

# OGP

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## Risk Assessment Data Directory

*Report No. 434 – 14.1*

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## Vulnerability of humans

*International Association of Oil & Gas Producers*



# Publications

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## Abbreviations:

<b>API</b>	<b>American Petroleum Institute</b>
<b>BLEVE</b>	<b>Boiling Liquid Expanding Vapour Explosion</b>
<b>BR</b>	<b>Breathing Rate</b>
<b>CIA</b>	<b>Chemical Industries Association</b>
<b>CO</b>	<b>Carbon Monoxide</b>
<b>CO<sub>2</sub></b>	<b>Carbon Dioxide</b>
<b>COHb</b>	<b>Carboxyhaemoglobin</b>
<b>CSTR</b>	<b>Continuous Stirred Tank Reactor</b>
<b>DNV</b>	<b>Det Norske Veritas</b>
<b>DTL</b>	<b>Dangerous Toxic Load</b>
<b>ERPG</b>	<b>Emergency Response Planning Guideline</b>
<b>HSE</b>	<b>(UK) Health and Safety Executive</b>
<b>IDLH</b>	<b>Immediate Danger to Life or Health</b>
<b>LC<sub>x</sub></b>	<b>Lethal concentration resulting in x% fatalities</b>
<b>LD<sub>x</sub></b>	<b>Lethal dose resulting in x% fatalities</b>
<b>LFL</b>	<b>Lower Flammable Limit</b>
<b>O<sub>2</sub></b>	<b>Oxygen</b>
<b>QRA</b>	<b>Quantitative Risk Assessment (sometimes Analysis)</b>
<b>SFPE</b>	<b>Society of Fire Protection Engineers</b>
<b>SLOD</b>	<b>Significant Likelihood of Death</b>
<b>SLOT</b>	<b>Specified Level of Toxicity</b>
<b>tdu</b>	<b>Thermal Dose Units</b>
<b>TNO</b>	<b>Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk</b>
<b>Onderzoek</b>	<b>(Netherlands Organization for Applied Scientific Research)</b>
<b>TR</b>	<b>Temporary Refuge</b>
<b>VROM</b>	<b>(Dutch) Ministerie van Volkshuisvesting, Ruimtelijke Ordening en</b>
<b>Milieubeheer</b>	

## 1.0 Scope and Definitions

### 1.1 Application

This datasheet provides information on the vulnerability of humans to the consequences of major hazard events at onshore and offshore installations, primarily those producing and/or processing hydrocarbon fluids. The focus is on fatality criteria as QRAs generally address fatality risks, however injury thresholds are also identified where appropriate. Information is presented relating both to people who are out of doors and people within buildings. The following consequences are considered:

- Fire
- Explosion
- Toxic gases
- Smoke

Information on vulnerability within a Temporary Refuge and vulnerability following entry to water (e.g. during evacuation/escape from an offshore installation) is also presented.

For onshore installations, the information presented applies both to personnel working within the installation and to third parties outside the installation boundary fence. It can therefore be used for QRAs addressing onsite and offsite risks.

The focus of this datasheet is vulnerability to the consequences described in the *Consequence Modelling* datasheet. Vulnerability to other potentially fatal events such as dropped loads and vehicle impacts are not addressed here; information on these can be found in other datasheets.

### 1.2 Definitions

- **Fatality** is used to refer to *qualitative* effect
- **Lethality** refers to the *quantitative* effect, namely the fraction/percentage of the exposed population who would suffer fatality on exposure to a given consequence level.
- **Radiation** is here always used to refer to *thermal* radiation. The effects of ionising radiation are not considered in this datasheet.
- **Probit**: a function that relates lethality to the intensity or concentration of a hazardous effect and the duration of exposure. It typically takes the form:

$$Pr = a + b \ln V$$

where: Pr = probit

a, b are constants

V = “dose”, typically:

For toxic materials:

$$V = (c^n t) \text{ where } c = \text{concentration, } n = \text{constant, } t = \text{exposure duration}$$

For thermal radiation:

$$V = (I^{4/3} t) \text{ where } I = \text{thermal radiation, } t = \text{exposure duration}$$

Lethality is related to probit as shown in Appendix I.

## 2.0 Summary of Recommended Data

The data presented in this section are set out as follows:

- Fire (engulfment, thermal radiation, and exposure of buildings): Section 2.1
- Explosion (effects of overpressure): Section 2.2
- Toxic gases (excluding smoke): Section 2.3
- Smoke: Section 2.4
- Vulnerability inside a Temporary Refuge (including smoke and unignited gas): Section 2.5
- Cold water immersion: Section 2.6

### 2.1 Fire

Depending on the duration, intensity and area of exposure, the effects of fire range from pain, through 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> degree burns, to fatality. 2<sup>nd</sup> degree burns may result in fatality in a small number of cases (1% lethality for average clothing); 3<sup>rd</sup> degree burns are likely to result in fatality (50% lethality for average clothing).

As identified in the *Consequence Modelling* datasheet, several different types of fire are potentially of concern depending on the release material and scenario:

- Flash fire
- Jet fire
- Pool fire
- Fireball/BLEVE

Humans are vulnerable to fire in the following ways:

- Engulfment by the fire
- Thermal radiation from the fire (outside the fire)
- Inside a building that is exposed to fire/radiation

The relationship between fire type and potential vulnerability can be illustrated thus as shown in Table 2.1.

**Table 2.1 Relationships between Fire Types and Potential Vulnerabilities**

Fire type	Potential Vulnerability		
	Engulfment	Radiation	Inside Building
Flash fire	✓	x	possibly
Jet fire	✓	✓	✓
Pool fire	✓	✓	✓
Fireball/BLEVE	✓	✓	possibly

### 2.1.1 Engulfment by fire

A person momentarily and only partially exposed directly to fire is most likely to suffer pain and non-fatal burns.

A person fully or substantially engulfed by fire can be considered to suffer fatality.

For the purposes of QRA, the following lethality levels are recommended:

- **100% lethality for people outdoors engulfed by a jet fire, pool fire or fireball**
- **100% lethality for members of the public outdoors engulfed by a flash fire**
- **50% to 100% lethality, depending on ease of escape, for workers wearing fire resistant clothing made from fabrics meeting the requirements of NFPA 2112 [11] or equivalent**

People indoors are considered separately in Section 2.1.3

### 2.1.2 Thermal radiation

The effects of thermal radiation depend strongly on the thermal radiation flux, the duration of exposure, the type of clothing worn, the ease of sheltering, and the individual exposed. Hence the information provided below provides guidance on the range of effects rather than exact relationships between thermal radiation and effects valid in all circumstances.

