a level, at which a physiological impact can strongly affect human health and an ability to evacuate. The tolerable value for the members of the public will be around 9 vol. %; above this level people may have health problems. As for Responders equipped with PPE (personal protective equipment) such as breathing apparatus, the tolerable value of hydrogen content in air will be higher and can reach up to 100 vol. %. However, the presence of Responders in a flammable hydrogen-air atmosphere is not a recommended practice during the intervention.

Another type of hazard, which should be considered by Responders, is an *acoustic hazard* associated with the releases of high-pressurized hydrogen. The health effects of different noise levels are indicated in Figure 1. It is seen that ear damages may occur at noise levels above 85-90 dB and hearing protection is recommended. The pain threshold limit is 130 dB; at noise levels higher than 140 dB a sudden loss of hearing is very likely. Please note that a blast noise can lead to an *acoustic trauma* - a sudden change in hearing because of a single exposure to a sudden burst or sound [7].

level	Noise source	Health effects
140dB	Jet plane take off, firecracker, gun shot	Sudden damage to hearing
130dB	Pain threshold exceeded	
120dB	Ambulance siren, pneumatic drill, rock concert	
110dB	Night clubs, disco	
100dB	Motor cycle at 50km/h	
90dB	Heavy goods vehicle at 50km/h	
85dB	Hearing protection recommended in industry	Hearing loss, tinnitus
75dB		Cardiovascular effects
70dB		Sleep disturbances
65dB		Stress effects
60dB		Annoyance
55dB	Desirable outdoor level	
50dB	Normal conversation level	
40dB	Quiet suburb	
30dB	Shoft whisper	
20dB	Normal conversation level	

Source: Nopher, a European Commission concerted action to reduce the health effects of noise pollution. http://www.ucl.ac.uk/noiseandhealth/EC%20Brochure1.pdf

Figure 1. Health effects of noise levels [6]

4.2 Liquefied hydrogen

Liquefied hydrogen is stored/used at extremely low temperatures due to its low boiling point (-253 °C). Health hazards associated with the release of liquefied hydrogen are outlined below.

- Contact with liquid hydrogen or its splashes on the skin or in the eyes can cause serious cold burns by *frostbite or hypothermia.*
- *Cryogenic burns* can also result from contact of unprotected parts of human body with either cold fluids or cold surfaces.
- Inhalation of cold hydrogen vapours may cause *respiratory discomfort* and can result in *asphyxiation*.
- Direct physical contact with LH_2, cold vapours or cold equipment can cause serious *tissue damage.* Momentary contact with a small amount of the liquid may not pose as great a danger of a burn because a protective film of evaporating gaseous hydrogen may form. Danger of freezing occurs when large amounts are spilled, and exposure is extensive[4].
- Personnel should not touch cold metal parts and they should wear *protective clothing*. They also need to protect the affected area with a loose cover.
- *Cardiac malfunctions* are likely when the internal body temperature drops to 27°C or lower, and death may result when the internal body temperature drops lower than 15°C [5].
- *Asphyxiation* is also possible if liquefied hydrogen released and vaporised indoors.

5. Harmful effects of hydrogen combustion on humans

An inhalation of combustion products originated from conventional fuels is one of the major causes of an injury and a primary consequence of a fire. It is considered less serious in the case of hydrogen because the sole combustion product is water vapour (non-toxic, non-poisonous). However, secondary fires can produce smoke or other combustion products that present a health hazard.

5.1 Effect of air temperature

During hydrogen fire the surrounding air is heated up significantly and this can affect people located nearby. Direct contact with combusting hydrogen or hot post-flame gases resulting from combustion of hydrogen will cause severe *thermal burns.* An increase in air temperature can cause difficulty berating or respiratory tract burns. High temperature may also lead to a collapse.

[4] Effect of liquid nitrogen: https://www.youtube.com/watch?v=F9dhZJQk80A&feature=youtu.be&t=291

Table 1. Effect of the air temperature on people [12]

Temperature of air, °C	Physiological response
70	No fatal issue in a closed space except uncomfortable situation
115	Threshold for pain (exposure time longer than 5 minutes)
127	Difficulty breathing
149	Breathing via mouth is difficult, temperature limit for escape
160	Rapid, unbearable pain with dry skin
182	Irreversible injuries in 30 seconds
203	Respiratory systems tolerance time is less than four minutes with wet skin
309	Third degree burns for 20 seconds exposure, causes burns to larynx after a few minutes, escape is impossible

As per DNV (a research organisation in Norway) report, 2001 [12], the effects of air temperature (for apparently quiescent atmosphere) rise are classified as follows:

- when temperature is lower than 70 °C, there is no fatality in a confined space, except for uncomfortable feeling.
- when temperature is in a range between 70 °C and 150 °C, the impact on people is dominated by difficulty to breath.
- if the temperature rises higher than 150 °C, the skin burns occur in less than 5 minutes.

