HAZARD DISTANCE NOMOGRAMS FOR A BLAST WAVE FROM A COMPRESSED HYDROGEN TANK RUPTURE IN A FIRE

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ABSTRACT

Nomograms for assessment of hazard distances from a blast wave, generated by a catastrophic rupture of stand-alone (stationary) and onboard compressed hydrogen cylinder in a fire are presented. The nomograms are easy to use hydrogen safety engineering tools. They were built using the validated and recently published analytical model. Two types of nomograms were developed – one for use by first responders and another for hydrogen safety engineers. The paper underlines the importance of an international effort to unify harm and damage criteria across different countries, as the discrepancies identified by the authors gave the expected results of different hazard distances for different criteria.

1.0 INTRODUCTION

The hazard distances from a hydrogen storage system and/or infrastructure are estimated through the presence of various threats. When exposed to a fire, a high-pressure storage vessel may possibly rupture catastrophically. The depressurisation of a container is followed by a blast and a rapidly burning hydrogen when released and mixed with air. The combusted hydrogen gas forms a fireball diameter of which may reach tens of meters. These effects produce irreversible injuries to people or even deaths as well as destruction of buildings or full demolition, leaving no possibility for evacuation or rescue.

The published methodology for blast wave decay after rupture of a compressed hydrogen vessel in a fire [1] demonstrated the effect from combusted hydrogen gas (i.e. effect from chemical energy) on a blast strength and therefore filled the knowledge gap in hydrogen safety engineering.

It was demonstrated that the technique introducing contribution of chemical energy reproduces the experimental data with the stand-alone and under-vehicle (onboard) hydrogen vessels with significantly improved agreement. The stand-alone and onboard compressed hydrogen storage applications are recognised for their practical industrial use. Thus, large stand-alone vessels are installed at hydrogen refuelling stations. Onboard storage vessels for vehicular use are installed on a variety electrically powered applications. These are fuel cell electric vehicles (FCEV) such as passenger cars, motorcycles, scooters, buses, hydrogen-powered forklifts, etc.

The developed methodology [1] was used for development of the engineering tools, i.e. nomograms. The nomograms can be used by first responders and hydrogen safety engineers. The nomograms are categorised according to the needs of the users. The nomograms of the first category can be used used by first responders on an accident scene. These tools are easy to use due to pre-selected harm criteria for people and damage criteria for buildings. Thus, a first responder can quickly identify specific hazard distances or evacuation perimeter. These nomograms allow to find the distances to such harmful to people thresholds as: “No harm”, “Injury”, and “Fatality” by picking of a tank volume and internal pressure. The second category of the tools includes nomograms as the graphical interpretation of the methodology diagrams. They are used to find the hazard distances depending on more specific knowledge in overpressures and impulses in blast waves. It allows hydrogen safety engineers to apply any national or international harm and damage criteria for assessment of hazard distances. The nomograms can be used as hydrogen safety engineering tools to assess overpressure and impulse in a blast at different distances from an initial vessel location.

The choice of different harm criteria to people (including indoor occupants, people outdoors and indirect effects, such as fragments) and damage criteria to structures is given for the convenience of nomograms users those who intend to compare the effect from selecting different harm/damage thresholds.

2.0 VULNERABILITY OF PEOPLE AND DAMAGE OF BUILDINGS DUE TO BLASTS

2.1. Harm effects to people

People can be affected directly by a blast wave, i.e. through injuring human organs sensitive to pressure, i.e. eardrums and lungs. Therefore, consequences are eardrum rupture and lung haemorrhage. Indirect effects to a human body involve displacement and possible getting fatal injuries. Thus, a human may hit the head or receive lethal fractures if the body is projected against obstacles. The said effects are applied to people outdoors. The people are more susceptible to harm when being indoors. This is due to more potential effects, such as the fragment effect, e.g. skin lacerations by flying glass, injuries from falling building parts, e.g. shattered walls and brickworks. Harm criteria give further in this study was gathered from different national and international literature, including codes, guidelines and best practices. The harm effects to people due to blast wave overpressure, ΔP, and impulse, I, are shown in Table 1.

Table 1. Effects on people from blast waves.

Effects on people	ΔP, kPa	I,kPa·s
People (unprotected) outdoors		
50% blowdown [2]	-	0.06
Lung haemorrhage threshold [2]	-	0.18
Severe lung haemorrhage [2]	-	0.36
1% serious injury from displacement [2]	-	0.37
1% fatality probability [2]	-	0.59
50% fatality probability [2]	-	0.9

Effects on people	ΔP, kPa	I,kPa·s
People (unprotected) outdoors		
Irreversible effects from “grave” danger threshold [3]	5	-
People are knocked down [4]	10.3-20	-
Fatality effects threshold from “grave danger” [3]	14	-
Eardrum rupture threshold [4]	13.8	-
Possible fatality by projection against obstacles [4]	13.8	-
1% eardrum rupture probability [5, 6] [1]	16.5	-
Maximum survivable blast overpressure [7]	17-21	-
Fatal effects from “very grave” danger threshold [3]	20	-
1% eardrum rupture [2]	23	-
1% fatality probability [7]	25-35	-
Eardrum rupture [8]–[10]	34.47	-
50% eardrum rupture probability [4]	34.5-48.3	-
15% fatality probability [7]	35	-
50% eardrum rupture probability [5], [6]	43.5	-
Internal injuries threshold [4]	48.3	-
50% fatality probability [7]	50-100	-
Lethal head injury [8–10]	55.16	-
Standing people are thrown by distance [4]	55.2-110.3	-
90% eardrum rupture probability [4]	68.9-103.4	-
Severe lung damage [8–10]	68.95	-
Lethal injury to body [8–10]	75.84	-
Lung haemorrhage threshold [4]	82.7-103.4	-
90% eardrum rupture probability [5, 6]	84	-
1% fatality probability (lung haemorrhage) [5, 6] [2]	100	-
50% eardrum rupture probability [2]	110	-
50% fatality probability (lung haemorrhage) [4]	137.9-172.4	-
50% fatality probability (lung haemorrhage) [5, 6]	140	-
99% fatality probability (lung haemorrhage) [5, 6]	200	-
90% fatality probability (lung haemorrhage) [4]	206.8-241.3	-
Instant fatalities [4]	482.6-1379	-
People indoors		
10% occupant vulnerability (wood-frame and non-reinforced masonry bldg.) [11] [3]	6.9	-
Injuries likely from broken glass and structure debris, personnel are highly protected from fatality and serious injury [11]	8.27	-
20% occupant vulnerability (non-reinforced masonry) [11]	8.62	-
40% occupant vulnerability (steel-frame bldg.) [11]	10.34-17.24	-
Injuries from secondary blast effect (e.g. debris) [11]	11.72	-