Table 2.2 summarises thermal radiation exposure effects over a range of radiation fluxes. Table 2.3 sets out thermal radiation criteria applicable to longer fire durations, i.e. to jet fires and pool fires, for which the exposure duration is more dependent on the ability to escape than on the fire duration. Figure 2.1 shows exposure times to the pain threshold and 2<sup>nd</sup> degree burns for different thermal radiation levels. ANSI/API Standard 521 [3] sets out permissible design levels for thermal radiation exposure to flares.

**Table 2.2 Thermal Radiation Exposure Effects [1]**

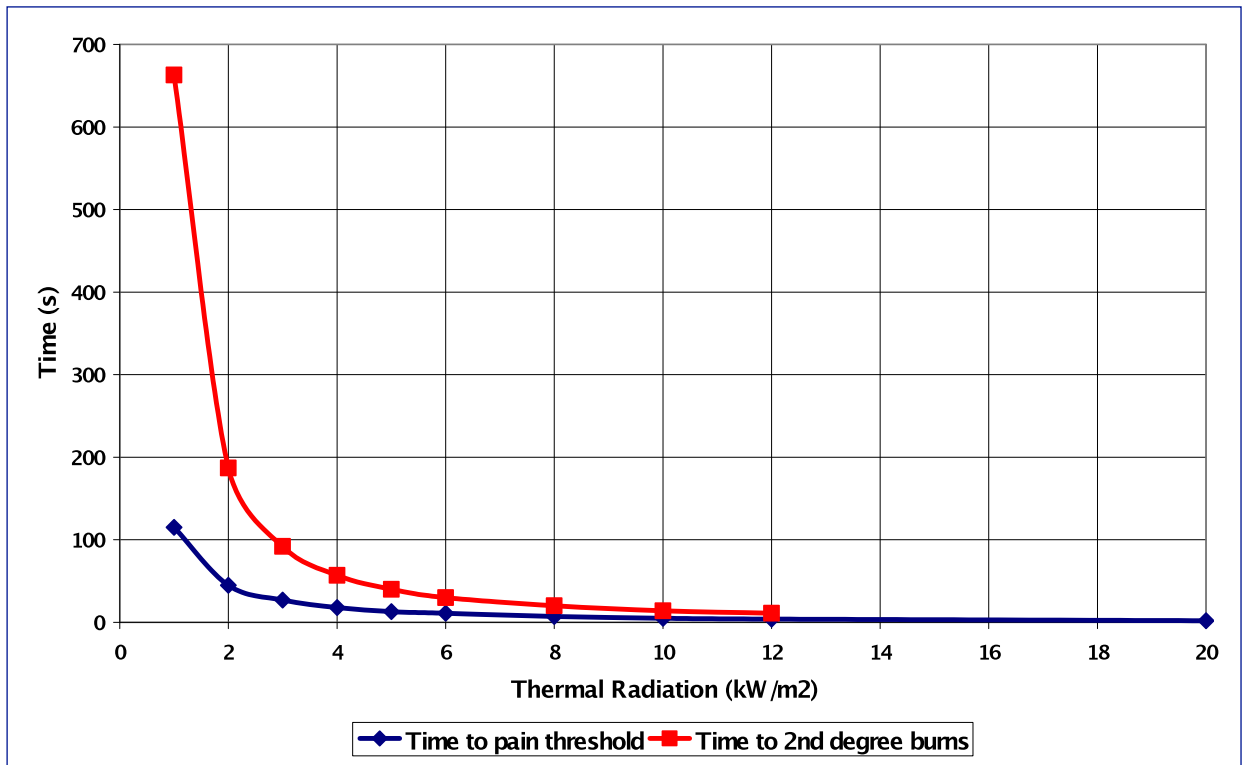
<b>Thermal Radiation (kW/m<sup>2</sup>)</b>	<b>Effect</b>
1.2	Received from the sun at noon in summer
2	Minimum to cause pain after 1 minute
Less than 5	Will cause pain in 15 to 20 seconds and injury after 30 seconds' exposure
Greater than 6	Pain within approximately 10 seconds; rapid escape only is possible
12.5	<ul style="list-style-type: none"> <li>• Significant chance of fatality for medium duration exposure.</li> <li>• Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure.</li> <li>• Wood ignites after prolonged exposure.</li> </ul>
25	<ul style="list-style-type: none"> <li>• Likely fatality for extended exposure.</li> <li>• Spontaneous ignition of wood after long exposure.</li> <li>• Unprotected steel will reach thermal stress temperatures that can cause failure.</li> </ul>
35	<ul style="list-style-type: none"> <li>• Significant chance of fatality for people exposed instantaneously.</li> <li>• Cellulosic material will pilot ignite within one minute's exposure.</li> </ul>

**Table 2.3 Thermal Radiation Criteria (use for jet/pool fires)**

Thermal Radiation (kW/m <sup>2</sup> )	Effect
35	Immediate fatality (100% lethality)
20	Incapacitation, leading to fatality unless rescue is effected quickly
12.5	Extreme pain within 20 s; movement to shelter is instinctive; fatality if escape is not possible. Outdoors/offshore: 70% lethality Indoors onshore: 30% lethality*
6	Impairment of escape routes
4	Impairment of TEMPSC embarkation areas

\* People indoors are only vulnerable if they have line-of-sight exposure to thermal radiation, hence a lower lethality than for people outdoors.

**Figure 2.1 Times to Pain Threshold and 2<sup>nd</sup> Degree Burns [2]**



For short exposures (up to a few tens of seconds, typical of fireballs), **thermal radiation dose units (tdu)** should be used:

$$\text{Dose (tdu)} = (I^{4/3})t$$

where:  $I$  = incident thermal flux ( $\text{kW/m}^2$ )

$t$  = duration of exposure (s)

Thermal dose units thus have the units  $(\text{kW/m}^2)^{4/3}\text{s}$ .

Table 2.4 sets out thermal dose criteria, which should be used for fireballs.