More details on the physiological response caused by heated air are given in Table 1.

The acceptance criteria for hot air temperature include: 70 °C - tolerable value for public; 115 °C - tolerable value for occupants to escape with exposure time of 5 minutes; 149 °C - maximum air temperature which prevents occupants from escaping. It is considered that Responders have an adequate PPE such as breathing apparatus, which can protect their respiratory systems from the effects of high temperatures. It was found that proximity suits can provide a protection against air heated up to 1093 °C for a short period of time [15].

5.2 Effect of direct contact with hydrogen flames

The hydrogen flame impact on humans is similar to one by the flames of other common fuels. Direct contact with combusting hydrogen or hot post-flame gases resulting from combustion of hydrogen will cause severe burns [11]. A study carried out on hydrocarbon fires at HSE (Health and Safety Executive) [16] established different types of fires and their effect on population, depending on their intensities, duration and size (Table 2).

Table 2. Characteristics of main types of hydrogen fires [16]

Type of fire	Duration of fire	Size of fire	Intensity of fire	Impact on people
Fireball	Very short	Large	Very high	Radiation, little chance to escape
Flash fire	Very short	Large	Medium	Engulfment: fatalities usually within the fire boundary, little chance to escape
Pool fire	Short	Medium	Low or Medium	Radiation, engulfment, good chance to escape
Jet fire	Medium or Long	Medium	High	Radiation, direct flame contact, good chance to escape

5.3 Effect of radiant heat flux from hydrogen fires

A hydrogen flame radiates significantly less heat compared to hydrocarbon one and is practically invisible in a broad daylight. The maximum wavelength of its emission is about 311 nm, which is near ultraviolet (UV) part of radiation spectrum [11]. This means that people located near a hydrogen flame might not sense its proximity until they are in contact with it [11]. Without suitable detection equipment, the first indication of a small flame is likely to be a "hissing" noise of the gas escaping through an orifice and perhaps appearance "heat ripples" [11].

Please note that a hydrogen flame radiates minimum of infrared radiation and virtually no visible radiation.

For people who are not in direct contact with hydrogen flames, there is a potential of being exposed to high radiation heat fluxes for time sufficient to result in first-, second- or third-degree burns.

5.4 Effect of overpressure on people

The levels of overpressures caused by hydrogen combustion vary significantly and depend on the accident scenario. The least dangerous is a *flash fire* that occurs when hydrogen is rapidly consumed in a form of diffusive (non-premixed) combustion while being released (e.g. from a ruptured pipeline, broken valve or through a failed gasket). Flash fires, similar to conventional fires, do not produce substantial pressure waves and level of overpressure is typically very low.

Vapour Cloud Explosions (VCE) happen when released hydrogen mixes with air to form a flammable cloud prior to its ignition. 'The overpressure effects produced by a vapour cloud explosion may vary greatly and are determined by the speed of flame propagation. In most cases, a *deflagration* occurs where flame front is subsonic. A detonation event involves a supersonic flame front and results in significant overpressures' [19].

The level of overpressure generated can vary greatly from one scenario to another and can be influenced by many factors including the level of confinement, turbulence, the presence of obstacles, volume and concentration of the flammable mixture, speed of flame propagation, etc.

Hydrogen releases taking place in confined spaces have a greater explosive potential compared to the releases happening in the open. Delayed ignition of a hydrogen jet, or ignition of a flammable cloud will result in overpressure, which can cause damage to people and property. In the worst-case scenario, i.e. in the case of the catastrophic rupture of a hydrogen storage tank, a *blast wave* and a *fireball* will be produced.

The effects of overpressure events on people could be direct and indirect. The main direct effect is the significant and sudden increase in pressure that can cause damage to pressure-sensitive organs such as lungs and ears. Indirect effects include the impact from projectiles and debris associated with the equipment damage, displacement of objects, structure collapse, etc. Large explosions can move a person some distance [19]. As the drag forces are strong enough to displace even large objects, a person can also become a projectile.