Effects on people	ΔP, kPa	I,kPa·s
People indoors		
Temporal loss of hearing / injury from secondary blast effect (structure debris / body translation); no fatality or serious injury; injuries from fragments to personnel in open [11]	15.86	-
100% vulnerability (non-reinforced masonry) [11]	20.68	-
20% fatality probability [7]	21	-
Personnel serious injury (fragments/firebrands) [11]	24.13	-
100% vulnerability (wood- & steel-frame bldg.) [11]	34.47	-
Serious injury is likely to be brought by blast, missiles, debris and translation of a body [11]	55.16	-
100% fatality probability (unprotected structures) [7]	70	-

Notes:

[1] – Selected in this study as the "Injury" threshold.

[2] – Selected in this study as the "Fatality" threshold.

[3] – Occupant vulnerability is probability of serious injury/death [12].

The "No harm" (or evacuation perimeter) was defined as the "temporary threshold shift", TTS, i.e. temporal loss of hearing [16]. Such harm to people corresponds to overpressure above 1.35 kPa and impulse above 1 Pa·s. The selected "No harm" criterion was described in more details in the relevant publication [1].

The harm thresholds divide the zone of exposure by a decaying blast wave after hydrogen tank rupture into several zones of different degree of harm. These harmful zone were adopted from the UK Health and Safety Executive [13]. During the accident, the blast wave travels outwards and covers the outlined by the above thresholds, the following areas: These zones are: Fatality, Serious injury, Slight injury and the rest – No harm zone, i.e. evacuation perimeter (please see Figure 1).

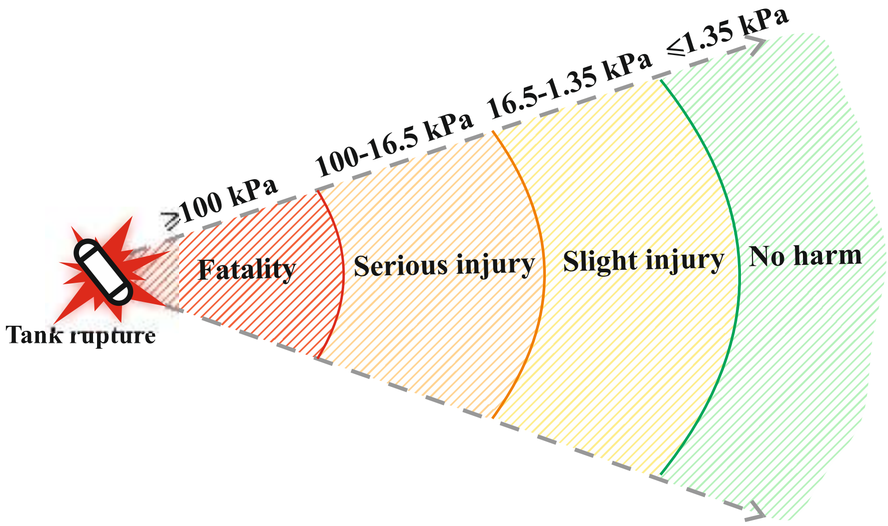

Figure 1. Graphic representation of hazard zones for people from tank rupture.

In other words, the blast wave decay over distance applied to this graph (Figure 1) would mean that overpressure 100 kPa (see the effects in Table 1) and higher will belong to Fatality area. Thus, all people trapped within this circumferential area during the tank rupture accident, will get fatal injuries due to lung haemorrhage [5, 6]. Then, overpressures under 100 kPa but outlined by threshold 16.5 kPa (1% eardrum rupture [5, 6], as per Table 1) represent the Serious injury area. The principle applies to the other areas shown in Figure 1.

2.2. Damage effects to structures

Three typical damage thresholds to buildings, such as “Minor damage”, “Partial demolition” and “Total destruction” were selected from available criteria [5] for the nomograms. Those are: Minor damage to house structures (4.8 kPa); “Partial demolition” of a house, turns inhabitable (6.9 kPa); Almost total destruction of house (lower overpressure value selected, i.e. 34.5 kPa). Table 2 shows the selection of damage criteria to structures.

Table 2. Effects on buildings from blast waves.

Building/ element	Effects	ΔP, kPa	I,kPa·s
General structures	Limited minor damage to structures [5], [15]	2.8	-
	Slight damage to structures threshold [3]	5	-
	Repairable damage to structures and facades of dwellings [12, 14]	6.9-16.55	-
	Serious damage to structures [3]	14	-
	Essential damage to structures and processing equipment [12, 14]	17.24-34.47	-

	Domino effect threshold [3]	20	-
	Very serious damage to structures threshold [3]	30	-
	Possible total destruction of building [5]	69	-
House [5, 15, 16]	Minor damage to house structures [1]	4.8	-
	Partial demolition of house, turns non-habitable [2]	6.9	-
	Partial collapse of walls and roof of house	13.8	-
	50% destruction of brickwork of house	17.3	-
	Almost total destruction of house [3]	34.5-48.3	-
Industrial building [5]	Break of cladding of light industrial building	27.6	-
Window/ glass	5% of window frame broken [5]	0.69-1.0	-
	Damage to glass, 10% of panes [12, 14]	1.03-2.07	-
	50% of window frame broken [5]	1.45-2.5	-
	Damage to glass [12, 14]	3.45-6.9	-
	90% of window frame broken [5]	3.7-6.0	-
	50% big windows (from 1.5 m^2 to 2.3 m^2) breakage [2]	-	0.021
	50% small windows (from 0.12 m2 to 0.56 m2) breakage [2]	-	0.055

Notes:

[1] – Selected in this study as the “Minor damage” threshold.

[2] – Selected in this study as the “Partial demolition” threshold.

[3] – Selected (lower value, i.e. 34.5 kPa) in this study as the “Total destruction” threshold.

The zones approach described above in Figure 1 is equivalently applied for damage criteria to structures, please see Figure 2.

