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LECTURE - Harm criteria for people and environment, damage criteria for structures and equipment

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Contents

Introduction

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 general public as well as for First 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 HyResponse 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.

Objectives of the lecture

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

- Describe main health hazards associated with the unignited releases, fires, deflagrations and detonations of gaseous and liquefied hydrogen;
- Define harmful effects related to unignited hydrogen releases in confined spaces:
    - safe concentration levels of hydrogen and oxygen;
    - 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.

Main definitions

It is important for First 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].

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. In case of fires, hydrogen flame is almost invisible in daylight and its temperature can reach 2000 ^{o}C. Although hydrogen flame radiates little compared to a hydrocarbon one, there is a risk for First Responders to walk into the flame. Propagation of flame through hydrogen-air mixture is much faster compared to CNG and LPG fuels, and thus the risk of

transition to detonation cannot be ruled out. As for liquid state of hydrogen, the main risks are associated with extremely low temperatures and possible vaporization (1 L of liquid hydrogen vaporises to 870 L of gas at NTP), which can also lead to asphyxiation if LH_2 released indoors.

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, teratogenicity, embryotoxicity 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.

Table 1 indicates the physiological effects caused by oxygen depletion. Hydrogen can cause asphyxiation by diluting oxygen in the air to the concentrations below safe level, lower than 19 vol. %. Oxygen concentration levels below 19.5 vol. % by volume are biologically inactive for humans, and no effects of oxygen deficiency are usually observed. At oxygen concentrations below 12 vol. %, immediate unconsciousness may occur with no prior warning symptoms.

Table 1. Human response to oxygen depletion [4].

H_2 concentration, vol. %	O_2 concentration, vol. %	Physiological effect
0-9	21-19	No specific symptoms
9-28	15-19	Decreased ability to perform tasks, may induce early symptoms in persons with heart, lung, or blood circulation problems
28-42	12-15	Deeper respiration, faster pulse, poor coordination
42-52	10-12	Dizziness, poor judgment, slightly-blue lips
52-62	8-10	Nausea, vomiting, unconsciousness, ashen face, fainting, mental failure, with a tolerance time of 5 min
62-71	6-8	Unconsciousness in 3 min, death in 8 min. 50% death and 50% recovery with treatment in 6 min, 100% recovery with treatment in 4-5 min
71-86	3-6	Coma in 40 s, convulsions, respiration ceases then death
86-100	0-3	Death within 45 s

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 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 have to be measured with a suitable detector [5].

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 First Responders equipped with PPE 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 First Responders in a flammable hydrogen-air atmosphere is not a recommended practice during the intervention.

Another type of hazard, which should be taken into account by First 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 85-90dB 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.

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].

Please note that a blast noise can lead to an *acoustic trauma* - a sudden change in hearing as a result of a single exposure to a sudden burst or sound [7].

As is shown in Figure 2, even small hydrogen leaks can generate sufficient ultrasonic noise to afford detection in most industrial environments [7]. While *audible acoustic noise* typically ranges between

60 and 110 dB in industrial sites, the *ultrasonic noise levels* (frequency range of 25-100 kHz) span from 68 to 78 dB in high noise areas, where rotating machinery like compressors and turbines are installed, and rarely exceed 60 dB in low noise areas. Consequently, ultrasonic gas leak detectors can detect hydrogen leaks without being affected by background noise. And since the instruments respond to the release of gas rather than the gas itself, they can alarm rapidly, often within milliseconds. As it follows from Figure 2 the ultrasonic sound pressure level (SPL) is almost reversely proportional to the distance from the noise source (i.e. hydrogen leak).

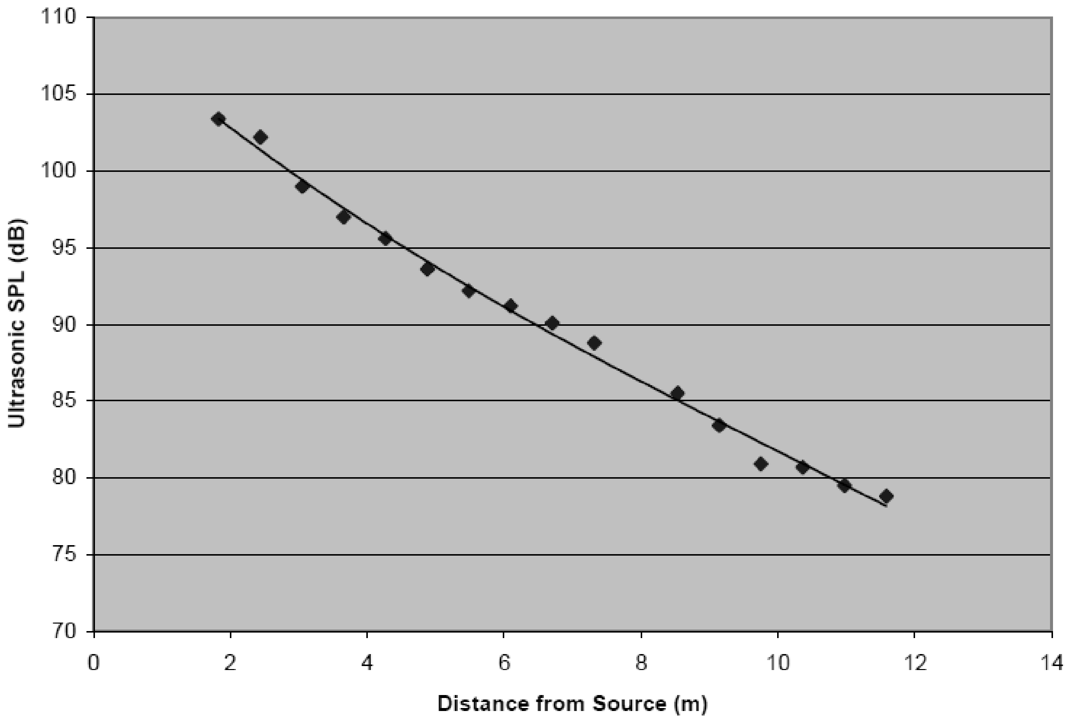


Figure 2. Sound pressure level *versus* distance from the source of hydrogen leak (leak diameter: 1 mm; pressure: 5,515 kPa; leak rate: 0.003 kg/s) [7].

