DEVELOPMENT OF UNIFORM HARM CRITERIA FOR USE IN QUANTITATIVE RISK ANALYSIS OF THE HYDROGEN INFRASTRUCTURE

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ABSTRACT

This paper discusses the preliminary results of the *Risk Management* subtask efforts within the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) Task 19 on Hydrogen Safety to develop uniform harm criteria for use in the Quantitative Risk Assessments (QRAs) of hydrogen facilities. The IEA HIA Task 19 efforts are focused on developing guidelines and criteria for performing QRAs of hydrogen facilities. The performance of QRAs requires that the level of harm that is represented in the risk evaluation be established using deterministic models. The level of harm is a function of the type and level of hazard. The principle hazard associated with hydrogen facilities is uncontrolled accumulation of hydrogen in (semi)confined spaces and consecutive ignition. Another significant hazard is combustion of accidentally released hydrogen gas or liquid, which may or may not happen instantaneously. The primary consequences from fire hazards consist of personnel injury or facility and equipment damage due to high air temperatures, radiant heat fluxes, or direct contact with hydrogen flames. The possible consequences of explosions on humans and structures or equipment include blast wave overpressure effects, impact from fragments generated by the explosion, the collapse of buildings, and the heat effects from subsequent fire balls. A harm criterion is used to translate the consequences of an accident, evaluated from deterministic models, to a probability of harm to people, structures, or components. Different methods can be used to establish harm criteria including the use of threshold consequence levels and continuous functions that relate the level of a hazard to a probability of damage. This paper presents a survey of harm criteria that can be utilized in QRAs and makes recommendations on the criteria that should be utilized for hydrogen-related hazards.

1.0 HARM CRITERIA FOR FIRE HAZARDS

The primary consequences from fire hazards are that people, components, or structures will be exposed to flames, high air temperatures, or high heat fluxes from fires. The size, intensity, and duration of hydrogen fires are dependent upon the type of hydrogen release and the resulting accident scenario. For example, jet fires resulting from immediate ignition of hydrogen jets can result in direct flame contact or exposure to high radiant heat fluxes. Factors such as the diameter and pressure of the leak and the volume of hydrogen gas can influence the potential harm to people and equipment.

For people, harm criteria can be expressed in terms of injury or death. It is also possible to use a “no harm” criterion which limits the level of acceptable consequences to a low enough level that no injury would occur. For fires, exposures to flames or radiant heat fluxes can result in first, second, or third degree burns. In addition, high air temperatures can result in breathing difficulty and respiratory damage. The resulting level of harm is dependent upon several factors including the amount and location of exposed skin, the age of the person, the exposure time, and the speed and type of medical treatment.

A large fraction of people typically die from second or third degree burns that cover a large percentage of their body [1]. For that reason, direct flame contact (including the hot gasses released by the flame) can be conservatively assumed to result in lethality. Alternatively, burn mortality data can be used to generate a probability of a fatality. Prolonged direct flame contact can occur due to engulfment in gaseous hydrogen jet fires or liquid hydrogen pool fires. Direct flame contact can also occur from accidents involving a delayed hydrogen ignition such as a flash fire or vapor cloud explosion. For these delayed ignition accidents, a person located within the 4% envelope at the time of ignition can be assumed to be a fatality.

For people not in the flame, there is still a potential for exposure to high radiation heat fluxes for a sufficient time to result in first, second, or third degree burns. A variety of radiant heat flux levels and associated injury or damage levels are quoted in the literature. Table 1 presents a sample of cited values which could be used as harm criteria. Note that the harm level is a function of both the heat flux intensity and the period of exposure. Thus, harm from radiant heat fluxes is better expressed in terms of a thermal dose unit which combines the heat flux intensity and exposure time by the following equation:

$$\text{Thermal Dose Unit} = I^{4/3}t \qquad (1)$$

where I is the radiant heat flux in kW/m^2 and t is the exposure time in seconds. Although most thermal dose units are evaluated using the radiation intensity to the 4/3rds power, some thermal dose calculations use other values.

Table 1. Example radiant heat flux harm criteria for people [2].