**Table 2.4 Thermal Dose Fatality Criteria (use for fireballs)**

<b>Thermal Dose Units ((<math>\text{kW/m}^2</math>)<sup>4/3</sup>s)</b>	<b>Effect</b>
1000	1% lethality
1800	50% lethality, members of the public
2000	50% lethality, offshore workers
3200	100% lethality

### 2.1.3 People inside buildings

Besides being vulnerable to thermal radiation if they have a direct line of sight to a jet or pool fire, people inside buildings may be vulnerable to the building catching fire if combustible building material is exposed to the fire (either to a directly impinging fire or to radiation).

Two types of ignition are recognised:

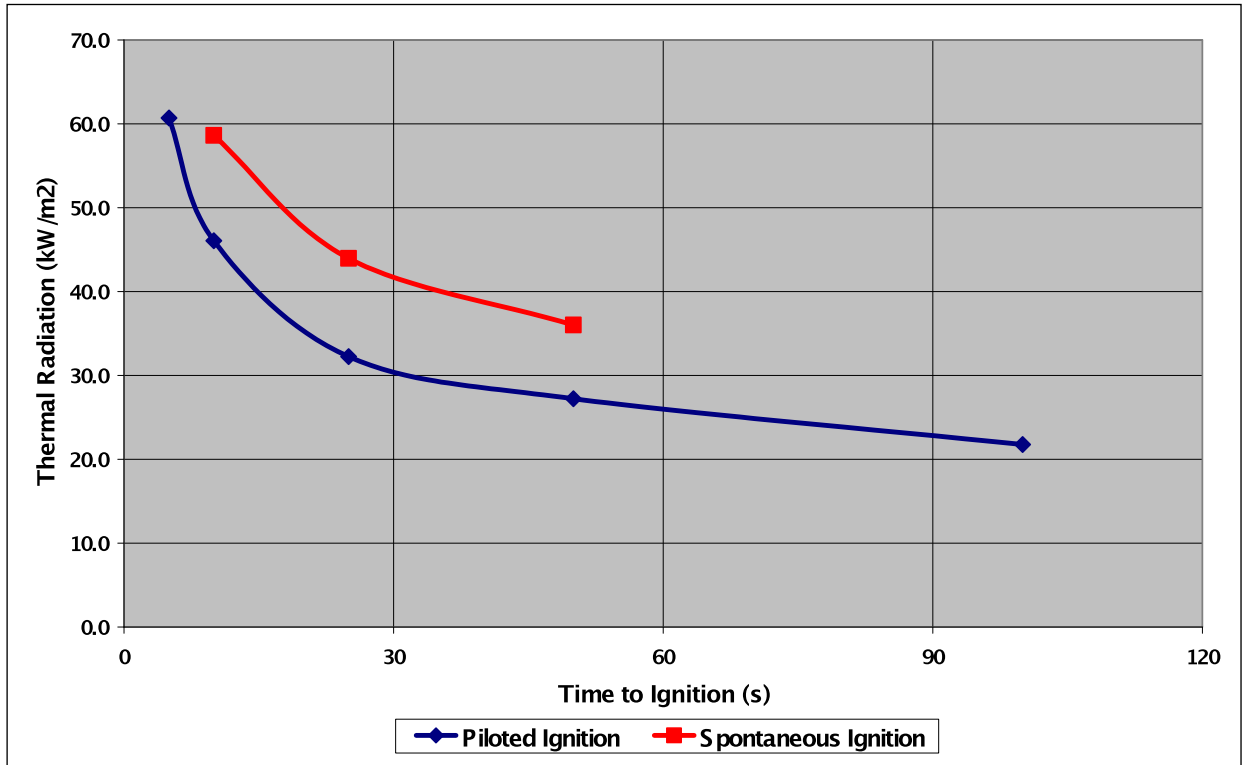
- Piloted ignition, resulting from the flame impinging directly on a surface
- Spontaneous ignition, resulting from exposure to thermal radiation from a fire

Table 2.2 indicates thermal radiation levels for ignition of wood and cellulosic material. Figure 2.2 shows, as an example, the relationship between thermal radiation and time to ignition (both piloted and spontaneous) for oak.

Personnel inside a building are vulnerable to the building catching fire if they cannot escape in sufficient time. This will depend on the time to ignition as compared to the time to alert the people inside to the source fire and evacuate them.

People inside a building are also vulnerable if escape routes are exposed to thermal radiation: in this case the criterion of  $6 \text{ kW/m}^2$  given in Table 2.3 can be applied.

**Figure 2.2 Example Times to Ignition of Oak**



## 2.2 Explosion

Explosions generate overpressures and drag forces that in turn result in damage to buildings and structures, and generate missiles (fragments of damaged structures, window glass shards, or loose objects). The effects of overpressure on humans are normally categorised as follows:

- **Direct or Primary:** injury to the body as a result of the pressure change
- **Secondary:** injury as a result of fragments or debris produced by the overpressure impacting on the body
- **Tertiary:** injury as a result of the body (especially the head) being thrown by the explosion drag and impacting on stationary objects or structures

For QRA, lethality is not typically estimated independently for these effects; instead, an overall lethality is estimated based on the combination of these effects.

Casualties requiring medical treatment from direct blast effects are typically produced by overpressures between 1.0 and 3.4 bar. However, other effects (such as secondary effects and thermal injuries) are so predominant that casualties with only direct blast injuries make up a small part of an exposed group.

For people *onshore*, outdoors and in the open, the following lethality levels are recommended:

- **0.35 bar overpressure: 15% lethality for people outdoors, in the open**
- **0.5 bar overpressure: 50% lethality for people outdoors, in the open**

For people *onshore*, outdoors but adjacent to buildings or in unprotected structures (e.g. process units), the following lethality levels are recommended:

- **0.35 bar overpressure: 30% lethality for people outdoors**
- **0.5 bar overpressure: 100% lethality for people outdoors**