One of the important indirect effects of overpressure results from flying fragments (aka missiles or projectiles). The level of injury will depend on the size and the weight of fragments, the impact velocity and the location of the impact on a human body [28]. The velocity of missile acceleration is the main factor causing injury. The probability of a penetration wound increases with the increase of velocity, particularly for small size missiles such as glass fragments.

6. Impact of overpressure on structures and equipment

Some examples of accidents involving hydrogen systems and resulting in the structural damages and human fatalities include:

- Hydrogen tank (15-tonnes) explosion at a chemical plant, 1953. Nagoya, Japan. 16 people were killed and 230 seriously injured. For more details please follow the link: https://www.youtube.com/watch?v=eGAfBi6KyMw
- Hydrogen fire and explosion at a large petrochemical complex. 1984; Polysar Ltd, Sarnia, Canada. A release of about 30 kg of hydrogen gas into a compressor shed from a burst flange operating at 4800 kPa. 2 persons killed and 2 injured. Extensive major structural damage observed in the near field; glass and minor structural damage - up to 1 km.
- Hydrogen explosion at the Muskingum River Power Plant's 585-MW coal-fired supercritical Unit 5, 2007. Ohio, USA. The explosion happened during a routine delivery of hydrogen when a relief device failed; the contents of the hydrogen tank escaped and ignited by an unknown source. 1 person was killed and 10 injured, significant damage to several buildings. For more details follow the link: http://www.powermag.com/lessons-learned-from-a-hydrogen-explosion/

7. Labelling of hydrogen systems

The pictograms for commercial transport of hydrogen are shown in Figure 2, in which "1049" denotes gaseous hydrogen, while "1966" denotes liquid hydrogen [36].

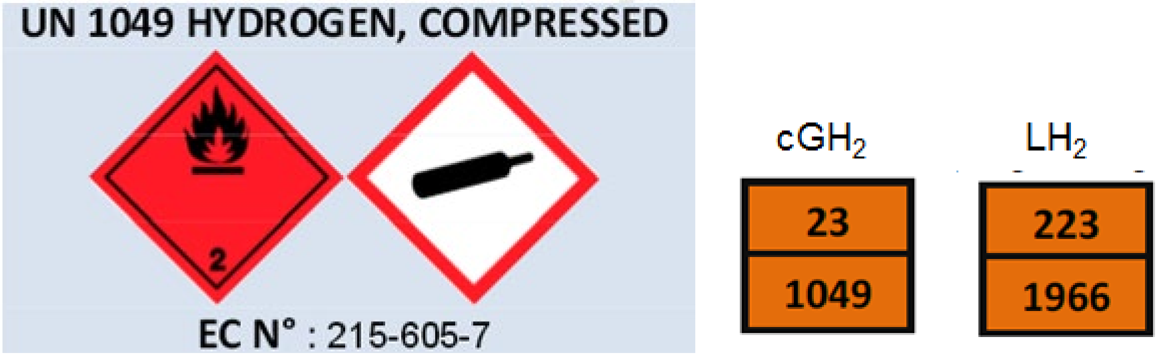


Figure 2. Examples of pictograms used for hydrogen transportation.

For FC vehicles EU regulation, No. 406/2010 recommends using green diamonds in white frames with words ‘H2 GAS’ or ‘LIQUID H2’ written in white letters [37].

The main steps in the development of symbols for formal hazard identification are presented in Figures 3 and 4. These colours are also used in Rescue Information and to colour vehicle components (Rescue Sheets).