Thermal Radiation Intensity (kW/m^2)	**Type of Damage**
1.6	No harm for long exposures
4 to 5	Pain for 20 second exposure; first degree burn
9.5	Second degree burn after 20 seconds
12.5 to 15	First degree burn after 10 seconds; 1% lethality in 1 minute
25	Significant injury in 10 seconds; 100% lethality in 1 minute
35 to 37.5	1% lethality in 10 seconds

Table 2 presents a range of thermal doses presented in the literature that can result in first, second, or third degree burns. As indicated in the table, the thermal dose levels are a function of whether the radiation spectrum is in the ultraviolet or infrared range. The radiation heat flux in the infrared spectrum is of most concern for generating burns. Many factors account for range of values including the type of heat source and type of animal skin used in experiments (some values are based on nuclear blast data).

Table 2. Radiation burn data [3].

Burn Severity	**Threshold Dose (kW/m2)$^{4/3}$s**	
	Ultraviolet	**Infrared**
First Degree	260-440	80-130
Second Degree	670-1100	240-730
Third Degree	1220-3100	870-2640

Thermal dose levels have also been used to define “Dangerous Dose” levels, which are usually defined as dose resulting in death to 1% of the exposed population. In addition, “LD50” values have also been specified. An LD50 is the lethal dose (LD) where 50% of exposed population would die. Table 3 presents “Dangerous Dose” and LD50 values cited in the literature for infrared radiation (no values are cited for ultraviolet radiation). Either parameter could be used as a harm criterion. However, the use of a point value is not suitable for QRAs since the consequences from analyzed accidents can result in a full spectrum of thermal doses and associated harm potential. The Health and Safety Executive

(HSE) of Great Britain has proposed the use of an LD50 of 2000 $(kW/m^2)^{4/3}s$ for offshore oil and gas facilities [3].

Table 3. Dangerous dose and LD50 thermal dose levels.

Source	**Thermal Dose $(kW/m2)^{4/3}s$ for Infrared Radiation**	
	Dangerous Dose	**LD50**
Eisenberg [4]	960	2380
Tsao & Perry [5]	420	1050
The Netherlands Organization of Applied Scientific Research (TNO) [6]	590	1460
Lees [7]	1655	3600[1]
HSE [3]	1000	2000

[1] Based on ignition of clothing at 3600 $(kW/m^2)^{4/3}s$.

Another method to express the consequences from a thermal dose is to use a probit function which translates the dose level to a probability of injury or fatality. A probit function is the inverse cumulative distribution function associated with the standard normal distribution. Probit functions are particularly useful in QRA since they can provide harm probabilities for the range of accidents included in risk assessments. Several probit functions are available to evaluate the probability of injury or fatality as a function of thermal dose. Table 4 lists available probit functions that can be used to determine the probability of a first degree or second degree burn, or a fatality from a radiation heat flux. Figure 1 shows a comparison of the four fatality probit functions. The HSE recommended values for "Dangerous Dose" and LD50 are also shown on the figure for comparison.

Table 4. Thermal dose probit functions for human response.

Probit	**Probit Equation**	**Comment**
First Degree Burn		
TNO [6]	$Y= -39.83+3.0186 \ln [V]^1$	Based on Eisenberg model but accounts for infrared radiation
Second Degree Burn		
TNO [6]	$Y= -43.14+3.0186 \ln [V]^1$	Based on Eisenberg model but accounts for infrared radiation
Fatality		
Eisenberg [4]	$Y = -38.48 + 2.56 \ln [V]^1$	Based on nuclear data from Hiroshima and Nagasaki (ultraviolet radiation)
Tsao & Perry [5]	$Y = -36.38 + 2.56 \ln [V]^1$	Eisenberg model modified to account for infrared (2.23 factor)
TNO [8]	$Y= -37.23 + 2.56 \ln [V]^1$	Tsao and Perry model modified to account for clothing (14%)
Lees [7]	$Y = -29.02 + 1.99 \ln [V']^2$	Accounts for clothing, based on porcine skin experiments using ultraviolet source to determine skin damage, uses burn mortality information

[1] $V = I^{4/3}t$ = thermal dose in $(W/m^2)^{4/3}s$.

[2] $V' = F*I^{4/3}t$ = thermal dose in $(W/m^2)^{4/3}s$ where F=0.5 for normally clothed population and 1.0 when clothing ignition occurs.

The probability of a obtaining a first or second degree burn or a fatality is evaluated using the following equation:

P(fatality) = 50*(1+(Y-5)/ABS(Y-5)+ERF(ABS(Y-5)/SQRT(2))) (2)

where Y= probit function from Table 4.