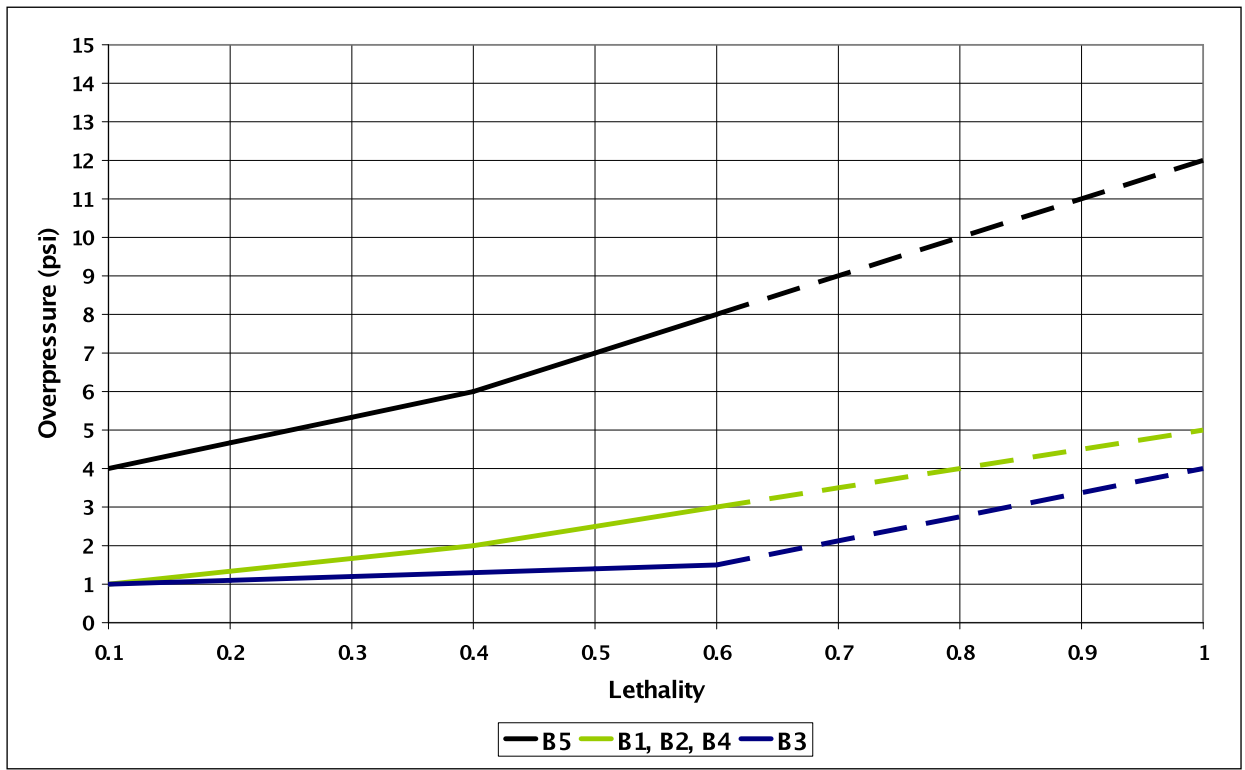
For people indoors, the lethality level depends on the building type as well as the overpressure. Two frequently used sets of relationships between lethality level and over-pressure are presented below: Figure 2.3 shows that from API RP 752 [4], Figure 2.4 that from the CIA Guidance [6]. Both differentiate between building construction types.

For personnel *offshore* in modules affected by an explosion, the following approach is suggested:

- **100% lethality for personnel in the module where the explosion occurs, if the explosion overpressure exceeds 0.2 to 0.3 barg**
- **100% lethality in adjacent modules if the intervening partition (wall or deck) is destroyed by the explosion.**

A more sophisticated approach could involve more detailed study of other explosion characteristics: overpressure phase duration and impulse. A probabilistic approach is recommended to estimate the likelihood of exceeding overpressures that could result in immediate fatality, escalation within the module, and escalation to adjacent areas.

**Figure 2.3 Overpressure – Lethality Relationships from API 752\* [4]**

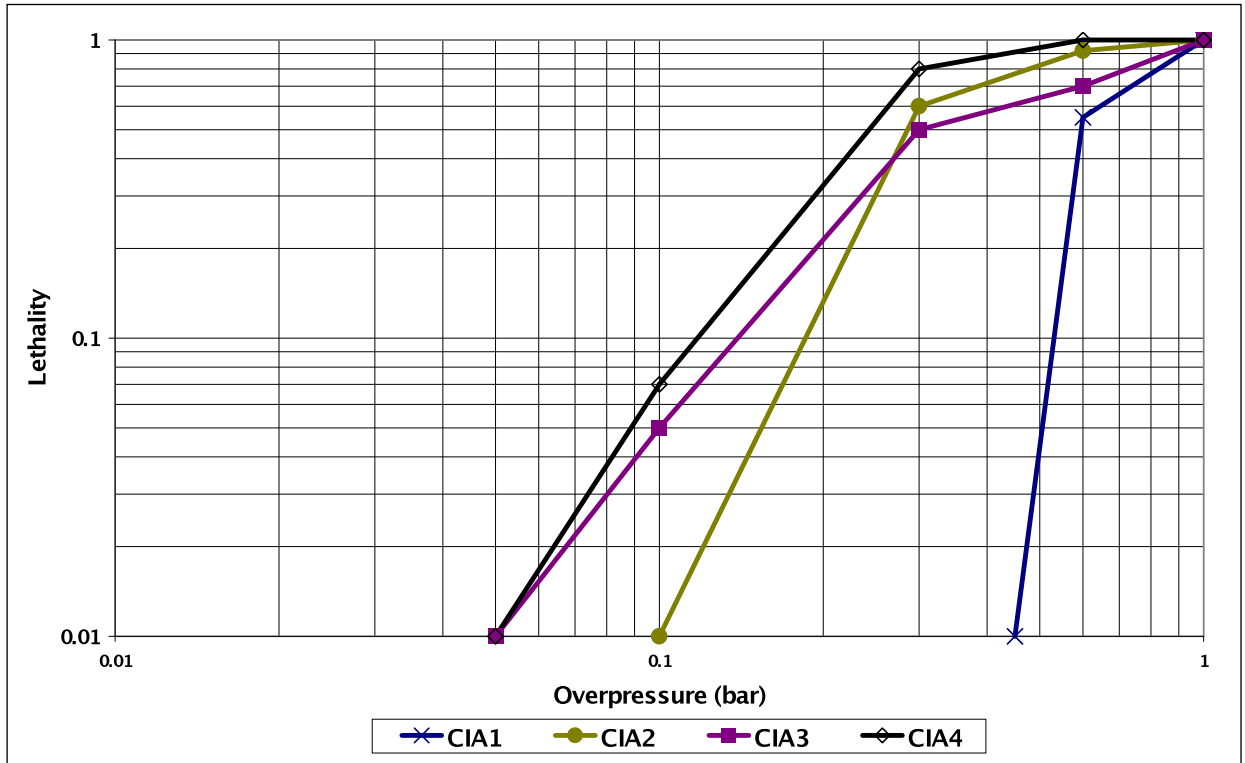


**Building Types**

- B1:** Wood-frame trailer or shack.
- B2:** Steel-frame/metal siding or pre-engineered building.
- B3:** Unreinforced masonry bearing wall building.
- B4:** Steel or concrete framed with reinforced masonry infill or cladding.
- B5:** Reinforced concrete or reinforced masonry shear wall building.