GREY	DIESEL
RED	GASOLINE
GREEN	GAS
WHITE	CRYOGEN LNG
BLUE	HYDROGEN
ORANGE	HIGH VOLTAGE

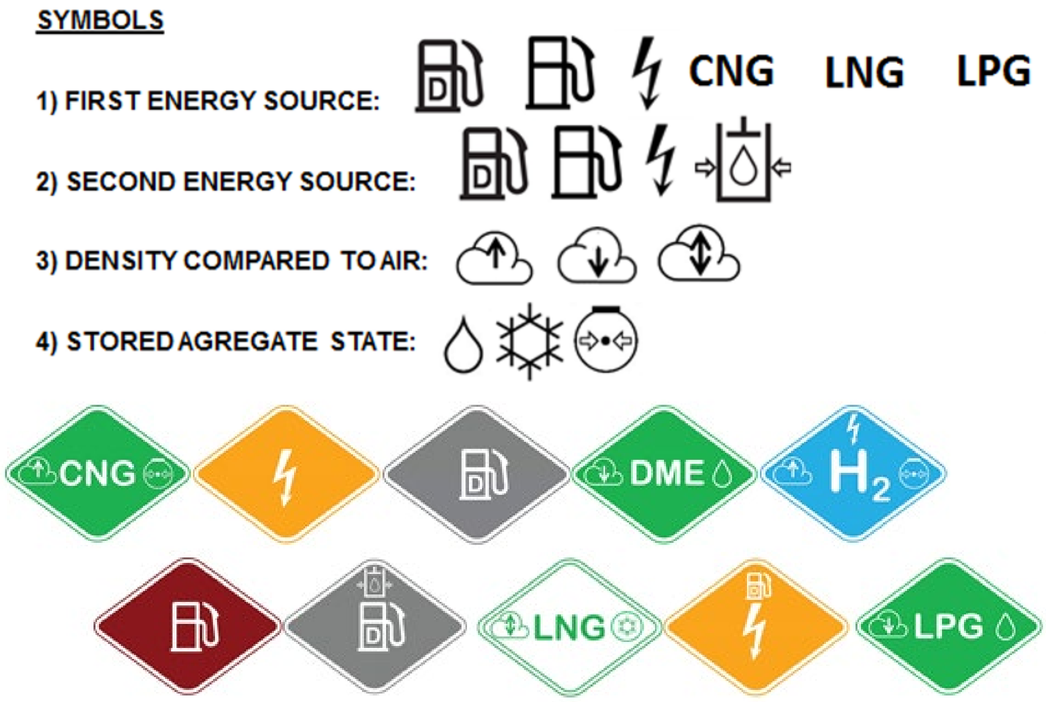
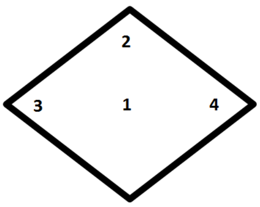


Figure 3. Colours and symbols suggested by CTIF for the development of standardized signs



1	First energy source
2	Second energy source
3	Density compared to air
4	Stored aggregate state

Figure 4. A diamond shape suggested by CTIF for identification of vehicle hazards [38]

Figure 5 shows the most recent version of a label for FC vehicle indicating two main energy soruces: hydrogen (in the centre) and electricity in the top corner. Symbol in the left corner indiates that the first energy source (i.e. hydrogen) is lighter than air; the symbol in the right corner indicate that this is compressed gas. ISO 17840-4 provides responders with valuable information regading dangers, which is visible from a long distance.

Figure 5. A symbol developed by CTIF for FC vehicle powered by compressed gaseous hydrogen [38]

The examples of symbols suggested by CTIF for other types of vehicles, traditional and hybrid ones are shown on Figure 6.