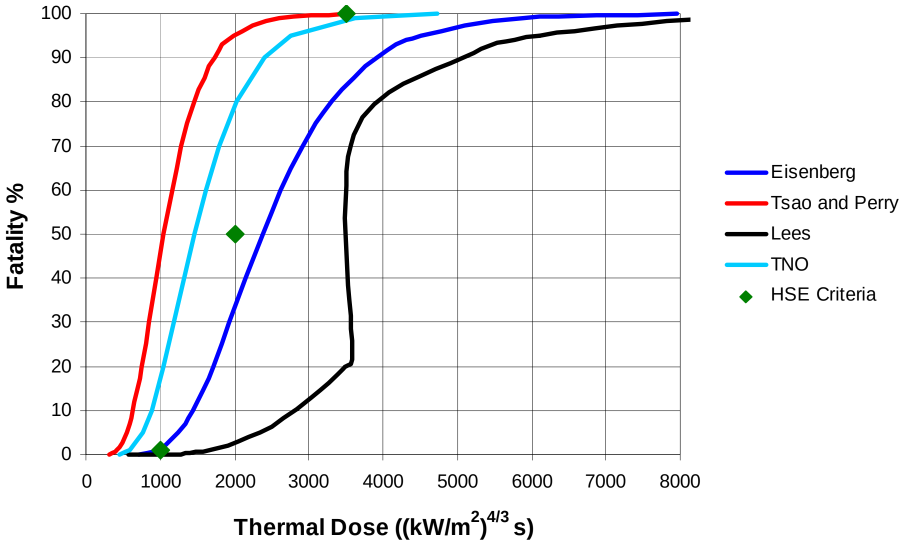

Figure 1. Comparison of thermal radiation probit functions.

It is important to consider the following points in selecting the most appropriate probit function:

1. The probit functions shown in Fig. 1 provide the probability of fatality given a thermal dose. The Tsao and Perry probit function include the infrared spectrum where the Eisenberg and Lee probit functions only include ultraviolet. Both the infrared and ultraviolet spectrums from a fire can contribute to the generated radiation heat flux. The contributions are different for hydrocarbon fires and hydrogen fires. Thus, a probit function that does not include the infrared spectrum would under predict the consequences from any fire. Thus, the Lee probit function is likely not appropriate for both hydrocarbon and hydrogen fires.

2. The Eisenberg and Tsao and Perry probit functions are both highly uncertain. The Eisenberg probit was developed from analyzing data from Hiroshima (the thermal heat radiation from a nuclear explosion is in the ultraviolet spectrum). The uncertainty associated with back-calculating the probability of fatality based on people's location versus the blast is unknown. The Tsao and Perry probit function is a modified version of the Eisenberg probit that accounts for the infrared spectrum by increasing the thermal dose by a factor of 2.23, which was determined based on measurements of both ultraviolet and infrared heat fluxes from hydrocarbon fires (twice as much ultraviolet radiation is required to produce an equivalent level of damage that would be caused by infrared radiation). Its validity for hydrogen fires is thus even more questionable than the Eisenberg probit function.

3. The combustion products from hydrocarbon fires (water and carbon dioxide) and hydrogen fires (water) emit in the infrared range. However, hydrogen fires emit less intensive infrared radiation than hydrocarbon fires (especially hydrocarbon fires that produce soot). That is one reason why one can get closer to a hydrogen fire. The differences in the emitted infrared spectrum between hydrocarbon

and hydrogen fires suggest that the Tsao and Perry probit function may be conservative when used for hydrogen fires.

4. Unlike the Eisenberg and Tsao and Perry probit functions, the TNO and Lees probit functions account for the affects of clothing. The Lees model was developed based on burn mortality data and thus takes into account age and burn area impacts. Thus, the Lees model accounts for the fact that clothing will provide a degree of protection from radiant heat fluxes. Typically the unclothed body area (the head, neck, arms, and hands) is approximately 20% of the total body area. A review of actual mortality information [10] indicates that for the 40 to 45 age group a burn area of 20% would be expected to only result in a fatality probability of 0.1 (it increases significantly for older ages). Averaged over all age groups, the probability of a fatality is approximately 0.14 when clothing is taken into account (the TNO probit uses this factor to adjust the Tsao and Perry results). However at a high heat flux, clothing will ignite resulting in burns to the covered skin. TNO has estimated that a thermal dose of 3600 $(kW/m^2)^{4/3}s$ is required to ignite clothing [6]. Thus, a high probability of a fatality is predicted for heat fluxes in this range since it results in burns over the majority of the body. As indicated in Fig. 1, the other probit functions predict a high probability of fatality at this heat flux level indicating that the impact of clothing ignition is implicitly accounted for in those models.