Equipment pressurised to 200 bar and fitted with a lyre type outlet with orifice diameter of 4 mm produces a noise of 130 dB. During the tests carried out by Air Liquide on a pipe, which had a diameter of 5 mm and was pressurised to 700 bar, the noise level ranged from 100 to 140 dB. Hydrogen leaks producing sound pressure 50-60 dB do not present any risk for persons in the vicinity, unless they are in a confined space configuration [8].

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[1].
- 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.

Friedrich et al. (2012) measured sound levels from unignited and ignited cryogenic jets (nozzle diameter 1 mm, pressure up to 30 bar, hydrogen mass flow rate up to 8 g/s, temperature 34-65 K). Please note that the sound level will depend on the spouting pressure and the mass flow rate. Four different meters for sound level evaluation were installed at distances of 1.23 m, 1.65 m, 2.91 m, and 4.55 m to the release nozzle inside a testing cell [9]. The steady-state levels of the sound meter signals are illustrated in Figure 3. 'The ignited jets generated about 10 dB (A) higher sound levels compared to unignited jets. There seems to be a weak increase of the sound level with increasing hydrogen mass flow rate. The initial burn-out of the hydrogen inventory in the unreacted jet causes the highest sound emissions' [9].

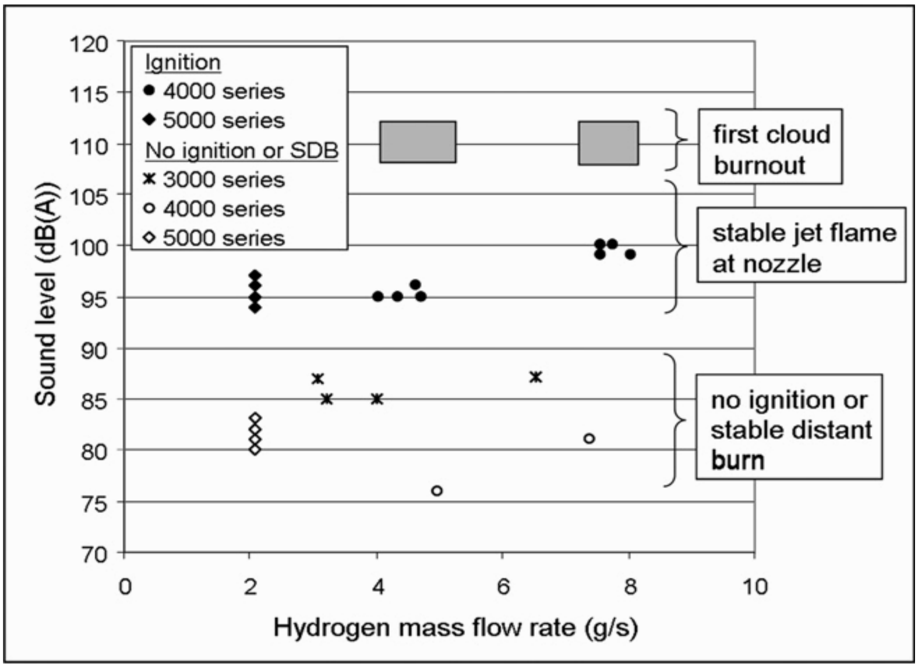


Figure 3. Measured sound levels from ignited and unignited stationary cryogenic hydrogen jets [9].

The sound levels measured in this study (≤112 dB(A)) are considered hazardous only in case of permanent or long-time exposures. An ear damage from short sound waves becomes possible for 120 dB(A) and above. 'So the sound levels from unignited and ignited cryogenic hydrogen jets measured in this study pose no health hazards, even at the close distances investigated (1.2-4.5 m).

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

On the other side, the measured sound levels are loud enough to allow an early identification and location of a free hydrogen jet or jet flame with sound meters' [9].

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). Contrary, carbon monoxide CO can be lethal at concentrations just above 400 ppm (parts per million) [10]. However, secondary fires can produce smoke or other combustion products that present a health hazard.

Effect of air temperature

The flame temperature of a stoichiometric hydrogen-air mixture is about 2,403 K [11]. 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.

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

- When temperature is lower than 70 ^{o}C, there is no fatality in a confined space, with the exception of uncomfortable feeling.
- When temperature is in a range between 70 ^{o}C and 150 ^{o}C, the impact on people is dominated by difficulty to breath.
- If the temperature rises higher than 150 ^{o}C, the skin burns occur in less than 5 minutes.

More details on the physiological response caused by heated air are given in Table 2.

Table 2. Effect of the air temperature on people [12].

Temperature of air, ^{o}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

The temperature value of 149 ^{o}C is the limiting temperature for escape. The value of 115 ^{o}C is the estimated threshold for pain given in BSI PD7974-6:2004 [13] for exposures lasting longer than 5 minutes. In addition, two equations, coming from [12] and [14] respectively, can be very useful in evaluating the time to incapacitation (t_{inc}, min) depending on the air temperature:

$$t_{inc} = 5.33 \times 10^{8} \times T_{air}^{-3.66} \quad (1)$$

$$t_{inc} = 5 \times 10^{7} \times T_{air}^{-3.4} \quad (2)$$

Figure 4 shows two graphs plotted based on the above equations (1) and (2) and applied for the temperature range between 0 and 210 °C. Please note that dash line portions of the graphs, at lower temperatures, should not be considered. The equation based on BS 7879-2 (blue plot) gives more conservative values as opposed to the values calculated from equation based DNV approach (red plot). Let us compare the values indicated in Table 2 with those shown on Figure 4. Temperature of 149 °C is a limit temperature that incapacitates occupants of the facility to evacuate. As per Figure 4 the incapacitation time corresponding to this temperature is between 2 minutes (blue graph) and 5 minutes (red graph). If we consider temperature corresponding to the pain threshold (115 °C) it occurs between 5 minutes (BS 7879-2 approach) and 15 minutes (DNV approach).