\* Note that API RP 753 [5] has superseded API RP 752 [4] with regard to locating portable buildings (building type B1). However, it does not give any overpressure-lethality relationship for such buildings, for which API RP 753 [5] should be followed rather than using the curve on the above graph.

**Figure 2.4 Overpressure – Lethality Relationships from CIA Guidance [6]**



**Building Types**

**CIA1: Hardened structure building: special construction, no windows**

**CIA2: Typical office block: four storey, concrete frame and roof, brick block wall panels**

**CIA3: Typical domestic building: two-storey, brick, walls, timber floors**

**CIA4: ‘Portacabin’ type timber construction, single storey**

**Note that the presentations of the graphs in Figure 2.3 and Figure 2.4 follow those of the original publications and no attempt has been made to convert either or both to a common set of axes.**

## 2.3 Toxic gases

### 2.3.1 General

Various approaches are used to determine the consequences of toxic gases (not including smoke, which is addressed separately in Section 2.4):

- IDLH
- ERPG
- Probit
- SLOT & SLOD DTLs

Of these, the IDLH (“Immediate Danger to Life or Health”) is the maximum concentration from which escape is possible within 30 minutes without any escape-impairing symptoms or irreversible health effects. Its use as the limiting value for the onset of fatalities has several disadvantages, chief amongst them as regards QRA is significant conservatism. IDLHs are more suitable for use as a workplace risk management tool rather than in a major accident risk assessment. In most cases, exposure to the IDLH concentration would be extremely unlikely (<< 1%) to result in fatalities.

ERPGs – Emergency Response Planning Guidelines – are precisely what their name implies, i.e. they are used (in the USA) to plan emergency response to an incident, knowing the likely ranges of health effects resulting from the incident and consequent numbers of casualties.

Neither IDLH nor ERPG values are therefore recommended for major hazard QRAs, however both are useful as indicators of the hazard effects of toxic materials.

The probit approach has been used for at least 30 years, with probit functions being developed for a wide range of toxic materials. They have been used especially, but not exclusively, in the Netherlands. They enable the lethality to be estimated for any combination of concentration and duration of exposure, including time dependent concentrations (resulting from time varying release rates). They can be used to provide fine resolution in fatality estimates, especially for third party (offsite) risks onshore, using the results of atmospheric dispersion models (see *Consequence Modelling* datasheet). Probabilities recommended below are those published by recognised bodies (TNO and the UK HSE) and used by regulators.

The SLOT and SLOD DTLs technique has been proposed and developed by the UK HSE as an alternative to the probit approach.

The SLOT (Specified Level Of Toxicity) DTL (Dangerous Toxic Load) is usually defined as the dose that results in highly susceptible people being killed and a substantial portion of the exposed population requiring medical attention and severe distress to the remainder exposed. As such it represents the dose that will result in the onset of fatality for an exposed population (commonly referred to as LD<sub>1</sub> or LD<sub>1-5</sub>).

The SLOD (Significant Likelihood of Death) DTL is defined as the dose to typically result in 50% lethality (LD<sub>50</sub>) within an exposed population and is the value typically used for group risk of death calculation onshore.

Both the SLOT and SLOD DTLs are calculated as:

$$DTL = c^n t$$

where:      c      = concentration in ppm

**t** = exposure duration in minutes

Table 2.6 gives SLOT and SLOD values, and both HSE and TNO probits, for selected toxic materials. See Section 5.0 for references to data sources for other materials.

Table 2.7 gives the resulting concentrations that give 1% and 50% lethality for 10 minutes and 30 minutes exposure. There is no clear pattern regarding whether the HSE or TNO probits indicate higher or lower concentrations for a given lethality level.

- For studies of facilities falling under the UK regulatory regime, the HSE probits or SLOT/SLOD values are recommended.
- In other regulatory regimes that have specified probits, the use of those probits is recommended.
- For all other studies, the TNO probit is recommended.

### 2.3.2 Hydrogen Sulphide

Other than toxic products from combustion of hydrocarbons (see Section 2.4) the most likely toxic gas present in oil and gas production hydrocarbon fluids is Hydrogen Sulphide (H<sub>2</sub>S). The effects likely to be experienced by humans exposed to various concentrations of H<sub>2</sub>S are described in Table 2.5.

**Table 2.5 Effects of Exposure to Hydrogen Sulphide [1]**

<b>H<sub>2</sub>S Concentration</b>	<b>Effect</b>
20 – 30 ppm	Conjunctivitis
50 ppm	Objection to light after 4 hours exposure. Lacrimation
150 - 200 ppm	Objection to light, irritation of mucous membranes, headache
200 - 400 ppm	Slight symptoms of poisoning after several hours
250 - 600 ppm	Pulmonary edema and bronchial pneumonia after prolonged exposure
500 - 1000 ppm	Painful eye irritation, vomiting.
1000 ppm	Immediate acute poisoning
1000 - 2000 ppm	Lethal after 30 to 60 minutes
> 2000 ppm	Rapidly lethal

**Table 2.6 SLOT & SLOD DTL Values and Probit Constants (concentration in ppm, duration in minutes)**

Material	HSE SLOT & SLOD			HSE Probit			TNO Probit		
	SLOT	SLOD	“n”	a	b	n	a	b	n
Ammonia	$3.78 \times 10^8$	$1.09 \times 10^9$	2	-43.24	2.32	2	-16.33	1	2
Carbon Monoxide	40125	57000	1	-67.68	6.64	1	-7.26	1	1
Chlorine	$1.08 \times 10^5$	$4.84 \times 10^5$	2	-15.33	1.55	2	-4.89	0.5	2.75
Hydrogen Sulphide	$2 \times 10^{12}$	$1.5 \times 10^{13}$	4	-30.08	1.16	4	-10.87	1	1.9
Sulphur Dioxide	$4.66 \times 10^6$	$7.45 \times 10^7$	2	-10.23	0.84	2	-16.89	1	2.4
Hydrogen Fluoride	12000	41000	1	-36.44	4.16	1	-8.70	1	1.5
Nitrogen Dioxide	96000	$6.24 \times 10^5$	2	-11.61	1.24	2	-16.26	1	3.7