Based on the above points, it appears that the use of the Tsao and Perry probit would result in conservative results for exposure to hydrogen fires. Because the Eisenberg probit does not include the infrared spectrum, it may provide lower estimates of fatalities for a hydrogen fire. However, if one accepts the HSE criteria for hydrocarbon fires, the Eisenberg probit function is likely more appropriate than the Tsao and Perry probit. This is due to the radiant fraction in the infrared spectrum from hydrogen flames being significantly less than for hydrocarbon fires. Although the Tsao & Perry probit appears to be applicable for hydrocarbon fuels, the reality is that the Eisenberg function is being applied to hydrocarbon fires. The failure to account for the infrared spectrum is countered somewhat by the improvement in medical treatment for burns that has occurred since Hiroshima. The best values for hydrogen fires is unknown and may lie somewhere between the two probit predictions, probably closer to the prediction by the Eisenberg probit function. Rather than selecting one as the preferred probit, both the Tsao and Perry and Eisenberg probit functions can be used to evaluate the uncertainty in the harm predictions from radiant heat fluxes.

The harm criteria for structures and equipment can also be expressed in terms of exposure to radiant heat flux or direct flames. Some typical heat flux values and exposure times for damage to structures and components are provided in Table 5 [2,6]. Unfortunately, no probit functions have been identified for thermal effects on structures and equipment. Thus, criteria such as exemplified in Table 5 currently will have to be used in hydrogen QRAs. However, because the exposure times required for damage is long (>30 minutes), the impact of thermal radiation from hydrogen fires on structures and equipment is not generally significant.

Table 5. Damage to structures and equipment from thermal radiation.

Thermal Radiation Intensity (kW/m^2)	**Type of Damage**
4	Glass breakage (30 minute exposure)
12.5 to 15	Piloted ignition of wood , melting of plastics (>30 minute exposure)
18 to 20	Cable insulation degrades (>30 minute exposure)
10 or 20	Ignition of fuel oil (120 or 40 seconds, respectively)
25 to 32	Unpiloted ignition of wood, steel deformation (>30 minute exposure)
35 to 37.5	Process equipment and structural damage (including storage tanks)(>30 minute exposure time)
100	Steel structure collapse (>30 minute exposure)

2.0 HARM CRITERIA FOR OVERPRESSURE HAZARDS

Overpressures created from hydrogen combustion can vary significantly based on the scenario. The least significant is a flash fire where the hydrogen is consumed rapidly as it is released thus preventing the formation of a large volume of gas. Flash fires result in very small over pressures. Vapor cloud explosions involve a large release of hydrogen outdoors that mixes with air to form a large flammable cloud before ignition occurs. The overpressure effects produced by a vapor cloud explosion can vary greatly and are determined by the speed of flame propagation. In most cases, a deflagration occurs where the flame front is subsonic and the resulting behaviour is similar to a flash fire. A detonation event involves a supersonic flame front and results in significant overpressures. The presence of turbulence in the hydrogen release, unburned gases, or externally produced due to the presence of objects can potentially result in a transition from a deflagration to a detonation event. Hydrogen releases indoors have a greater explosion potential since the released hydrogen is confined. Finally, a BLEVE involving a liquid hydrogen vessel can also result in a significant over pressure due to the rapid vaporization and expansion of the hydrogen leading to an explosive vessel failure. A BLEVE also involve a significant fireball that can provide thermal challenges to people, structures, and any combustible objects in the vicinity.

Possible effects of overpressure events on humans include both direct and indirect effects. The main direct effect is the sudden increase in pressure that occurs from the event. Significant increases in pressure can cause damage to pressure-sensitive organs such as the lungs and ears. Indirect effects include the impact from fragments and debris generated by the overpressure event, collapse of structures, and heat radiation (e.g., from the fireball generated during a vapor cloud explosion or BLEVE). Large explosions can also carry a person some distance resulting in injury from collisions with structures or from the resulting violent movement. Table 6 provides examples of the level of overpressure required to result in damage to both humans and structures.

Table 6. Damage to humans, structures, and equipment from overpressure events.