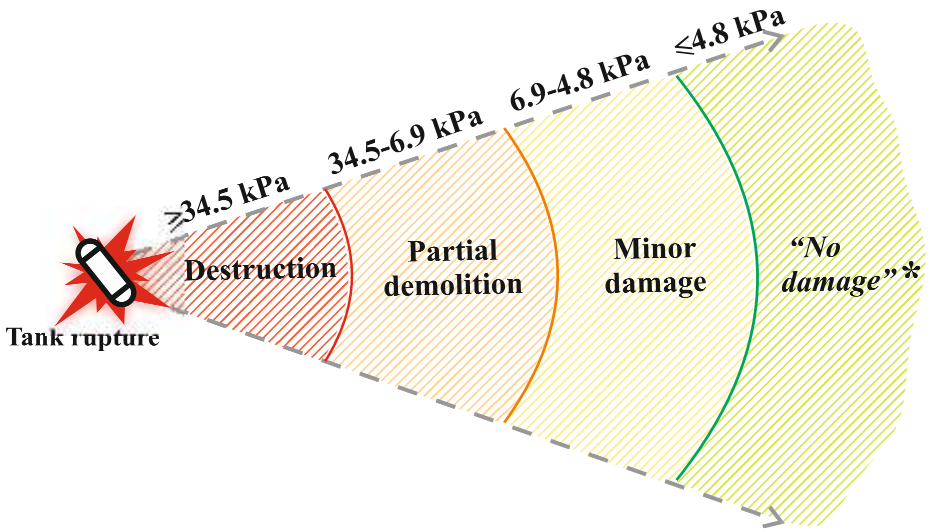

Figure 2. Graphic representation of hazard zones for buildings from tank rupture; * "no damage" – no substantial building damage, but not fully excluding the damage.

Note: * – "No damage" does not fully exclude the damage of building parts; indeed, there will be no significant building destruction when exposed to overpressures below 4.8 kPa, but a slight damage may occur, e.g. glass or window frames breakage [5]. However, the analysis of such a low damage effects is out of scope of this study.

3.0 NOMOGRAMS FOR FIRST RESPONDERS AND HYDROGEN SAFETY ENGINEERS

3.1. Blast wave decay after rupture of a stand-alone tank

In the nomograms for use by responders the vessel storage pressure is a function of a produced hazard distance. The available tank volumes range from 10 to 10,000 L and hazard distances can be found for typical storage pressures, i.e. 200 bar, 350 bar, 700 bar, 1000 bar.

A first responder working at the scene of accident can pick the hydrogen tank volume and internal pressure in the nomogram and deduce a corresponding hazard distance. The information regarding a vessel volume and operating pressure can be available through recognition of a hydrogen powered vehicle or a special signage on a vehicle, storage or infrastructure. After a hazard distance, e.g. evacuation perimeter is defined, no other actions with the tool are required.

In the nomograms the damage thresholds to structures were defined by the authors and assigned to the hazard distances. The following structural damage thresholds are: "Minor damage" (4.8 kPa [5]), "Partial demolition" (6.9 kPa [5]), and "Total destruction" (34.5 kPa [5]).

The selected harm criteria to people and damage criteria to structures were selected by the authors exceptionally from the reviewed variety of overpressure/impulse thresholds across the literature sources from different countries. The harm criteria to people were selected from the thresholds in the UK and USA sources. The damage to buldings criteria are mainly adopted from the thresholds of the UK sources. It should be noted that harm criteria in Japan are also adopted from USA and UK (HSE [16]) sources, as the authors were informed [18].

The selected overpressure/impulse (or both) thresholds and associated with them harm/damage criteria are used in this study as examples for assessment of hazard distances and building the nomograms for hydrogen safety engineers. These nomograms therefore allow for finding the distances to these pre-defined by authors criteria. The authors do not take any responsibility for defining of specific criteria to safety engineering of hydrogen systems and infrastructure. For the reader's remark, the overpressures and/or impulse of "equivalent" harm effects collected from sources from different countries diverge significantly. It shall further be highlighted in the study that making criteria consistent throughout the countries is highly desirable.

A hydrogen refuelling station may host several hydrogen storage vessels, voume of which may be quite large (e.g. 300 L each) and the storage pressure may be as high as 1000 bar. Such an example is determined in the tool below (for the stand-alone tank).

The nomograms were built using the blast wave decay methodology [1]. The methodology assumptions included positioning of the pressure vessel on a ground when the rupture happens. The mechanical energy of the compressed hydrogen gas is calculated implrementing the Abel-Noble real gas. At the moment of rupture, the model implies that the vessel wall instantaneously disappears and the starting shock (or contact pressure), as the highest overpressure in a blast, decays in the air normally. The contribution of the chemical energy (assuming combusted hydrogen in stoichiometric mixture with air) to the mechanical energy of hydrogen occurs dynamically, as the blast wave front propagates outwards. The surrounding air pressure is atmospheric and the temperatures of both, ambient air and the hydrogen in the vessel are 293 K. For the stand-alone tank problem the blast reflection from the ground and "cratering effect" were accounted for, i.e. coefficient 1.8 was applied for mechanical energy. Only 5.2% of chemical energy of hydrogen gas combusted after rupture contributed to the blast wave strength [1]. Figure 3 shows the nomogram for the stand-alone tank rupture with assessed hazard distances to people and Figure 4 shows the nomogram for the hazard distances to buildings.