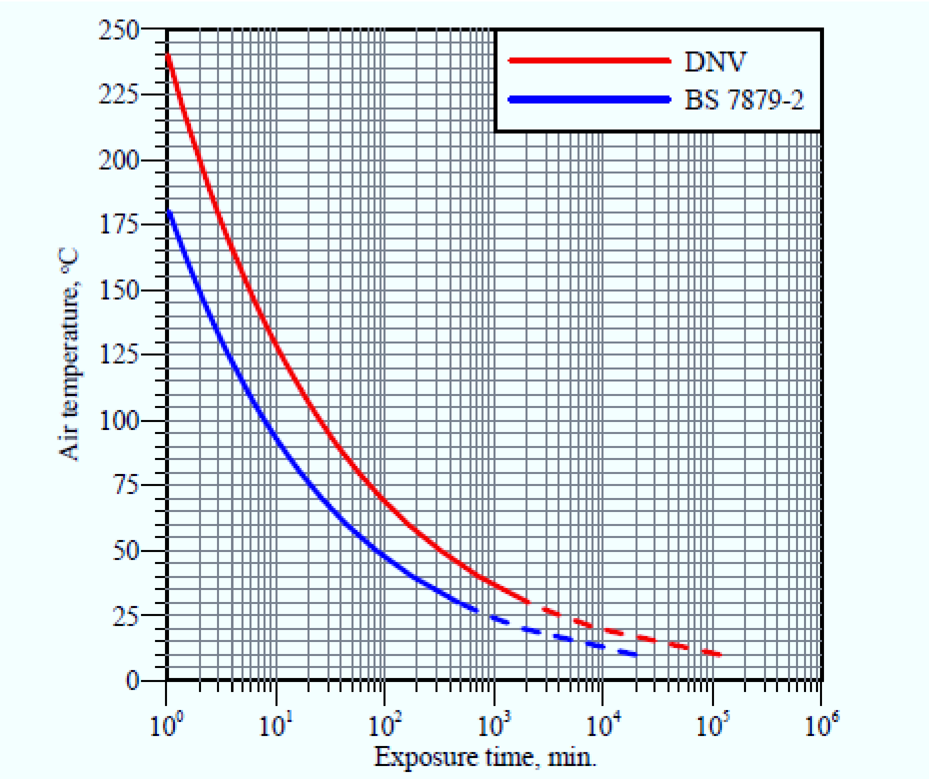


Figure 4. Time to incapacitation (t_{inc}) as a function of exposure time according to [12] (red line), and [14] (blue line).

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 First 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].

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 [16] established different types of fires and their effect on population, depending on their intensities, duration and size (Table 3).

Table 3. 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

Data presented in Table 4 shows an impact of a person's age and burned surface area of skin on the probability of the fatality.

Table 4. Burned skin area resulting in 50% probability of fatality [16].

Age group, years	Burned area, %
0-4	60.0
5-34	71.2
35-49	61.8
50-59	52.1
60-74	33.7
Over 75	19.6

In addition, Table 5 gives an estimation of probability of fatality in the age group of 40-44 year olds, depending on the percentage of the burned body area. It is obvious that the large number of people dies due to an extensive burns covering large percentage of their body surface.

Table 5. Probability of fatality as a function of burned skin for 40-44 year olds [17].

Body area burned, %	Probability of fatality, %
78-100	100
68-77	90
63-67	80
53-62	70
48-52	60
43-47	40
33-42	30
28-32	20
18-27	10
0-17	0

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. Due to the absence of carbon dioxide CO_2 radiation bands and the strong absorption by ambient water vapour, the ratio of visible (with the aid of special techniques or at night time) to infrared hydrogen jet flames is 0.88 and the ratio of ultraviolet to infrared flame length is 0.78 [18]. Nevertheless, convective and radiative heat fluxes still remain important and must be assessed for the protection of life, property and the environment.

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. Table 6 summarises the effects of different levels of radiant fluxes on people, which can be used as harm criteria [19].

Table 6. The impact of radiant heat flux on people *[19].

Radiant heat flux intensity, kW/m^2	**Effects on people**
1.5	No harm; safe for the general public and for the stationery personnel
2.5	Intensity tolerable for 5 min; severe pain above this exposure time
3	Intensity tolerable for non-frequent emergency situations for 30 min
5	Pain for 20 s exposure, first degree burn. Intensity tolerable for those performing emergency operations
6	Intensity tolerable for escaping emergency personnel
9.5	Second degree burn after 20 seconds
12.5-15	First degree burn after 10 seconds, 1% fatality in 1 min
25	Significant injury in 10 s, 100% fatality in 1 min
35-37.5	1% fatality in 10 s

*These are generic values for hydrocarbon fires

The acceptance criteria are defined as follows:

- The heat flux of 1.5 kW/m^2 is considered to be safe for members of the public (for comparison, 1.3 kW/m^2 is the average intensity of radiant heat from the sun on a hot day) [1].
- The PD 7974-6: 2004 [13] proposed the radiant heat flux of 2.5 kW/m^2 as a limit for exposure of un-protected skin to radiant heat, above which it will lead to severe pain. The tolerance time at this intensity is 5 min [13]. Nevertheless, an exposure to this level of intensity could lead to various degrees of burns, depending on the exposure time. This is a tolerable intensity for an occupant. Above this value of heat flux or duration of exposure, the dose received should be calculated to evaluate an impact on people [1].
- The heat flux of 5 kW/m^2 is a threshold of tolerability for First Responders wearing protective clothing. However long exposures this intensity should be avoided.
- The intensity of 6 kW/m^2 is tolerable for occupants when evacuating and should be considered as an important threshold value. For this intensity pain is reached within 12 s, and it is lethal in about 38 s [1].

The threshold values may vary from country to country. For examples, as per French doctrine the threshold values are set at 3, 5 and 8 kW/m^2 [8]. Correlations between thermal fluxes and distances during combustion of a hydrogen leak on a pipe depending of the diameter of the leak and the pressure in the storage tank used in French doctrine can be found in Annex 1.

The harm level depends on not only the heat flux intensity but also on the period of exposure. With this in mind, the harm from radiant heat is often expressed in terms of thermal dose unit, which combines its intensity and time [19] as per equation (3):

$$\text{Thermal dose unit: TDU} = I^{4/3} \times t \quad (3),$$

where I is the radiant flux (in kW/m^2) and t is the duration of exposure (in s), 1 thermal dose unit (TDU) = 1 (kW/m^2)$^{4/3}$s.

For First Responders it is crucial to know the harm based on the dose for different wave lengths of radiation. As it was stated earlier hydrogen fire radiates more in UV part of spectrum than in IR one. Table 7 indicates the values of thermal dose units leading to 1st, 2nd and 3rd degree burns only for ultraviolet (UV) and only for infrared (IR) spectrum range. The radiation heat flux in IR spectrum is of the most concern for producing skin burns at the dose value much lower compared to the UV. Many factors influence the threshold values shown in Table 7 including the type of heat source, the type of animal skin used in experiments [19].