**Table 2.7 Example Concentrations (ppm) to give 1% and 50% Lethality for 10 minute and 30 minute Exposures**

Material	10 minutes, 1% lethality		30 minutes, 1% lethality		10 minutes, 50% lethality		30 minutes, 50% lethality	
	HSE SLOT	TNO Probit	HSE SLOT	TNO Probit	HSE SLOD	TNO Probit	HSE SLOD	TNO Probit
Ammonia	6148	4218	3550	2435	10149	13523	5859	7808
Carbon Monoxide	4013	2063	1338	688	5700	21203	1900	7068
Chlorine	104	105	60	71	220	573	127	384
Hydrogen Sulphide	669	371	508	208	1107	1265	841	709
Sulphur Dioxide	683	1327	394	840	2729	3504	1576	2217
Hydrogen Fluoride	1200	422	400	203	4100	1996	1367	960
Nitrogen Dioxide	9600	90	3200	67	62400	168	20800	125

## 2.4 Smoke

Smoke from hydrocarbon fires contains carbon monoxide, which is toxic, and carbon dioxide, which contributes to the physiological effects of smoke in various ways. Smoke is also deficient in oxygen, hence its inhalation will result in oxygen depletion. Hence the direct effect of smoke needs to consider the combined effects of these constituents: see Section 2.4.1.

Smoke also obscures vision and hence may prevent personnel from reaching the TR or lifeboat embarkation points on an offshore installation, or muster location onshore: see Section 2.4.2.

Once personnel are mustered in the TR offshore, they continue to be vulnerable through smoke ingress to the TR; this is addressed separately in Section 2.5.

### 2.4.1 Smoke Inhalation

#### 2.4.1.1 Effects of carbon monoxide exposure

**Table 2.8 Effects of Carbon Monoxide Exposure [1]**

CO concentration	Effects
1500 ppm	Headache after 15 minutes, collapse after 30 minutes, death after 1 hour
2000 ppm	Headache after 10 minutes, collapse after 20 minutes, death after 45 minutes
3000 ppm	Maximum "safe" exposure for 5 minutes, danger of collapse in 10 minutes, danger of death in 15 to 45 minutes
6000 ppm	Headache and dizziness in 1 to 2 minutes, danger of death in 10 to 15 minutes
12800 ppm	Immediate effect, unconscious after 2 to 3 breaths, danger of death in 1 to 3 minutes

The toxicity of carbon monoxide is due to the formation of blood carboxyhaemoglobin. This results in a reduction of the supply of oxygen to critical body organs and is referred to as anaemic anoxia. The affinity of haemoglobin for CO is extremely high (over 200 times higher than O<sub>2</sub>), so that the proportion of haemoglobin in the form of carboxyhaemoglobin (COHb) increases steadily as CO is inhaled. There is little doubt that CO is the most important toxic agent formed in hydrocarbon fires because:

- It is always present in fires, often at high concentrations.
- It causes confusion and loss of consciousness, thus impairing or, preventing escape.

The rate of change (per second) of the carboxyhaemoglobin level (COHb, %) is given by:

$$\frac{dC_{COHb}}{dt} = \frac{(100 - C_{COHb})}{100} 3.37 \times 10^{-5} \times (10^4 CO)^{1.036} \times BR \times 100\%$$

where *CO* is in %, *BR* is in m<sup>3</sup>/s and is the actual breathing rate (approximately 3 × 10<sup>-3</sup> m<sup>3</sup>/s for an average individual). The cumulative effect of CO can be calculated by integrating this expression.

The actual breathing rate may exceed the nominal breathing rate because of the effects of CO<sub>2</sub> and is estimated as follows:

$$BR (actual) = \frac{\exp[0.2496 \cdot CO_2(\%) + 1.9086]}{6.8} \times BR (nominal)$$

Table 2.9 shows the effects of COHb in blood. From this table it can be concluded that COHb levels in the range 10-20% represent a range of values where there is a reduced potential of ability to escape or carry out functions requiring dexterity or conscious effort. Above 20% COHb impairment and death become more certain within a relatively short period and recovery may not be possible. It is suggested that the upper limit for survivability without significant impairment is 15% COHb with a cautious best estimate of 10% COHb to be used where exposure is followed by intense physical activity such as escape or evacuation under harsh conditions.

**Table 2.9 Effects of COHb in Blood [1]**

<b>% COHb in Blood</b>	<b>Physiological and Subjective Symptoms</b>
2.5-5	No symptoms
5-10	Visual light threshold slightly increased
10-20	Tightness across forehead and slight headache, dyspnoea on moderate exertion, occasional headache, signs of abnormal vision
20-30	Definite headache, easily fatigued, Impaired judgment, possible dizziness and dim vision, impaired manual dexterity
30-40	Severe headache with dizziness, nausea and vomiting
40-50	Headache, collapse, confusion, fainting on exertion
60-70	Unconsciousness, convulsions, respiratory failure and death
80	Rapidly fatal
80+	Immediately fatal

#### 2.4.1.2 Effects of carbon dioxide exposure

**Table 2.10 Effects of Carbon Dioxide Exposure [1]**

<b>CO<sub>2</sub> Concentration</b>	<b>Responses</b>
45 000 ppm / 4.5%	Reduced concentration capability for more than 8 hours exposure, adaptation possible
55 000 ppm / 5.5%	Breathing difficulty, headache and increased heart rate after 1 hour
65 000 ppm / 6.5%	Dizziness, and confusion after 15 minutes exposure
70 000 ppm / 7.0%	Anxiety caused by breathing difficulty, effects becoming severe after 6 minutes exposure
100 000 ppm / 10%	Approaches threshold of unconsciousness in 30 minutes
120 000 ppm / 12%	Threshold of unconsciousness reached in 5 minutes
150 000 ppm / 15%	Exposure limit 1 minutes
200 000 ppm / 20%	Unconsciousness occurs in less than 1 minute

While carbon dioxide is not considered to be particularly toxic, at levels normally observed in fires, a moderate concentration does stimulate the rate of respiration. This would be expected to cause accelerated uptake of any toxic and/or irritant gasses present during an incident involving fire and fume as breathing rate increases 50% for 20 000 ppm (2% v/v) carbon dioxide and doubles for 30 000 ppm (3% v/v) carbon dioxide in air. At 50 000 ppm (5%v/v), breathing becomes laboured and difficult for some individuals as it represents a significant level of oxygen depletion.