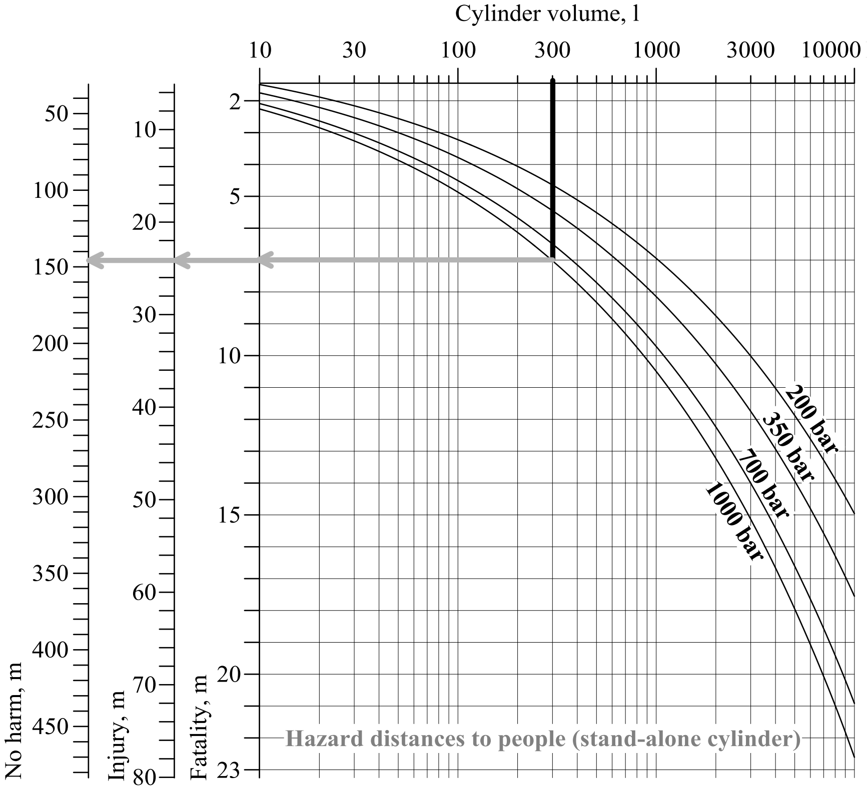

Figure 3. Nomograms for hazard distances to people from blast after stand-alone tank rupture (with the showh example of 300 L volume vessel with internal pressure 1000 bar).

These nomograms have demonstrate examples of the hydrogen storage application with the volume 300 l and storage pressure 1000 bar. The hazard distances were identified basing on thresholds described before.

The nomograms must be used as follows. A user selects the tank volume first and then draws a vertical line downwards until an intersection with the needed storage pressure curve (shown by the black bold line). Then, from that place, a horizontal line is drawn to the left (grey bold arrows) towards hazard distances axes, i.e. “Fatality”, “Injury” and “No harm”. The intersection with each axis on the left side provides the hazard distance in meters. In Figure 3 the 300 L tank with 1000 bar storage pressure results in the distance to “Fatality” 7 m (the first grey arrow drawn from the intersection with the pressure curve); the “Injury” distance is nearly 24 m; the “No harm” distance is about 145 m. The nomograms for structures is given below in Figure 4.

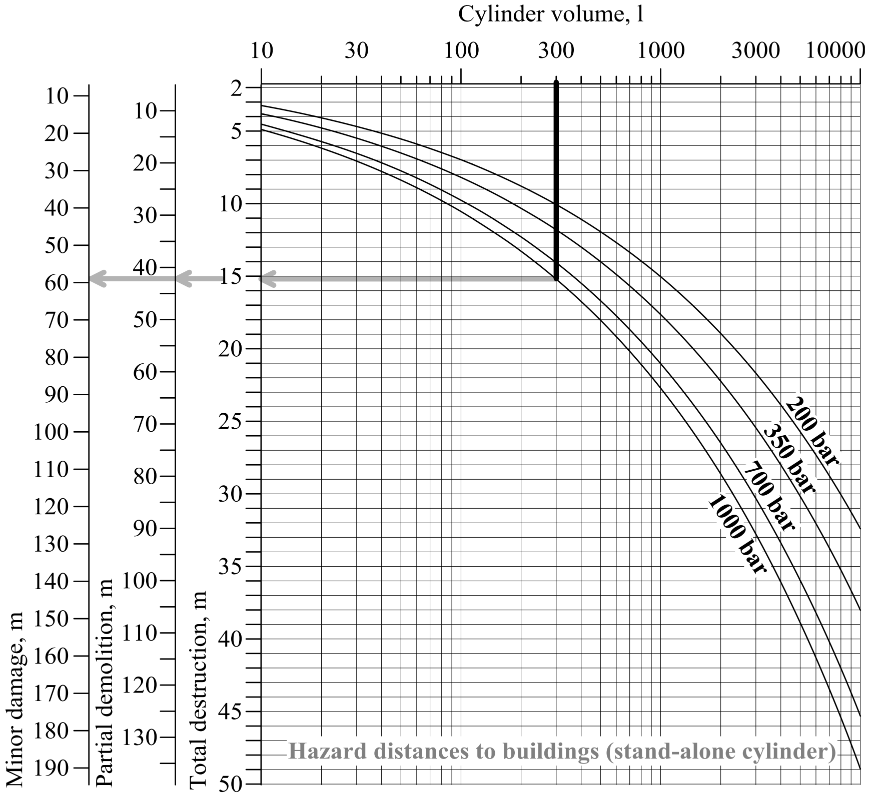

Figure 4. Nomograms for hazard distances to buildings from blast after stand-alone tank rupture (with the showh example of 300 L volume vessel with internal pressure 1000 bar).

To design the nomograms for hydrogen safety engineers, the pressure-impulse diagrams [17] were used. The nomograms provide flexibility for assessment of a required distance to harm. An overpressure and impulse are used as initial values. For the inverse problem, the hazard distance from the vessel, e.g. the "No harm" distance – the evacuation perimeter (defined by national or international regulations, codes and standards (RCS)) is applied to the nomograms for defining the harm and damage effects. The safety engineering nomograms for blast wave after rupture of a stand-alone tank are shown in Figure 5 and Figure 6 below. The overpressure and impulse of interest must be used to define a hazard distance for the particular volume and internal pressure of a vessel. Inversely, a user can select the distance from the tank position and find the corresponding overpressure and impulse values. The examples of use of the curves are shown below in Figure 5 and Figure 6.