Table 7. Radiation burn data [19].

Severity of burn	**Thermal dose threshold, (kW/m^2)$^{4/3}$s**	
	Ultraviolet	Infrared
First degree	260-440	80-130
Second degree	670-1100	240-730
Third degree	1220-3100	870-2640

Two parameters may be used as the lethal harm criteria: 1) 'dangerous dose', which corresponds to the dose level resulting in the death to 1% of the exposed population, and 2) lethal dose 'LD50' which denotes a dose, at which 50% human fatalities are expected. Table 8 collates the values of dangerous dose and LD50 reported in the literature. Rew proposed 2000 TDU as the equivalent of LD50 for incident thermal radiation on-shore [16]. It should be noted that LD50 value 3600 (kW/m^2)$^{4/3}$s reported by Lees [24] appears to be too high. Thus, O'Sullivan and Jagger [20] and Chang et al. [21] reported a guiding figure of 3500 TDU corresponding to 100% fatality for personnel in clothing. However, 100% fatality may occur at slightly lower doses. At 3500 TDU, un-piloted ignition of clothing will occur suggesting that 100% clothed individuals will not survive. At this level of thermal dose, self-extinguishment is unlikely due to injury from heat transmitted through the clothing. Health and Safety Executive, UK proposed to use LD50=2000 (kW/m^2)$^{4/3}$s for off-shore oil and gas facilities.

Table 8. Literature data for dangerous dose and LD50.

Literature source	**Thermal dose (kW/m^2)$^{4/3}$s for infrared radiation**	
	Dangerous dose	LD50
Eisenberg [22]	960	2380
Tsao and Perry [23]	420	1050
Lees [24]	1655	3600 (based on ignition of clothing at 3600 (kW/m^2)$^{4/3}$s)

HSE [16]	1000	2000
The Netherlands Organization of Applied Scientific Research (TNO) [25]	590	1460

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 raptured 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 (i.e. indoors) 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 (Tables 9 and 10). 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. The injuries sustained are called translational injuries because the human body is literally picked up and translated, and the velocity, at which the body is displaced, will determine the severity of the injury. 50% of people experienced the body displacement with the velocity above 0.6 m/s will suffer minor injuries; 1% of those with the velocity of about 4 m/s will sustain injuries such as ruptured organs and bone fractures [1]. Two factors can cause harm: the *level of overpressure* and the duration of the high pressure (the *impulse*). The summary of overpressure values for both direct and indirect effects resulting in harm to humans are shown in Tables 9 and 10.

Table 9. Direct effects on people from overpressure [19].

Δp, kPa	**Damage description**
8	No serious injuries to people located outdoors
10	Serious injuries to people indoors, few fatalities
13.8	Threshold for eardrum rupture

20	Threshold of survivability (20% probability of fatality indoors; 0% probability of fatality outdoors)
34.5-48.3	50% probability of eardrum rupture
54	Fatal head injury
68.9-103.4	90% probability of eardrum rupture
70	100% probability of fatality indoors
82.7-103.4	Threshold for lung haemorrhage (severe injury or death)
137.9-172.4	50% probability of fatality from lung haemorrhage
206.8-241.3	90% probability of fatality from lung haemorrhage
48.3	Threshold for internal injuries by blast
482.6-1379	Immediate blast fatalities

As it shown in Table 9 direct effects are primarily lung haemorrhage and eardrum rupture due to overpressure. It is important to remember that the harm to people caused by the blast occurring inside a building is more significant, compared to the situations when they are located outside, due to the enhanced indirect effects caused by the destruction of the building leading to a formation of projectiles (fragments). Indeed, the pressure levels corresponding to direct injuries to humans are much greater than for buildings.

Table 10. Indirect effects on people from overpressure events [19].

Δp, kPa	**Damage description**
3.0	Injuries by glass fragments
6.9-13.8	Threshold for skin lacerations by missiles
10.3-20.0	People knocked down by pressure wave
13.8	Possible fatality by being projected against obstacles
27.6-34.5	50% probability of fatality from missile wounds
48.3-68.9	100% probability of fatality from missile wounds
55.2-110.3	People standing up will be thrown a distance

For people indoors, who are positioned behind the windows, 3 kPa overpressure can cause injuries by glass fragments, while 10 kPa is a threshold for serious injuries. For people located outdoors the overpressure of 8 kPa will not lead to serious injuries (Tables 9 and 10). The threshold of survivability is 21 kPa, but other sources recommend using values from the interval 14-20 kPa [8]. The threshold for eardrum rupture is 13.8 kPa, and the range from 34.5 to 48.3 kPa corresponds to 50% probability of eardrum rupture, which can result in deafness, tinnitus and vertigo. These physiological effects represent threat to occupants, who will be attempting to escape: they will be quite disorientated and unable to communicate with each other. If people experience vertigo it could be dangerous for them to use stairs or evacuation routes. Interestingly, the indirect effects of explosions are more important in terms of safety. 'The indirect blast injuries are so predominant that people exposed only to direct blast injuries make up a small part of the patient workload' [26]. The direct overpressure effects do not extend out as far as from the point of explosion as other effects and are often masked by the drag force effects [27]. French recommendations for distances from overpressure events can be found in Annex 2.

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. Heavy missiles may not cause penetration wounds but may lead to more severe injuries such as fractures [26]. The threshold velocity for skull fractures from 4.5 milligram missiles is as small as 4.6 m/s [26]. However it is still difficult to evaluate fully the impact of missiles on people to a lack of properly validated models [1].

The duration of the blast wave generated during an explosion is very short (in majority of cases it is less than a second) and the occupants would not be able physically to escape to a safe place. Thus, it is impossible to evaluate the duration of people's exposure to the blast wave as the event is almost instant. However, the duration of the positive phase of overpressure can be used to assess the damages. For instance, Lees presented a probability of survival and a threshold for lung damage by blast wave, depending on the overpressure (vertical axis) and the duration of a positive phase of overpressure (horizontal axis), see Figure 5 [29]. At the constant pressure, the longer the impulse the more severe is the impact.