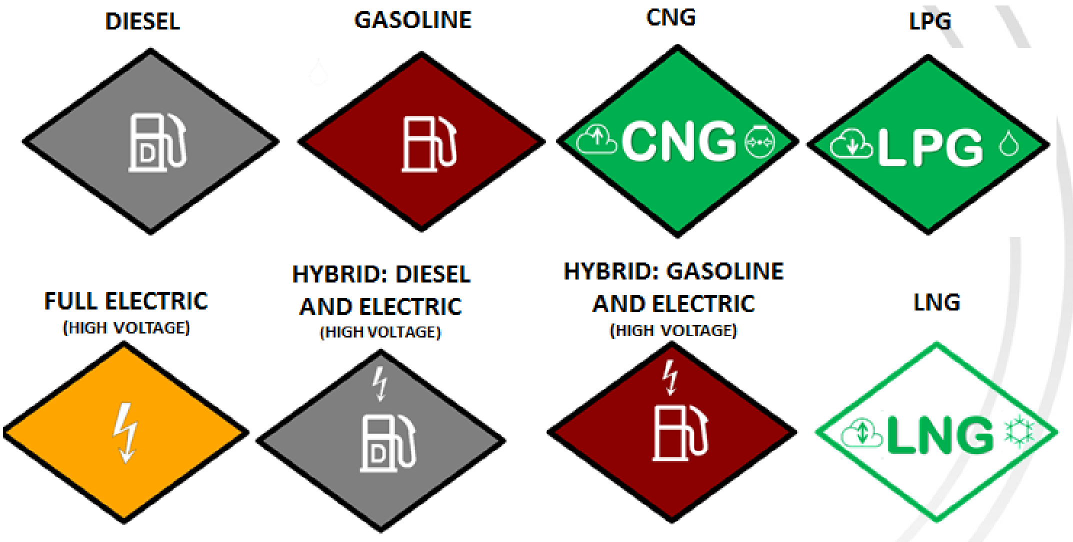


Figure 6. Symbols developed by CTIF for different types of vehicle fuels/energies [38]

Figure 7. Formal methods identification used in the US [36]

8. Personal protective equipment

Two main EU standards should be mentioned with regards to performance requirements of firefighting PPE. The (NF) EN 469:2006-02 [39] contains requirements for protective clothing for firefighters, and (NF) EN 136: 1998 [40] – those for respiratory protective devices.

Personnel performing operations at a hydrogen facility or system can reduce the possible consequences of a hazard by using appropriate protective equipment. Some of the conditions, for which personnel should be protected, including exposure to cryogenic temperatures, flame temperatures, thermal radiation from a hydrogen flame, and oxygen-deficient atmospheres of hydrogen or inert purge gases such as nitrogen and helium. The nature of the work determines which kind of PPE should be used. Some general guidelines for PPE were provided in ISO 15196 [11]. These guidelines do not include PPE that should be considered when involved in other activities such as working on electrical circuits or performing a cleaning or decontamination operation [11]. Necessary or mandatory parts of PPE must be selected on the basis of the conditions on-site.

- Eye protection should be worn if appropriate (e.g. a complete face shield should be worn when connecting and disconnecting lines or components or goggles during handling of LH_2).
- Properly insulated gloves should be worn when handling anything that comes in contact with LH_2 or cold GH_2. The gloves should fit loosely, remove easily, and not have large cuffs.
- Full-length trousers, preferably without cuffs, should be worn with the legs kept on the outside of boots or work shoes.
- Closed-toe shoes should be worn (open or porous shoes should not be worn).
- Clothing made of ordinary cotton, flame-retardant cotton or antistatic material should be worn. Avoid wearing clothing made of nylon or other synthetics, silk or wool because these materials can produce static electricity charges that can ignite flammable mixtures. Synthetic material (clothing) can melt and stick to the flesh, causing greater burn damage. Any clothing sprayed or splashed with hydrogen should be removed until they are completely free of hydrogen gas.
- Gauntlet gloves, tight clothing, or clothing that holds or traps (pockets) liquid against the body should be avoided.
- Hearing protection should be worn if the hydrogen facility or system involves equipment that creates loud noise.
- Hard hats/helmets should be worn if the hydrogen facility or system involves any danger from falling objects.
- Self-contained breathing equipment should be worn when working in a confined space that may have an oxygen-deficient atmosphere.
- Portable hydrogen- and fire-detection equipment should be used to warn of hydrogen leaks and fires.
- Thermal cameras and unmanned hose or monitor nozzle should be used by firemen.

- Personnel should ground themselves before touching or using a tool on a hydrogen system if any hydrogen is suspected to be in the area.

9. Impact on the environment

Hydrogen will not contaminate groundwater (it is a gas under normal atmospheric conditions), nor will a release of hydrogen contribute to atmospheric pollution. Hydrogen is found in terrestrial atmosphere at concentration of 0.5 ppm (parts per million) from ground level to 60 km altitude [1]. The sources of hydrogen emissions described by Schultz [41] include:

- Incomplete combustion of fossil fuels and biomass (40%),
- Atmospheric petrochemical oxidation of methane and non-methane hydrocarbons (50%),
- Emissions from volcanoes, oceans and nitrogen-fixing legumes (10%).

75% of hydrogen emissions are removed from atmosphere by dry deposition on soils while the remaining 25% are removed through oxidation in atmosphere [41].

Hydrogen when used as a fuel does not create "fumes or “smoke”. A FC vehicle has zero exhaust pipe emissions [42].

Acknowledgement

The HyResponse project is acknowledged as the materials presented here are extended based on the original HyResponse lectures.

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