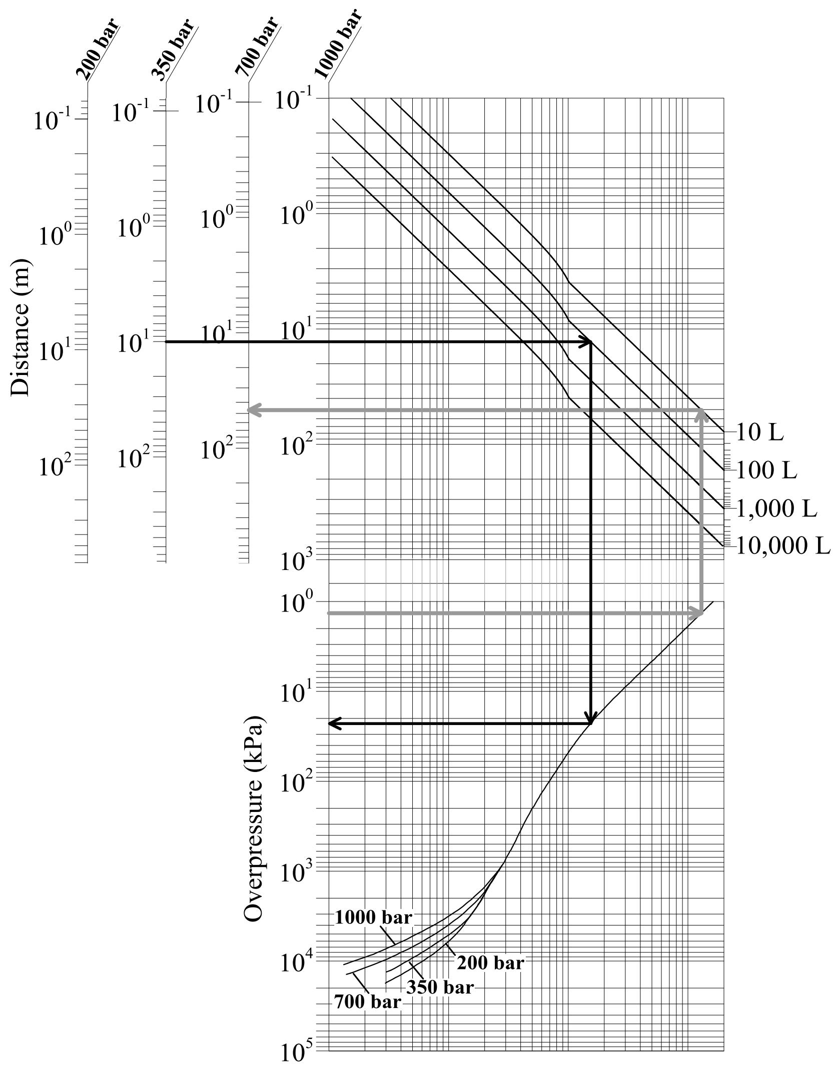

Figure 5. Nomogram for overpressure in the blast wave from a stand-alone tank rupture.

Let us consider the blast wave from rupture of the stand-alone tank of 10 L volume with 700 bar storage pressure. In order to find a hazard distance, let us firstly select the needed overpressure in a blast wave, i.e. "No harm" criterion (1.35 kPa) and draw a horizontal line (grey solid arrow in Figure 5) intersecting the storage pressure black curve. Then, the vertical line is drawn upwards and intersect the volume curve of interest (10 L), as it is shown in Figure 5 above with grey arrows. For any intermediate values of volume, e.g. 30 L, an additional curve must be plotted next to closest existing curve. The user should employ the divisions between volume curves on the right-hand side in the nomogram. Shall the volume be selected, the final horizontal line must be drawn towards left until intersection the needed storage pressure axis (pressures are given in lables on the top of vertical axes). The grey arrow shows the distance identified on the axis assigned for 700 bar storage pressure). In this case, the distance is nearly 47 m was obtained for the selected no-harm overpressure 1.35 kPa. If the selected harm criterion includes an impulse, the procedure should be performed involving additional selection of volume in a lower part of the impulse-distance graph (Figure 6).

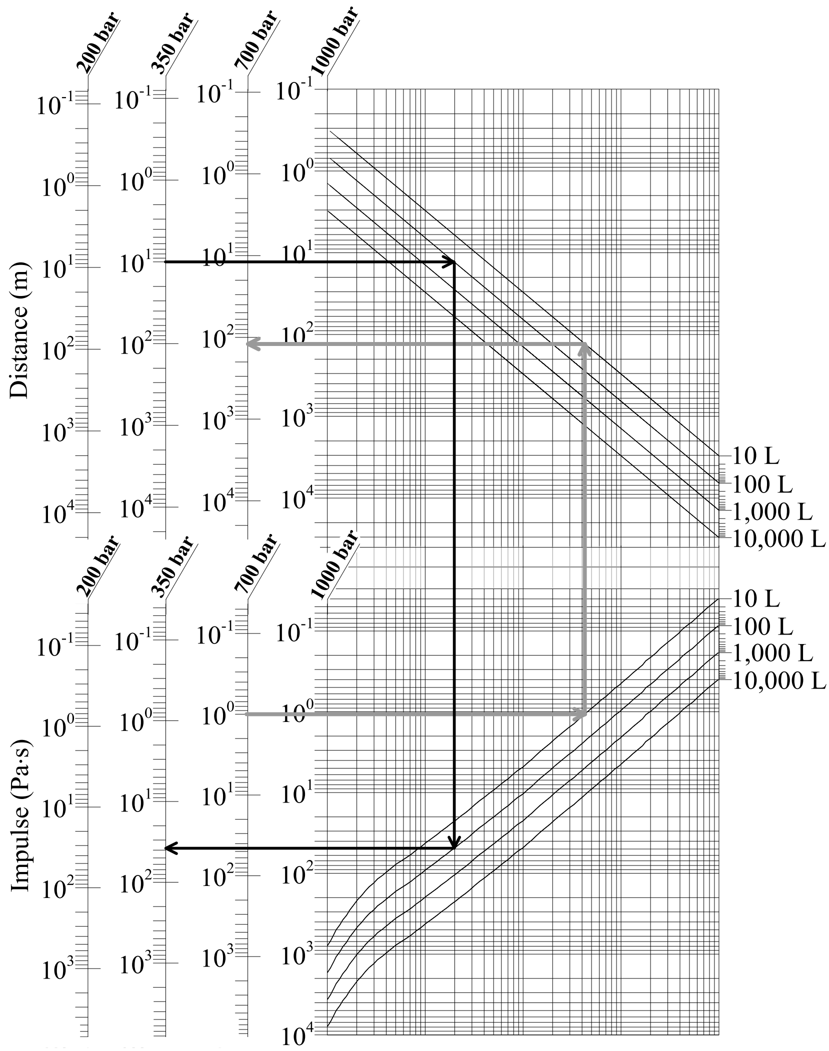

Figure 6. Nomogram for impulse in the blast wave from a stand-alone tank rupture.