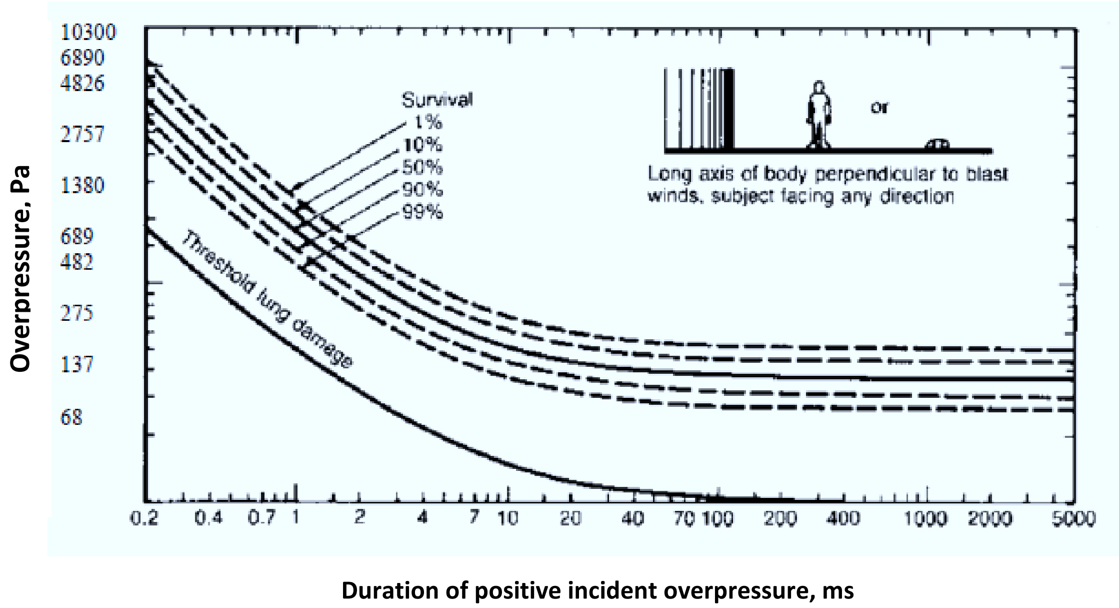


Figure 5. The effect of combined overpressure and impulse [29].

The acceptance criteria for overpressure values are shown below. These values should be treated as recommendations.

- The overpressure of 1 kPa is the tolerable value for the occupants located indoors. This level corresponds to the breakage of 5% of windows [30].
- The overpressure of 1.35 kPa and impulses of 1 Pa·s can be considered as a 'No harm' threshold for humans [31].
- The overpressure of 8 kPa is the tolerable value for people located outdoors [1].
- The overpressure of 10 kPa is the maximum value for the occupants located indoors. Above this threshold serious injuries and some fatalities are possible [1].
- The overpressure of 21 kPa is the survivability value for the occupants located outdoors. This threshold does not impair movements and has a low probability of injury or death .
- The overpressure of 21 kPa is the survivability threshold value for First Responders too as their PPE will not protect them from overpressure effects.

- The overpressure of 34 kPa is the maximum value for the occupants located outdoors. The levels of overpressure above 34 kPa physiologically impact occupants during evacuation procedures. This value is conservative regarding the 1% probability of lethality given in [29] and 1% probability of death primarily by lung haemorrhage (99 kPa) given by Lees [29], [1].

Damage to structures, equipment and environment caused by hydrogen fires

The damage criteria for structures, equipment and environment caused by hydrogen fires can be expressed in terms of exposure to radiant heat flux or direct flames. The impacts of radiant heat flux intensity on structures, equipment and environment are summarised in Table 11.

Table 11. Impacts of radiant heat flux on structures, equipment and environment [19, 29].

Radiant heat flux, kW/m^2	Effect on structures, materials, equipment and environments
4	Glass breakage (30 min exposure)
5	Significant windows breakage
8-12	Radiation intensity threshold capable to cause domino effects
10	Heating structures; increase of temperatures and pressures in LH_2/GH_2 storages
10-12	Ignition of vegetation
10 or 20	Ignition of fuel, oil (120 or 40 s, respectively)
12.5-15	Piloted ignition of wood; melting of plastics (>30 min exposure)
16	Failure of structures (except concrete) in prolonged exposures
18-20	Cable insulation degradation (>30 min exposure)
20	Intensity, which concrete structures can withstand for several hours
25-32	Unpiloted ignition of wood; steel deformation (>30 min exposure)
35-37.5	Process equipment and structural damage, including storage tanks (>30 min exposure)
100	Steel structure collapse (>30 min exposure)
200	Concrete structures failure (in several dozen of min)

The acceptance criteria are listed below:

- 5 kW/m^2 – threshold for light damages as this intensity corresponds to windows breakage;
- 10 kW/m^2 – threshold for moderate damages as this corresponds the heat flux level leading to structures being heated up and to a significant increase in pressure inside liquid or gaseous storages
- 10 kW/m^2 – is a sensitive area threshold
- The collapse thresholds depend strongly on the nature of material: the failure of non-concrete structures occurs at 16 kW/m^2 for prolonged exposure, while concrete structures fail at 200 kW/m^2.

Impact of overpressure on structures and equipment

The values of overpressure can provide First Responders with the guidance regarding the degree of destruction. Minor structural damages would occur at about 3-6 kPa of overpressure, whilst complete demolition will occur when overpressure is within 80-260 kPa interval.

The thresholds for buildings suggested by Mannan [32] are represented in Table 12.

Table12. Thresholds of damage overpressure for buildings from Mannan [32].

Overpressure, kPa	Degree of damage
4.8	Minor damage to the house
6.9	Partial demolition of the house-remains non-inhabitable
34.5-48.3	Almost total destruction of the house

These values have been recently adapted by Molkov and Kashkarov [33] for the evaluation of separation distances from the blast wave generated by the rupture of high pressure hydrogen storage tank. The details of this methodology will be discussed further in the Lecture on hydrogen detonations and deflagrations.

Table 13 summarises different effects of overpressure on structures reported in the literature [29, 30]. Window panes are particularly prone to breakage at low levels of overpressures [1]. Please remember that glass fragments can become missiles and cause harm to people.

Table 13. A response of structural elements to the different levels of overpressure.