Overpressure (kPa)	**Description of Damage**
Direct Effects on People [11]	
13.8	Threshold for eardrum rupture
34.5 to 48.3	50% probability of eardrum rupture
68.9 to 103.4	90% probability of eardrum rupture
82.7 to 103.4	Threshold for lung hemorrhage
137.9 to 172.4	50% probability of fatality from lung hemorrhage
206.8 to 241.3	90% probability of fatality from lung hemorrhage
48.3	Threshold of internal injuries by blast
482.6 to 1379	Immediate blast fatalities
Indirect Effects on People [11]	
10.3 to 20.0	People knocked down by pressure wave
13.8	Possible fatality by being projected against obstacles
55.2 to 110.3	People standing up will be thrown a distance
6.9-13.8	Threshold of skin lacerations by missiles
27.6 to 34.5	50% probability of fatality from missile wounds
48.3 to 68.9	100% probability of fatality from missile wounds
Effects on Structures and Equipment [12]	
1	Threshold for glass breakage
15-20	Collapse of unreinforced concrete or cinderblock walls
20 to 30	Collapse of industrial steel frame structure
35 to 40	Displacement of pipe bridge, breakage of piping
70	Total destruction of buildings; heavy machinery damaged
50 to 100	Displacement of cylindrical storage tank, failure of pipes

A review of the information in Table 6 suggests that indirect effects from overpressure events represent the most important concern for people. The overpressures required to cause fatal lung damage are significantly higher than the values required to throw a person against obstacles or to generate missiles that can penetrate the skin. In addition, a person inside a structure would more likely be killed by the facility collapse than from lung damage.

Although harm criteria can be extracted from information such as that presented in Table 6, it is more desirable in QRA to use models that provide a probability of damage or harm as a function of the peak overpressure and/or the associated impulse. Fortunately, there are probit functions available to predict the level of harm to people and structures from the impact of blast overpressures and flying debris. Some notable probit functions are provided in Table 7. Equation 2 is used to generate the required harm probabilities using the probit values generated from these models.

Table 7. Probit functions for damage caused by overpressure hazards.

Probit	**Probit Equation**	**Application**
Human Fatality		
Eisenberg [13]	$Y = -77.1 + 6.91 \ln [P_s]$[a]	Death due to lung hemorrhage
HSE [14]	$Y = 1.47 + 1.371 \ln [P_s]$[a]	Death due to lung hemorrhage
TNO [6]	$Y = 5 - 5.74 \ln [4.2\ P_o/P_{ef} + 1.3/i_{sc}]$[b]	Death due to lung hemorrhage
TNO [6]	$Y = 5 - 8.49 \ln [2430/P_s + 4x10^8/P_s i]$[c]	Death due to head impact
TNO [6]	$Y = 5 - 2.44 \ln [7380/P_s + 1.3x10^9/P_s i]$[c]	Death due to whole body impact
TNO [6]	$Y = -13.19 + 10.54 \ln [v_o]$[d]	Death due to fragments greater than 4.5 kg
TNO [6]	$Y = -17.56 + 5.3 \ln[S]$[e]	Death due to fragment masses of 0.1 to 4.5 kg
TNO [6]	$Y = -29.15 +2.1 \ln[S']$[f]	Death due to fragments masses of 0.001 to 0.1 kg
Structure Failure		
Eisenberg [13]	$Y = -23.8 + 2.92 \ln [P_s]$[a]	Total damage
TNO [6]	$Y = 5 - 0.26 \ln[V]$[g]	Minor damage
TNO [6]	$Y = 5 - 0.26 \ln[V']$[h]	Major damage
TNO [6]	$Y = 5 - 0.22 \ln[V'']$[i]	Collapse

[a] P_s = peak overpressure in Pa

[b] P_o = atmospheric pressure in Pa, $i_{sc} = i/(P_o^{1/2} *m^{1/3})$, m = mass of person in kg, $P_{ef} = P_s + 5*P_s^2/(2*P_s + 1.4x10^6)$, and P_s = peak overpressure in Pa

[c] P_s = peak overpressure in Pa, i = impulse of the shock wave (Pa*s)

[d] v_o = debris velocity in m/s

[e] $S = 0.5*m*v_o^2$, m = debris mass in kg, v_o = debris velocity in m/s

[f] $S' = m*v_o^{5.115}$, m = debris mass in kg, v_o = debris velocity in m/s

[g] $V = (4600/P_s)^{3..9} + (110/i)^{5.0}$, P_s = peak overpressure in Pa, i = impulse of the shock wave (Pa*s)

[h] $V = (17500/P_s)^{8.4} + (290/i)^{9..3}$, P_s = peak overpressure in Pa, i = impulse of the shock wave (Pa*s)