To determine an overpressure and impulse at a distance of interest, the nomogram is used as it is shown with black arrows in Figure 5, i.e. for tank of 100 L and 350 bar. The nomogram user picks the internal tank pressure by selecting the corresponding axis on the left upper part of the nomogram and draw a horizontal line towards right till its intersection with the curve representing the volume of interest. Once the volume is chosen, the line is drawn downwards till its intersection with the pressure curve and then a horizontal line is drawn to the left from that intersection. The identified value of overpressure axis represents the excessive pressure in a blast wave for the tank parameters and at the distance from the tank chosen by user (nearly 23 kPa in this particular case).

It should be noted that the distances obtained in the overpressure and impulse nomograms may differ. If the harm criterion with the known overpressure and impulse is applied, the user uses both nomogams, i.e. Figure 5 and Figure 6. Then, after two distances are found, the user should picks the shortest distance for the conservatism reason. Such approach is applicable for criteria involving overpressure and impulse. For the more advanced defining pressure-impulse relationship of “No harm” criterion, the methodology [1] should be used.

3.2. Blast wave decay after rupture of an under-vehicle tank

Estimation of hazard distances to people and structures from blast waves after explosions of various onboard hydrogen storage applications was performed in the relevant study [1]. It was found that rupture of an onboard hydrogen tank produced significantly lower overpressures in a blast wave compared to a rupture of a stand-alone tank. Consequently, the shorter hazard distances were obtained compared to the distances from the blast wave after rupture of same vessel, but with stand-alone model “settings”. This difference can be explained by the spenditure of the vast amount of compressed hydrogen mechanical energy in onboard tank on the vehicle destruction and even translation of its frame by 22 meters. The estimated difference in fractions of hydrogen mechanical energy for stand-alone and onboard tanks is 15 times.

The following nomograms (see Figure 7 and Figure 8) allow for finding hazard distances from blasts generated after an onboard tank rupture. For the onboard tank problem, the fraction of compressed hydrogen mechanical energy 12% and 9% of hydrogen chemical energy were accounted, as per methodology [1]. It is shown how the hazard distances can be found in the context of analyzing the existing application released on a market recently (60 L volumetric capacity and 700 bar storage Type 4 pressure tank) [19].

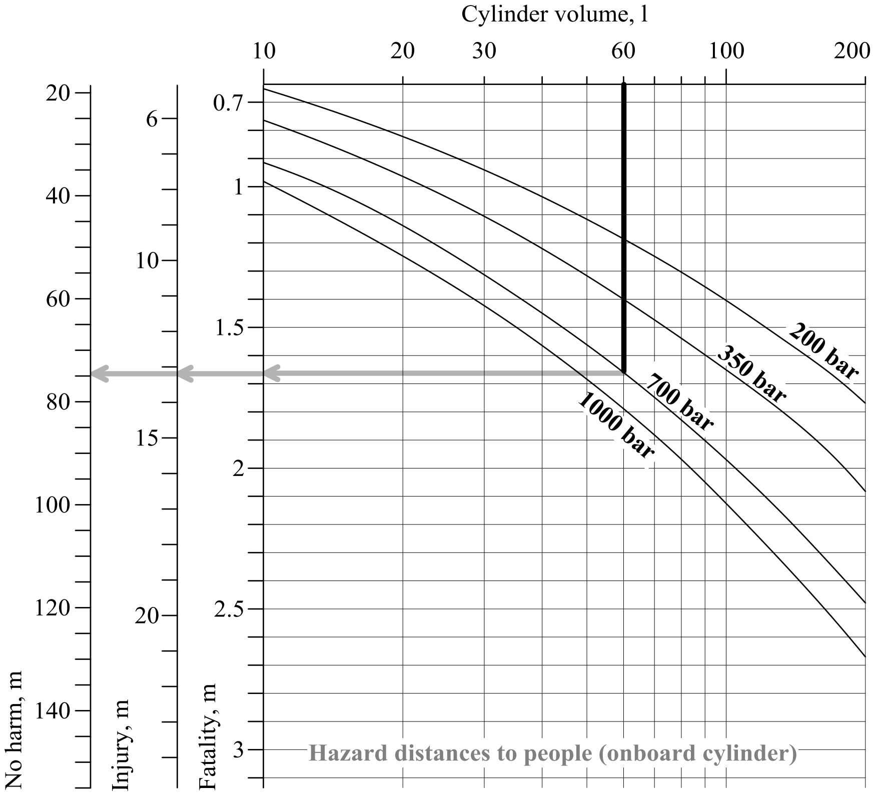

Figure 7. Nomograms for hazard distances to people from blast after onboard tank rupture (with the showh example of 60 L volume vessel with internal pressure 700 bar).

When using the nomogram above, i.e. Figure 7, the “Fatality“ distance (shown by grey arrow) would be within 1.6~1.7 m; the “Injury” distance would be ~13.2 m; the “No-harm” distance would be ~75 m. These are the found distances for the selected the onboard hydrogen storage application (volume 60 L and storage pressure 700 bar [19]), as shown with the black arrow.