The effect of CO<sub>2</sub> can be expressed as the fraction,  $F_{CO_2}$ , of the incapacitating dose by integrating the following expression:

$$\frac{dF_{CO_2}}{dt} = \frac{1}{(60 \exp[6.1623 - 0.5189 \cdot CO_2])}$$

where  $CO_2$  is the concentration of CO<sub>2</sub>(%) in air, which can be estimated using the approach suggested in Section 2.5.1 of the *Consequence Modelling* datasheet.. Concentrations of less than 3% are considered to have no effect.

#### 2.4.1.3 Effects of oxygen depletion

**Table 2.11 Effects of Oxygen Depletion [1]**

<b>% Oxygen in Air</b>	<b>Symptoms</b>
21-20	Normal
18	Night vision begins to be impaired
17	Respiration volume increases, muscular coordination diminishes, attention and thinking clearly requires more effort
12 to 15	Shortness of breath, headache, dizziness, quickened pulse, effort fatigues quickly, muscular coordination for skilled movement lost
10 to 12	Nausea and vomiting, exertion impossible, paralysis of motion
6 to 8	Collapse and unconsciousness occurs
6 or below	Death in 6 to 8 minutes

Oxygen constitutes approximately 21% v/v in clean air. Oxygen concentrations below 15% by volume produce oxygen starvation (hypoxia) effects such as increased breathing, faulty judgment and rapid onset of fatigue. Concentrations below 10% cause rapid loss of judgment and comprehension followed by loss of consciousness, leading to death within a few minutes. This is taken to be the limiting oxygen concentration where escape needs only a few seconds. If escape is not possible within few seconds, incapacitation and death is assumed to occur.

The effect of oxygen depletion can be expressed as the fraction,  $F_{O_2}$ , of the incapacitating dose by integrating the following expression:

$$\frac{dF_{O_2}}{dt} = \frac{1}{(60 \exp[8.13 - 0.54(20.9 - O_2)])}$$

where  $O_2$  is the oxygen concentration (%) in air.

#### 2.4.1.4 Combined effects of carbon monoxide, carbon dioxide and oxygen depletion

The combined effect of these smoke constituents can be considered to give an incapacitating dose,  $F_{Tot}$ , calculated as follows:

$$F_{Tot} = F_{CO_2} + F_{O_2} + \frac{C_{COHb}}{0.3}$$

If  $F_{Tot} > 1.0$ , impairment is considered to result.

#### 2.4.2 Smoke Obscuration

A visibility of 4-5 m is about the threshold of diminished performance, and this is the smoke level that should be considered in smoke ventilation system design. It is suggested that there should be a minimum of 3 m vision for escape from a primary compartment and at least 10 m for an escape route.

Important factors to consider in a risk analysis with regard to obscuration of vision (and time to escape) are:

- Exposure to smoke
- Arrangements of escape ways (layout, sign, illumination, railing, etc.)
- Training of personnel
- Familiarity with the installation

Where an escape way is well laid out and provided with high visibility marking or illumination (including effective provision of torches / light-sticks), then the 3 m criterion may be applied.

Alternatively, impairment of escape ways or of the TR can be considered to occur when the particulate concentration exceeds that giving a visibility reduction of 1 dB/m. This can be estimated using the approach suggested in Section 2.5.1 of the *Consequence Modelling* datasheet.

### 2.5 Vulnerability inside a Temporary Refuge

Personnel inside a Temporary Refuge continue to be vulnerable to the consequences of an incident that has caused them to muster there. They are vulnerable to:

- Smoke ingress to the TR
- Heat build-up in the TR
- Ingress to the TR of unignited hydrocarbon gas
- Delayed explosion or structural collapse resulting in the TR being breached or otherwise ceasing to be habitable

#### 2.5.1 Smoke ingress

Smoke ingress to the TR also results in heat build-up. CO<sub>2</sub> build-up and oxygen depletion are also enhanced through respiration. Hence application of a simple model for gas build-up in the TR such as the CSTR model suggested in Section 2.5.1 of the *Consequence Modelling* datasheet will under-estimate the effects of smoke ingress.

It can be assumed that the smoke plume totally engulfs the TR at a uniform concentration. It is further assumed that any smoke that enters the TR will be rapidly and evenly dispersed around the relevant interior space.

The CO and particulates concentrations,  $Conc$ , in the TR are evaluated as:

$$\frac{dConc}{dt} = (Conc_{in} - Conc_{out})(VentRate)$$

where:  $Conc_{in}$  is the concentration of CO/particulate inside the TR  
 $Conc_{out}$  is the concentration of CO/particulates outside the TR  
 $VentRate$  is the TR ventilation rate (air changes per second)

The CO<sub>2</sub> concentration,  $Conc$ , in the TR is calculated as:

$$\frac{dConc}{dt} = (Conc_{in} - Conc_{out})(VentRate) + \frac{C \times N \times BR}{V}$$

where:  $C$  is the concentration of CO<sub>2</sub> in exhaled air, assumed to be 3%  
 $N$  is the number of persons in the TR  
 $BR$  is an average individual's breathing rate (m<sup>3</sup>/s)  
 $V$  is the TR volume (m<sup>3</sup>)

The O<sub>2</sub> concentration in the TR is calculated as:

$$\frac{dConc}{dt} = (Conc_{in} - Conc_{out})(VentRate) + \frac{P \times N \times BR}{V}$$

where  $P$  is the percentage of inhaled air that is converted from O<sub>2</sub> to CO<sub>2</sub>, usually 3%.

The initial concentrations are all taken to be zero, except O<sub>2</sub> which is taken to be 20.9%.

The internal temperature (neglecting any changes in humidity level) is calculated by integrating the following function:

$$\frac{dT}{dt} = \frac{Q_1 + Q_2}{V\rho C} + (T_{in} - T_{out})(VentRate)$$

where  $Q_1$  is the heat conducted through the TR fabric (assumed zero)  
 $Q_2$  is the heat generated by the TR occupants (350 W per person at normal temperatures)  
 and  $V\rho C$  is the heat capacity of the TR air (volume × density × specific heat).