Elements	Overpressure, kPa	Damage description
Window pane	0.7 – 1.0	5% broken
	1.4 – 3.0	50% broken
	3. 0 – 6.0	90% broken
Building	1.4 – 3.0	Inhabitable after repair damage to ceilings, windows and tiling
	3.0 – 6.0	Limited minor structural damage. Partitions and joinery was wrenched from fixings. Damage to a house ceiling. 90 % of window glass is broken
	6.0 – 9.0	Door and window frames are broken
	9.0	Steel frame of clad building is slightly distorted
	14 – 28	Uninhabitable; partial or total collapse of roof, partial demolition of one or two external walls, severe damage to load-bearing partitions. Concrete or cinder block walls, not reinforced, shattered
	30	Destruction of all buildings that were not designed to withstand explosions
	35 – 80	50%-75% external brickwork destroyed or rendered unsafe
	80 – 260	Almost complete demolition
	50 – 100	Displacement of cylindrical storage, failure of pipes

Stephen [34] and Lees [29] give peak values of overpressure and the level of damage to structures indicated in Table 14.

Table 14. Classification of damages to structures for different overpressures.

Overpressure, kPa	Damage level
less than 3.5	Light damage
more than 17	Moderate damage
more than 35	Severe damage
more than 83	Total destruction

A pressure peak for domino effects at a value of 20 kPa, and used as threshold when applying COMAH Regulations [1]. As stated earlier the threshold values depend on the national regulations. The examples of French threshold values associated with overpressure effects on humans and structures are shown in Annex 3.

The combined impact of overpressure and impulse are indicated in Table 15 and Figure 6. These values can be used as thresholds. The values of overpressure and impulse corresponding to points A, B, C and D in Table 15 are also represented in Figure 6 and are in a good agreement with the level of damage 1, 2 and 3 (see Figure 6 legend). Figure 6 can be used to estimate the degree of damage caused to buildings for particular peak overpressure and impulse of the blast.

Table 15. Combined effect of overpressure and impulse on the level of damage [1].

Overpressure peak, kPa	Impulse, kPa·s	Damage description	Point in Figure 6
3.6	0.10	Border of minor structural damages	A
14.6	0.30	Threshold for moderate structural damages: failure of some load-bearing elements	B
34.5	0.52	Threshold for partial distraction: 50-75% of walls destroyed	C
70.1	0.77	Total destruction of buildings	D

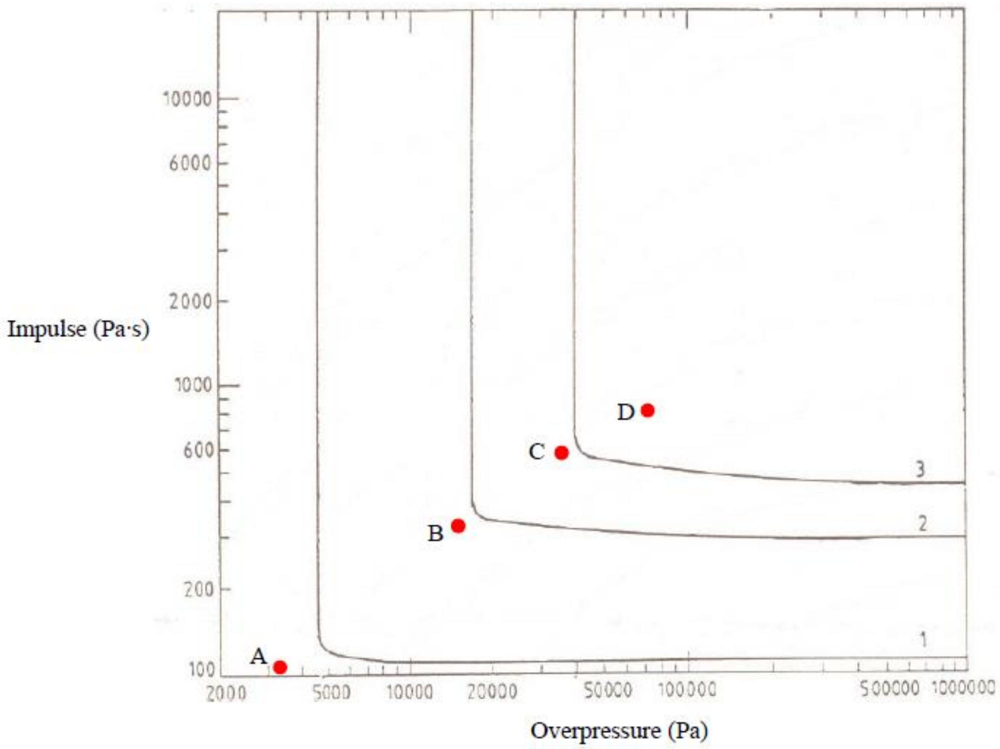


Figure 6. Overpressure-impulse diagram of a high explosive charge on the ground, producing a gradual level of damage to houses: level 1 – light damage; level 2 - structural damage; 3 – collapse [35].

The acceptance criteria are as follows [1?]:

- The threshold for light damages is at 3 kPa with the impulse greater than 100 Pa·s. At this level of overpressure, the infrastructure is inhabitable after repair damage to ceilings, window and tiling.
- The threshold for moderate damages is at 15 kPa with the impulse greater than 300 Pa·s.
- The threshold for civil structures collapse is at 35 kPa with the impulse higher than 500 Pa·s.
- The threshold for the sensitive area is at 20 kPa.

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 peopled 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 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/

Table 16 summarises the values of threshold (i.e. acceptance criteria for life safety and property loss) discussed earlier. They should be used as guidance rather than absolute numerical values.

Table 16. Values for the definition of acceptance criteria for life safety and property loss.

Location	Hazard to life	Threshold	First Responder	Occupant	Member of the public
Indoors and Outdoors	Hydrogen concentration, vol. %	Tolerable	9	28	9
		Maximum	-	40	-
	Temperature of air, °C	Tolerable	149	115	70
		Maximum	-	149	-
	Direct radiant heat flux, kW/m^2	Tolerable	5	2.5	1.5
		Maximum	-	6	-
	Direct overpressure, kPa	Tolerable	8	21	8
		Maximum	-	34	-
	Indirect overpressure – missiles from windows, kPa	Tolerable	1	1	1
		Maximum	-	10	-

Hazard to properties	Threshold	Values
Radiant Heat Flux, kW/m^2	Light damages	3
	Moderate damages	10
	Sensitive area	10
	Collapse	16-200
Overpressure, kPa	Light damages	6
	Moderate damages	15
	Sensitive area	20
	Collapse	35

Labelling of hydrogen systems

The pictograms for commercial transport of hydrogen are shown in Figure 7. "1049" denotes gaseous hydrogen, while"1966" denotes liquid hydrogen [36].