[i] $V = (40000/P_s)^{7.4} + (460/i)^{11..3}$, P_s = peak overpressure in Pa, i = impulse of the shock wave (Pa*s)

Figure 2 provides a comparison of the probabilities of a fatality based on the probit functions listed in Table 7. Unfortunately the results from the TNO fragment probit functions can not be included in the comparison as they are a function of fragment velocity and not peak overpressure. The values generated using the remaining TNO probit functions all assumed an overpressure pulse lasting 70 ms. As indicated in the figure, the HSE model provides the most conservative results for low peak overpressures but provides lower probabilities than the Eisenberg model at higher overpressures. The Eisenberg model predicts results that are in general agreement with lung hemorrhage information in Table 6. The TNO lung model predicts lower probabilities for the assumed pulse duration.

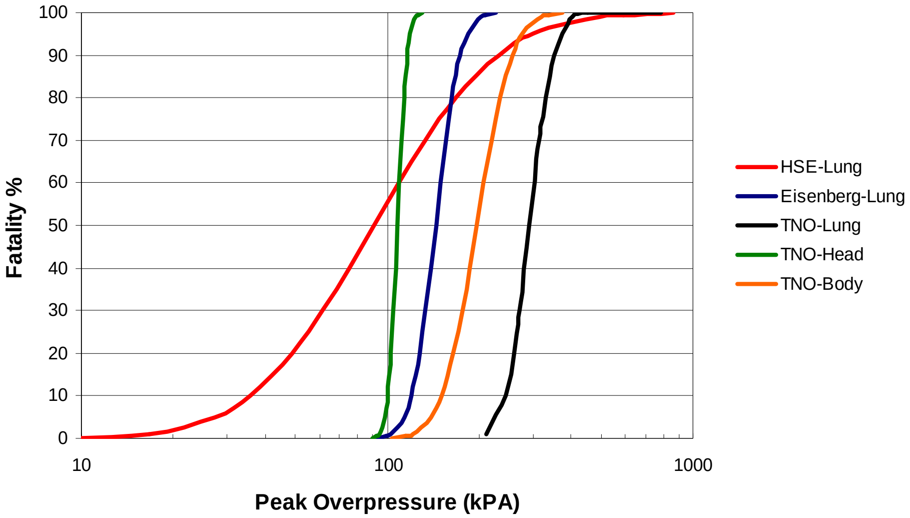

Figure 2. Comparison of overpressure probit functions for harm to people.

As previously discussed, the information in Table 6 suggests that higher fatality probabilities for a given overpressure should occur from indirect effects such as from head or whole body impacts against obstacles. This fact is reflected in the predictions in Fig. 3 for the TNO probit functions (calculated using a pressure pulse duration of 7 ms) which show that the probabilities for fatalities from structural collapse (assumed to result in a fatality) and head and whole body impacts are greater than for lung hemorrhages. Based on the information in Table 6, it is also likely that the contribution from fragments is greater than the lung hemorrhage contribution. This creates a dilemma on what probit or combinations of probit functions should be used to evaluate the probability of a fatality. Based on the results in Fig. 3, a person inside a structure would likely be a fatality from the structural collapse. The contributions from the other injury modes shown in Fig. 3 to the probability of a fatality would be negligible for a peak overpressure associated with a hydrogen explosion. If the person was located outdoors, the dominant injury mode would be from a head impact and again the other injury modes could be neglected. Thus, in a QRA one would use different models for people located indoors and outdoors. In both situations, the impact from fragments would have to be evaluated to determine its importance, though in most cases missiles would be of less importance for people located indoors. Note however that if the HSE or Eisenberg lung hemorrhage probit functions are selected, there can be contributions from multiple injury modes (see Fig. 2). In this situation, the contributions from each injury mode must be calculated and combined in such a way that the total probability of a fatality does not exceed 1.0.

Figure 4 provides a comparison of the structural failure probit functions presented in Table 7. The Eisenberg probit provides results that agree reasonably well with the data presented in Table 6. The TNO probit functions, which were evaluated assuming a 7 ms pressure pulse, provide lower damage amounts. However, higher percentages of damage would be predicted by the TNO models if the blast pulse is longer and thus the TNO probit functions could in some situations provide similar results to the Eisenberg probit.