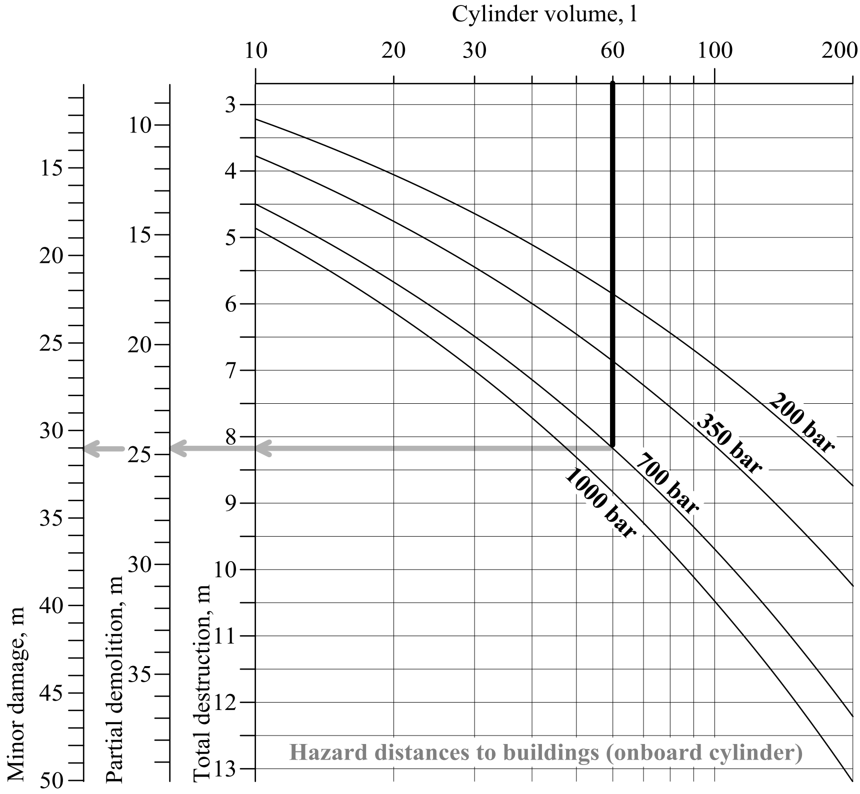

Figure 8. Nomograms for hazard distances to buildings from blast after onboard tank rupture (with the showh example of 60 L volume vessel with internal pressure 700 bar).

Figure 9 and Figure 10 represent two nomograms for determination of hazard distances and blast wave characteristics from onboard hydrogen storage tank rupture. The selected example of hydrogen storage application [19] is shown with arrows.

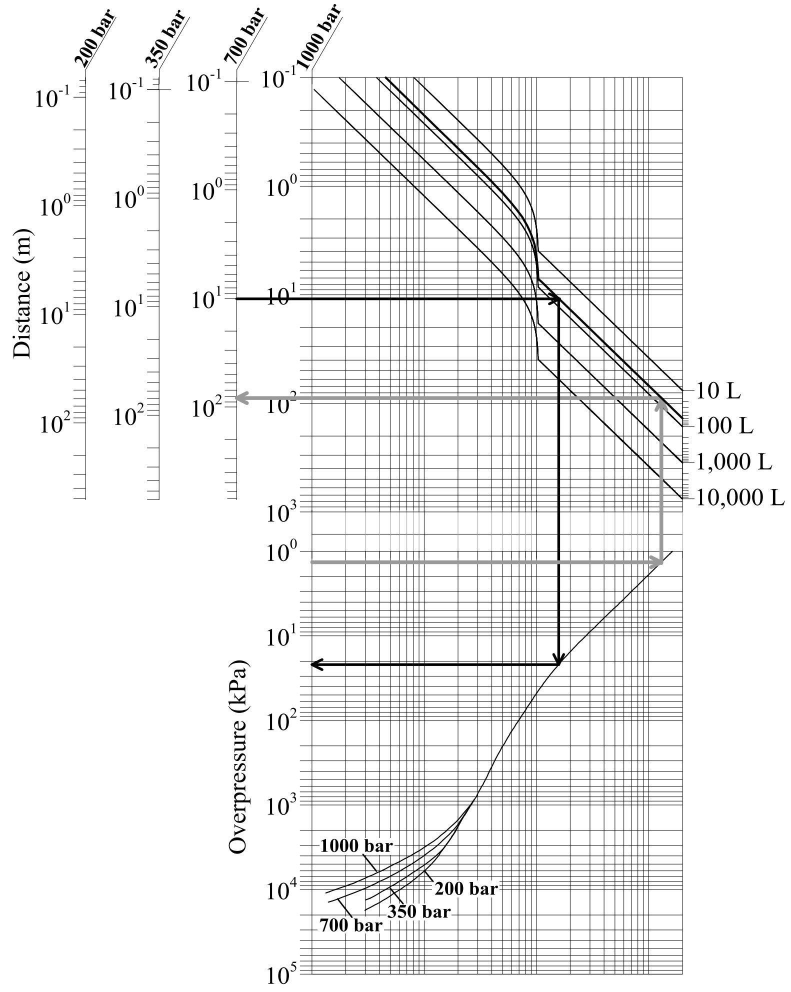

Figure 9. Nomogram for overpressure in the blast wave from an onboard tank rupture.

The example of using Figure 9 is as follows. To find an overpressure from the application under consideration, i.e. 700 bar, 60 L, the new volume curve for 60 L was drawn in Figure 9 (upper curves). It is deduced in the graph with the black arrow that the found overpressure value at the distance of 10 m is 22 kPa. To find the distance through selecting the needed overpressure at the beginning, i.e. 1.35 kPa ("No harm" threshold, or TTS [17]) draw a line intersecting with the pressure curve and then upwards to intersection with the new volume curve (for 60 L volume) in the upper part of the nomogram (as it is shown with grey arrows). Therefore, the obtained distance is about 82 m. This value somewhat differs (by 9%) from 75 m (obtained for the same tank using the nomogram in Figure 7). Still, the difference in obtained distances is below 10% error characteristic for graphical engineering tools. The equivalent procedure to use the tool is applied to the impulse nomogram, please see Figure 10.