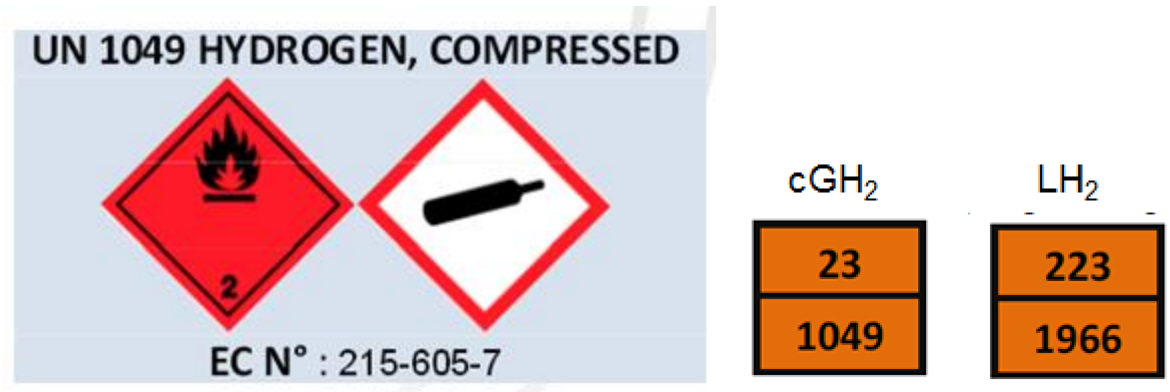


Figure 7. Examples of pictograms used for hydrogen transportation.

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]. However, there is no standardized system in place for labelling FC vehicles. The development of a new uniform signage in the EU is initiated by the Commission for Extrication and New Technologies (CTIF) [38]. Two drafts are currently in place:

- Draft “ISO Propulsion energy indification";
- Draft “10 chapters ISO template” used in the Rescue Sheet and the Emergency Response Guide together with standardized symbols and colours.

The main steps in the development of symbols for formal hazard identification are presented on Figures 8-9.

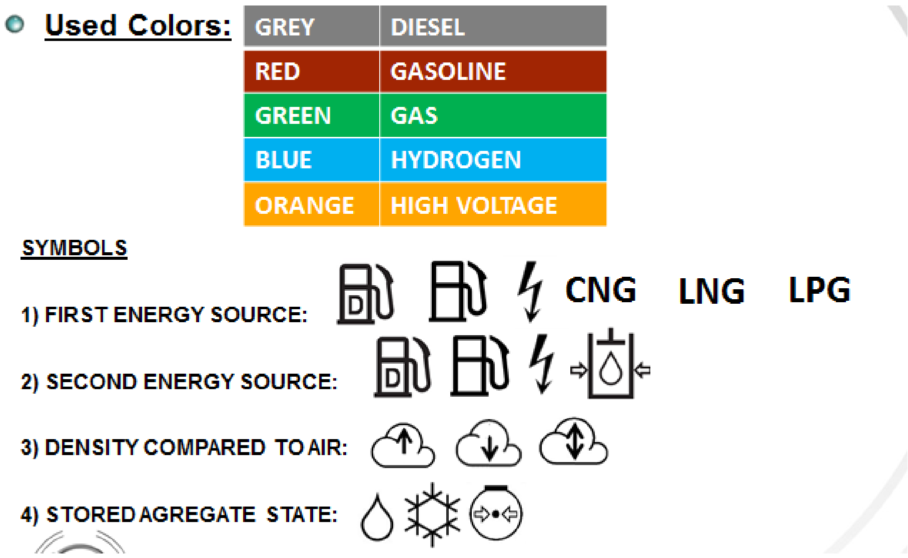
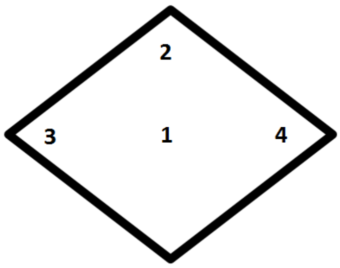


Figure 8. Colours and symbols suggested by CTIF for the development of standardized signs [38].

These colours are also used in Rescue Information and to colour vehicle components (Rescue Sheets).



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

Figure 9. A diamond shape suggested by CTIF for identification of vehicle hazards [38].

Figure 10 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. If these two drafts are approved it will provide First Responders with valuable information regading dangers, which is visible from a long distance.

Figure 10. 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 11.

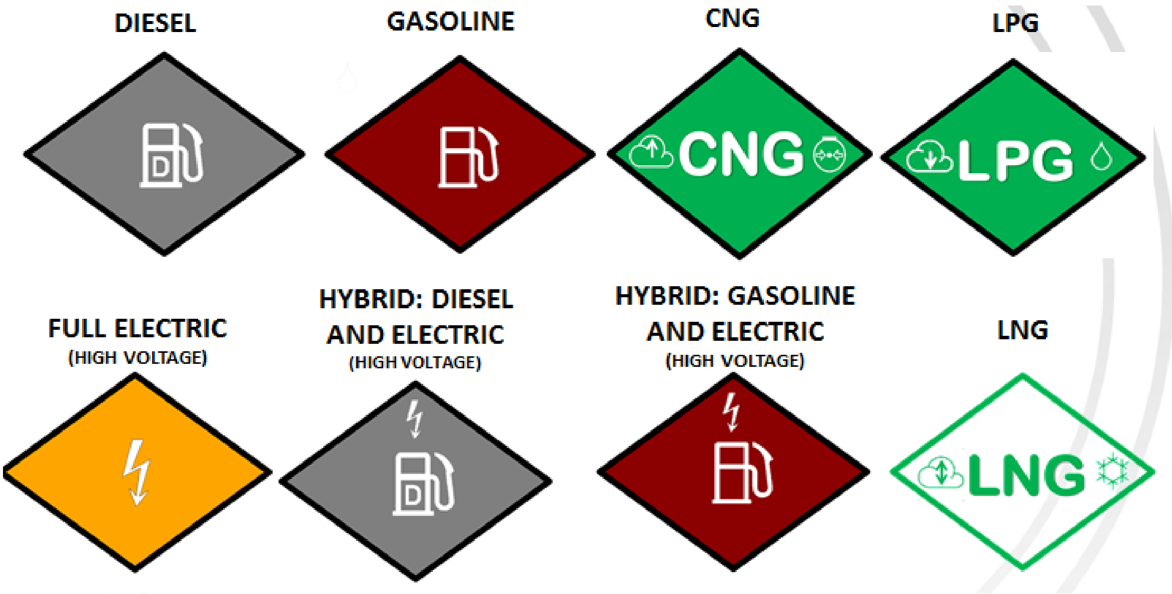


Figure 11. Symbols developed by CTIF for different types of vehicle fuels/energies [38].