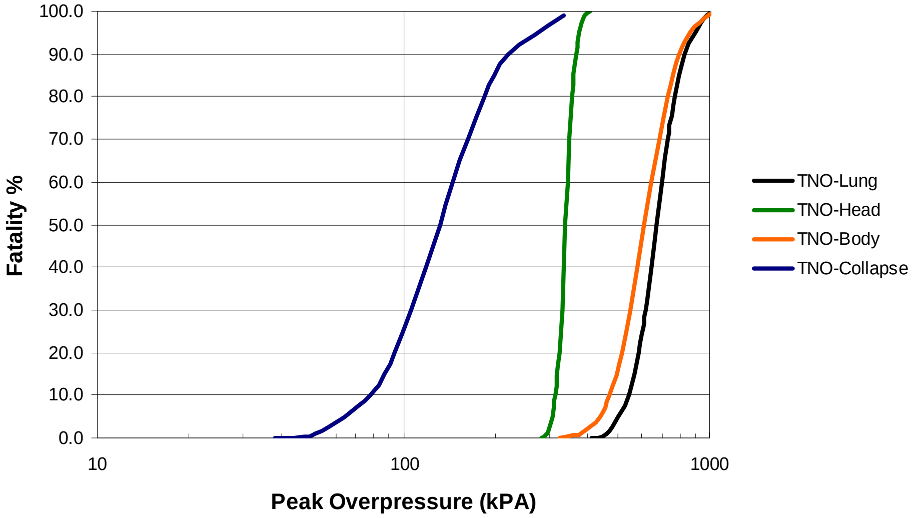

Figure 3. Comparison of TNO overpressure probit functions for harm to people.

Based on the need to evaluate probabilities of harm from overpressure events in a consistent fashion, the TNO overpressure probit functions for structural collapse, head impacts, and fragment impacts are recommended for use in hydrogen QRAs. With the exception of the fragment probit functions, all the TNO probits consistently use both the peak overpressure and the pressure impulse to evaluate the probability of harm to people or structures. These parameters are readily obtainable from deterministic explosion models. To include the harm from fragments in a QRA evaluation, additional work will be required to determine the velocity and size of generated fragments for important scenarios.

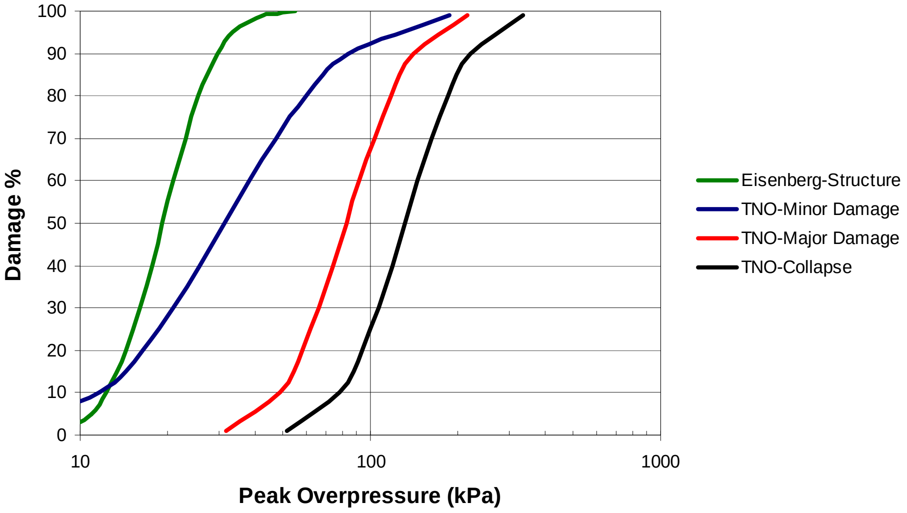

Figure 4. Comparison of structural damage probit functions.

3.0 SUMMARY OF RECOMMENDATIONS

The members of the IEA HIA Task 19 on Hydrogen Safety are developing uniform harm criteria for use in the QRAs of hydrogen facilities. This is part of the broader IEA HIA Task 19 efforts to develop guidelines and criteria for performing QRAs of hydrogen facilities. The performance of QRAs requires that the level of harm that is represented in the risk evaluation be established. A harm criterion is used to translate the consequences of an accident to a probability of harm to people, structures, or components. This paper presents a survey of different methods can be used to establish harm criteria and makes recommendations on the criteria that should be utilized for hydrogen-related hazards.