Impairment of the TR is then taken to occur if either:

- The particulate concentration exceeds that giving a visibility reduction of 1 dB/m, or,
- The total incapacitating dose of COHb, CO<sub>2</sub>, O<sub>2</sub>, and temperature effects exceeds 1.0. The total dose  $F_{Tot}$  is calculated as:

$$F_{Tot} = F_{CO_2} + F_{O_2} + F_{Temp} + \frac{C_{COHb}}{0.3}$$

### 2.5.2 Heat build-up

Besides heat build-up through smoke ingress, the TR may also be heated by an externally impinging fire. However, on many modern installations there is at least an H60 rated firewall protecting the TR from fire. Hence, provided the integrity of the firewall is not breached (e.g. by an explosion), the TR should not be impaired solely by the effects of heat build-up due to external radiation within its expected endurance time.

### 2.5.3 Ingress of unignited hydrocarbon gas

As discussed in Section 2.5.1 of the *Consequence Modelling* datasheet, a gas concentration inside the TR exceeding 60% of LFL can be assumed to cause TR impairment.

### 2.5.4 Structural collapse

Structural collapse and/or breach of the TR is addressed in the *Structural Vulnerability* datasheet.

## 2.6 Cold Water

The survival of people immersed in cold water (e.g. as a result of escape to water from an offshore installation) depends on a range of variables:

- Environmental factors: temperature, sea state, visibility
- Clothing: survival suit, lifejacket
- Personal factors, e.g. body fat, fitness

An HSE offshore safety report [7], published in 1996 but still referenced by the HSE, presents a comprehensive discussion of the subject and a recommended approach.

## 3.0 Guidance on use of data

### 3.1 General validity

The criteria set out in Section 2.0 should be used where no equivalent criteria are specified either by the regulatory authority or by the party commissioning the QRA. They should generally be considered valid for most studies related to onshore and offshore facilities.

Where the combustion products in smoke include other toxic materials besides CO, their effects should be incorporated in the analysis, e.g. by using the probits for those materials.

### 3.2 Uncertainties

Individuals' vulnerabilities to all the potential causes of injury/fatality discussed in Section 2.0 vary widely, depending on many factors such as:

- Personal factors: physical (e.g. fitness), psychological, training
- Clothing (applies to thermal radiation, exposure to fire, cold water immersion)
- Ability to escape (e.g. ease of egress, availability of escape routes/means)
- Availability and ongoing integrity of shelter (e.g. TR)
- Availability of means of breathing assistance (applies to toxic gases and smoke)

In addition, factors such as warning time, the reliability of HVAC shutdown systems and TR fabric integrity will impact on the dose received. All of these factors should be considered for their relevance and impact when using the criteria.

### 4.0 Review of data sources

For all of the impact criteria except cold water, an HSE document [1] provides a good general summary of vulnerabilities and physical effects of the hazards discussed in Section 2.0. It draws on a range of other published studies referenced within it. This document accordingly forms the basis of the recommended data.

Supplementary references are as follows:

- Fire                      API [3]
- Explosion             API [4] (but see note below Figure 2.3), CIA [6]
- Toxic gases          Dutch “Purple Book” [8], [12]
- Smoke                 SFPE [9]
- TR                      Purser [10]
- Cold Water          HSE [7]

### 5.0 Recommended data sources for further information

HSE SLOD and SLOT values for a wide range of materials additional to those presented in Section 2.3 are given in [12]. The “Purple Book” [8] likewise gives probits for a wide range of materials.

## 6.0 References

### 6.1 References for Sections 2.0 to 4.0

- [1] HSE, 2008. *Indicative Human Vulnerability to the Hazardous Agents Present Offshore for Application in Risk Assessment of Major Accidents*, HID Semi Permanent Circular no. SPC/Tech/OSD/30, <http://www.hse.gov.uk/foi/internalops/hid/spc/spctosd30.pdf>.
- [2] FEMA, 1989. *Handbook of Chemical Hazard Analysis Procedures*, Washington, D.C: Federal Emergency Management Agency.
- [3] American Petroleum Institute (API), 2007. *Pressure-Relieving and Depressuring Systems*, ANSI/API STD 521, 5<sup>th</sup> ed., Washington, D.C: API.
- [4] American Petroleum Institute (API), 2003. *Management of Hazards Associated with Location of Process Plant Buildings*, 2<sup>nd</sup> ed., API RP 752, Washington, D.C: API.

- [5] **American Petroleum Institute (API), 2007.** *Management of Hazards Associated with Location of Process Plant Portable Buildings*, 1<sup>st</sup>. ed., **API RP 753**, Washington, D.C: API.
- [6] **Chemical Industries Association (CIA), 2003.** *Guidance for the location and design of occupied buildings on chemical manufacturing sites*, 2<sup>nd</sup>. ed., London: **Chemical Industries Association**, ISBN 1 85897 114 4.
- [7] **HSE, 1996.** *Review of Probable Survival Times for Immersion in the North Sea*, **Offshore Technology Report OTO 95 038**,  
<http://www.hse.gov.uk/research/otopdf/1995/oto95038.pdf>.
- [8] **VROM, 1999/2005.** *Guidelines for quantitative risk assessment*, **Publication Series on Dangerous Substances, PGS 3 (formerly CPR18, “Purple Book”)**, Ministerie van Volkshuis-vesting, Ruimtelijke Ordening en Milieubeheer,  
<http://www.vrom.nl/pagina.html?id=20725>.
- [9] **SFPE, 2002.** *The SFPE Handbook of Fire Protection Engineering*, 3<sup>rd</sup>. ed., ch. 2-6, Quincy, MA: **National Fire Protection Association**.
- [10] **Purser, D, 1992.** *Toxic Effects of Fire Cases, Offshore Fire and Smoke Hazards*, Aberdeen.
- [11] **NFPA 2007.** *Standard on Flame-Resistant Garments for Protection of Industrial Personnel against Flash Fire*, **NFPA 2112**.
- [12] **HSE, 2008.** *Assessment of the Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) and Significant Likelihood of Death (SLOD)*,  
<http://www.hse.gov.uk/hid/haztox.htm>.

## Appendix I – Relationship between Lethality and Probit

The following table shows the percentage affected (lethality) for a given probit value.

Lethality (%)										
	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

### Examples:

- 1% is equivalent to 2.67 probits.
- 42% is equivalent to 4.80 probits.
- 50% is equivalent to 5.00 probits.
- 75% is equivalent to 5.67 probits.
- 99.9% is equivalent to 8.09 probits.



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