Please note that in USA First Responders are referred to the NFPA, which instructs on using 'FORMAL' and 'INFORMAL' methods of vehicle identification [36]. One formal ID is the *decals* and graphics on many of the vehicles and buses. They contain 'FCEV', 'FC', abbreviation of phrases 'Fuel Cell' or 'Hydrogen Fuel Cell'. However, that will not be the case the closer we get to commercialization. For example, Honda FCX Clarity leased to drivers in Southern California, does not have the decals. Although, it does have the vehicle *badging* next to the make and model like on any other vehicle (Figure 12). This is as per SAE International standard [36].

Figure 12. Formal methods identification used in the US [36].

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. According to heat resistant requirements of (NF) EN 469:2006-02 material used for clothing assembly when tested at a temperature of 180 ± 5 °C for an exposure time of 5 min shall not ignite or melt and shall not shrink more than 5 % in either machine or cross direction [39]. Please note that the incident heat flux is limited to a nominal level of 80 kW/m^2.

The results of testing are expressed as Heat Transfer Index (HTI_{24}) – the time (in seconds, s) it takes for the temperature in a calorimeter to rise to 24°C. For classification of firefighting clothing, the time (in s) corresponding to a 12°C temperature rise is also recorded (HTI_{12}). The response of material to heat transfer (flame) shall achieve the level of performance indicated below [39].

Level 1	Level 2
$HTI_{24} \geq 9.0$	$HTI_{24} \geq 13.0$
$HTI_{24} - HTI_{12} \geq 3.0$	$HTI_{24} - HTI_{12} \geq 4.0$

Heat flux density of 40 kW/m^2 is used to measure the material's performance against radiative heat. Radiative Heat Transfer Indices (RHTI) are measured. The EN 469:2006 requirements are shown below:

Level 1	Level 2
$RHTI_{24} \geq 10.0$	$RHTI_{24} \geq 18.0$
$RHTI_{24} - RHTI_{12} \geq 3.0$	$RHTI_{24} - RHTI_{12} \geq 4.0$

Residual strength of the material exposed to radiant heat of 10 kW/m^2 should be ≥ 450 N [39].
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, include: 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 have to 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.

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].

Summary

This lecture provides First Responders with the valuable information on the impact of hydrogen leaks, fires and explosions on human's health and environments. It also considers the damages 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 First 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 First Responders to the labelling system, which is already in place and/or under development by CTIF. Some requirements to personal protective equipment are also addressed here.

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Annex 1. French guidance on thermal effects associated with hydrogen combustion [8].

Scenario of a pipework leak	Tank pressure (bar)	Immediate combustion (flaming leak)			Delayed combustion (fire-ball)		
		Long duration thermal effects (kW/m^2)			Short-term thermal effects		
		3 kW/m^2	5 kW/m^2	8 kW/m^2	SEI[14]	SEL[15]	SELS[15]
		The distances are in m			The distances are in m		
Hose from an articulated trailer	200	7.2	7.2	7.2	7	6.4	6.4
0.1 mm		0.2	0.2	0.2	0.4	0.4	0.4
0.2 mm		0.5	0.4	0.4	0.9	0.8	0.8
4 mm		11	9	8	17.6	16	16
0.1 mm	525	0.4	0.3	0.3	0.8	0.7	0.7
0.2 mm		0.7	0.6	0.6	1.5	1.3	1.3
2.3 mm		9	7.9	7	17	15	15
4 mm		17	15	13	29	26	26
5.16 mm		22	19	17	37	34	34
0.1 mm	450	0.2	0.2	0.2	0.7	0.6	0.6
0.2 mm		0.3	0.3	0.3	1.5	1.2	1.2
4 mm		16	14	12	27	24	24
5.16 mm		21	18	16	35	31	31
0.1 mm	700	0.2	0.2	0.2	0.8	0.8	0.8
0.2 mm		0.8	0.4	0.4	1.72	1.5	1.5
2.3 mm		10	9	8	19	18	18
4 mm		19	17	15	33	30	30

Note: SEI – irreversible effects threshold; SEL – lethal effect threshold; SELS – significant lethal effect [8].

Annex 2. French guidance on overpressure effects for delayed hydrogen combustion [8].

Scenario of a pipework leak	Tank pressure (bar)	Length of flame (m)	Delayed combustion (fire-ball)			
			Effects of over-pressure (mbar)			
			20	50 (SEI)	140 (SEL)	200 (SELS)
			The distances are in m			
Hose from an articulated trailer	200		13.1	8.2		
0.1 mm		0.2	0.5			
0.2 mm		0.4	1	0.5		
4 mm		7	20	10	6	5
0.1 mm	525	0.4	1	0.5		
0.2 mm		0.8	2	1		
2.3 mm		7	18	9	6	5
4 mm		12	32	16	9	8
5.16 mm		15	42	21	12	10
0.1 mm	450	0.3	0.8	0.4		
0.2 mm		0.7	1.4	0.7		
4 mm		11	30	15	9	7
5.16 mm		14	38	19	11	9
0.1 mm	700	0.5	1	0.5		
0.2 mm		0.8	2	1		
2.3 mm		8	22	11	6	5
4 mm		14	38	19	11	9

Note: SEI – irreversible effects threshold; SEL – lethal effect threshold; SELS – significant lethal effect [8].

Annex 3. Reference values associated with the threshold for overpressure effects [8].

Level of overpressure	20 mbar	50 mbar	140 mbar	200 mbar	300 mbar
Effects on structures	Threshold for significant destruction of windows	Threshold for slight damage to structures	Threshold for serious damage to structures	Threshold for domino effects	Threshold for very serious damage to structures
Effects on man	Threshold for indirect effects by breakage of windows on man	Threshold for irreversible effects defined by significant danger to human life	Threshold for lethal effects defined by grave danger to human life	Threshold for lethal effects defined by very grave danger to human life	