The level of harm is a function of the type and level of hazard. The focus of the survey to date has been on the principle hazards associated with hydrogen facilities which are related to uncontrolled accumulation of hydrogen in (semi)confined spaces with consecutive ignition and combustion of accidentally released hydrogen gas or liquid. The primary consequences from fire hazards consist of personnel injury or facility and equipment damage due to high air temperatures, radiant heat fluxes, or direct contact with hydrogen flames. The possible consequences of explosions on humans and structures or equipment include blast wave overpressure effects, impact from fragments generated by the explosion, the collapse of buildings, and the heat effects from subsequent fire balls. Harm criteria have been identified for each of these hazards. Other hydrogen-related hazards such as asphyxiation and cryogenic burns are also possible but are generally of secondary importance compared to hydrogen combustion and were not addressed in this paper.

For fires, exposures to flames or radiant heat fluxes can result in first, second, or third degree burns. In addition, high air temperatures can result in breathing difficulty and respiratory damage. The resulting level of harm is dependent upon several factors including the amount and location of exposed skin, the age of the person, the exposure time, and the speed and type of medical treatment. Available burn mortality data indicates that a large fraction of people typically die from second or third degree burns that cover a large percentage of their body. For that reason, direct flame contact (including the hot gasses released by the flame) during any type of hydrogen accident can be conservatively assumed to result in lethality.

For people not in the flame, there is still a potential for exposure to high radiation heat fluxes for a sufficient time to result in first, second, or third degree burns. The harm level is a function of both the heat flux intensity and the period of exposure. Thus, harm from radiant heat fluxes is best expressed in terms of a thermal dose unit which combines the heat flux intensity and exposure time. Thermal dose levels have been used to define “Dangerous Dose” levels, which are usually defined as the dose resulting in death to 1% of the exposed population, or “LD50” values which specify the lethal dose (LD) where 50% of exposed population would die. Although either of these parameters could be used as a harm criterion, the use of a point value is not suitable for QRAs since the consequences from analyzed accidents can result in a full spectrum of thermal doses and associated harm potential. Thus, the use of probit functions is recommended to evaluate the harm from radiant heat fluxes.

A probit function translates a thermal dose level to a probability of injury or fatality. Probit functions are particularly useful in QRA since they can provide harm probabilities for the range of accidents included in risk assessments. Several probit functions are available to evaluate the probability of injury or fatality as a function of thermal dose. Unfortunately, there is no probit function that has been generated specifically for hydrogen fires. Therefore, the advantages and disadvantages of the available probit functions were evaluated with respect to their use for hydrogen scenarios. Based on this evaluation, the Eisenberg probit function is likely the most appropriate probit function. However, use of both the Tsao and Perry and Eisenberg probit functions is recommended in order to evaluate the uncertainty in the harm predictions from radiant heat fluxes.

The harm criteria for structures and equipment can also be expressed in terms of exposure to radiant heat flux or direct flames. Some typical heat flux values and exposure times for structures and components are available in the literature and have been cited in this paper. Most of the information indicates that the exposure times required for damage is long (>30 minutes). Thus, the impact of thermal heat fluxes from hydrogen fires on structures and equipment is generally not significant for the expected duration of a hydrogen fire and is of secondary importance to a QRA.

Overpressures created from hydrogen combustion can vary significantly based on the scenario. Possible effects of overpressure events on humans include both direct and indirect effects. The main direct effect is that sudden increases in pressure can cause damage to pressure-sensitive organs such as the lungs and ears. Indirect effects include the impact from fragments and debris generated by the overpressure event, collapse of structures, and heat radiation. Large explosions can also carry a person some distance resulting in injury from collisions with structures or from the resulting violent movement. A review of actual damage information suggests that indirect effects from overpressure events represent the most important concern for people. The overpressures required to cause fatal lung damage are significantly higher than the values required to throw a person against obstacles or to generate missiles that can penetrate the skin. In addition, a person inside a structure would more likely be killed by the facility collapse than from lung damage.

As with the harm from radiant heat flux, it is desirable in QRA to use models that provide a probability of damage or harm as a function of the peak overpressure and/or the associated impulse. Fortunately, there are probit functions available to predict the level of harm to people from both direct and indirect effects. The potential for fatalities from both direct and indirect effects must be evaluated using a consistent approach and combined when needed. Based on this need, the TNO overpressure probit functions for structural collapse, head impacts, and fragment impacts are recommended for use in hydrogen QRAs. With the exception of the fragment probit functions, all the TNO probits consistently use both the peak overpressure and the pressure impulse to evaluate the probability of harm to people or structures. These parameters are readily obtainable from deterministic explosion models. To include the harm from fragments in a QRA evaluation, additional work will be required to determine the velocity and size of generated missiles for important scenarios.

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