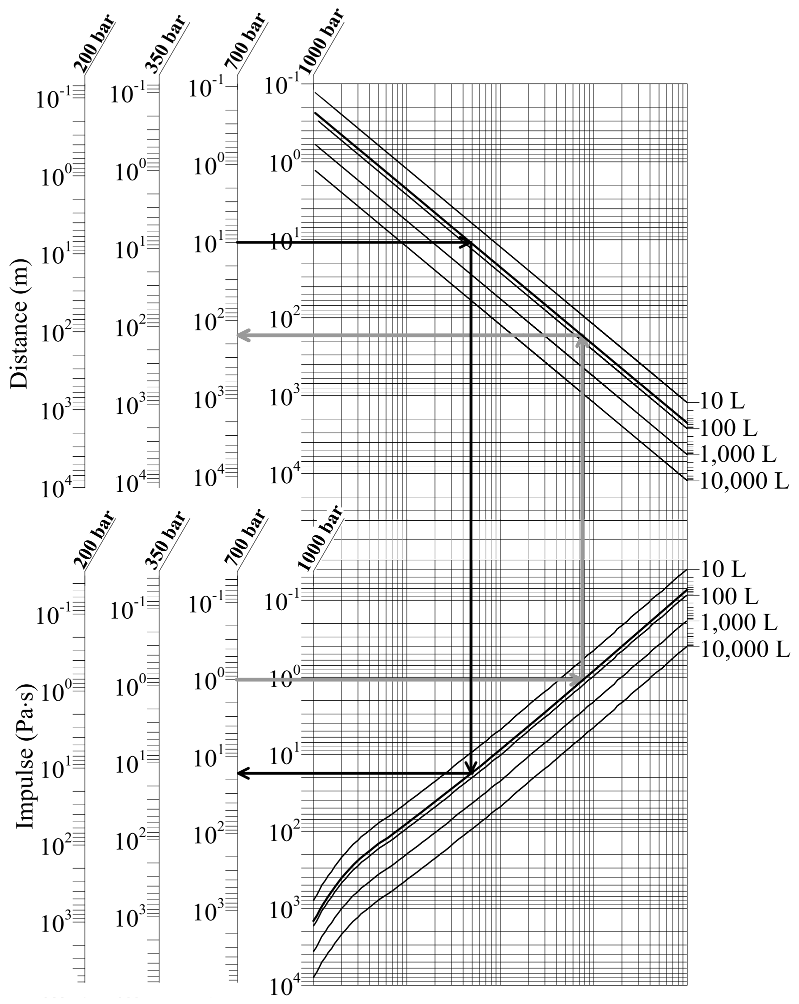

Figure 10. Nomogram for impulse in the blast wave from an onboard tank rupture.

4.0 COMPARISON OF HAZARD DISTANCES ACROSS COUNTRIES

During calculations of hazard distances to people and buildings from typical hydrogen storage applications, it was found that the harm/damage criteria even of an equivalent or a similar severity differ in pressure/impulse values significantly. The disparate limits vary depending on the country where the criteria were published.

The criteria for people from the sources of different countries were selected and categorised with regard to the severity level and the hazard distances were estimated. Table 3 shall show how the hazard distances from a blast after rupture of a stand-alone vessel at refuelling station (300 L and 1000 bar) differ.

Table 3. Hazard distances to people from blast wave after rupture of 300 L and 1000 bar stand-alone hydrogen tank.

Country	Effects	ΔP,kPa	Distance,m
Eardrum rupture			
UK [4]	Eardrum rupture threshold	13.8	27.2
USA [2]	1% eardrum rupture	23	19.3
USA [8-10]	Eardrum rupture	34.47	15.1
Fatality			
UK [4]	Possible fatality by projection against obstacles	13.8	27.2
France [3]	Fatality threshold from "grave danger"	14	26.8
USA [8-10]	Fatal head injury	55.16	10.8

The evaluation was performed using the harm criteria from the UK, France, and the USA. It can be seen from Table 3 above that UK and USA sources gave different values of the "Injury" distance. In particular, the thresholds eardrum rupture thresholds and 1% eardrum rupture probability limit were selected by the authors and accepted as equivalent or identical. Eardrum rupture threshold from the UK source [4] provides the distance 27.2 m. USA sources, in turn, result in difference between hazard distances in ~1.5 and ~2 times, i.e. 19.3 and 15.1 m respectively. The lethal thresholds from the UK, France and the USA are quite different and cannot be comparable due to the impact type, e.g. projection of body against obstacles, head injury, etc. However, Table 3 demonstrates that such criteria as in the UK (projection against obstacles) [4] and in France (fatality from "grave danger") [3] provide similar hazard distances, i.e. 27.2 m and 26.8 m (1.5% difference). The USA criterion (fatal head injury [8-10]) gives the distance that differs drastically, i.e. 10.8 m (more than twice shorter than European ones).

The damage criteria to structures were also gathered for the comparison of hazard distances. The UK and French damage criteria were selected and will be described furter in Table 4.

Table 4. Hazard distances to buildings from blast wave after rupture of 300 L and 1000 bar stand-alone hydrogen tank.

Country	Effects	ΔP,kPa	Distance,m
Minor damage to structures			
France [3]	Slight damage to structures threshold	5	56.8
UK [5,15,16]	Minor damage to house structures	4.8	59.3
Total destruction			
France [3]	Very serious damage to structures threshold	30	16.1
UK [5,15,16]	Almost total destruction of house	34.5-48.3	15-12.5

The difference in hazard distances for structures is not as large as it is for people. The "Minor damage" distances diverse by about 4% (see Table 4). The hazard distance according to criteria in Fracne is almost 57 m following the slight damage threshold [3], and UK is nearly 59 m following "Minor damage" criterion [5], [15-16].

The "Total destruction" hazard distance following the "threshold for very serious damage" [3] of France is 16.1 m. This is longer than the range of distances from 15 m down to 12.5 m by nearly a quarter, as assessed using the UK criterion "Almost total destruction of house" [5], [15-16].

5.0 CONCLUSIONS

The paper represents the developed engineering tools for determination of hazard distances from a blast wave decaying after rupture of a high-pressure hydrogen storage tank in a fire. The tools allow for assessment of hazard distances from a stand-alone tank rupture, e.g. at refuelling station, and an onboard tank rupture, e.g. fuel cell vehicle. The tools (nomograms) were built implementing the validated blast wave decay prediction model [1]. These nomograms were designed and categorised in accordance to the needs of two types of users. One type of users is the first responders, who have to deal with hydrogen vehicles and refuelling stations at the accident scene. Another type of users is the hydrogen safety engineers, who may use a deeper analysis of hazard distances and blast wave characteristics. The tools for first responders are more easy to use as they include pre-selected by the authors harm criteria for people and damage criteria for structures. These tools allow to assess three hazard distances to people and structures by selecting a hydrogen vessel volume and storage pressure only. The second category of nomograms, in turn, gives an engineer more flexibility for the more advanced choice of harm/damage thresholds, as these nomograms include all features of the methodology [1]. They allow to select and harm and damage criteria to further apply them for finding a hazard distance. This is important as criteria vary depending on countries. The latter tools are suggested for hydrogen safety engineering. They can easily provide an overpressure and an impulse in a blast wave at different locations from the accident epicentre.

The study raises the issue of the selection of harm criteria to people and damage criteria to buildings in different countries. The reason is the high dependence of hazard distances on selected thresholds. The tools' users, especially for hydrogen safety engineering, must be aware of the environment around the scene of an accident, e.g. confined space or any obstructions nearby that could affect human, to have a possibility to apply a needed harm criterion. There is a high need for international hydrogen safety community in making the harm and damage criteria consistent and unified across different countries.

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