Vulnerability of humans
Acknowledgements

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About

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, but injury thresholds are identified where appropriate. It is part of IOGP’s Risk Assessment Data Directory series.

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Vulnerability of humans

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## Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>BLEVE</td>
<td>Boiling Liquid Expanding Vapour Explosion</td>
</tr>
<tr>
<td>BR</td>
<td>Breathing Rate</td>
</tr>
<tr>
<td>BTU</td>
<td>British Thermal Unit</td>
</tr>
<tr>
<td>CCPS</td>
<td>Center for Chemical Process Safety</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>COHb</td>
<td>Carboxyhaemoglobin</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuous Stirred Tank Reactor</td>
</tr>
<tr>
<td>DTL</td>
<td>Dangerous Toxic Load</td>
</tr>
<tr>
<td>EPA</td>
<td>[United States] Environmental Protection Agency</td>
</tr>
<tr>
<td>ERPG</td>
<td>Emergency Response Planning Guideline</td>
</tr>
<tr>
<td>HSE</td>
<td>[UK] Health and Safety Executive</td>
</tr>
<tr>
<td>IDLH</td>
<td>Immediate Danger to Life or Health</td>
</tr>
<tr>
<td>IOGP</td>
<td>International Association of Oil and Gas Producers</td>
</tr>
<tr>
<td>LFL</td>
<td>Lower Flammable Limit</td>
</tr>
<tr>
<td>NFPA</td>
<td>National Fire Protection Association</td>
</tr>
<tr>
<td>O2</td>
<td>Oxygen</td>
</tr>
<tr>
<td>PPE</td>
<td>Personal Protective Equipment</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per millions</td>
</tr>
<tr>
<td>QRA</td>
<td>Quantitative Risk Assessment (sometimes Analysis)</td>
</tr>
<tr>
<td>SFPE</td>
<td>Society of Fire Protection Engineers</td>
</tr>
<tr>
<td>SO2</td>
<td>Sulphur Dioxide</td>
</tr>
<tr>
<td>SLOD</td>
<td>Significant Likelihood of Death</td>
</tr>
<tr>
<td>SLOT</td>
<td>Specified Level of Toxicity</td>
</tr>
<tr>
<td>TDU</td>
<td>Thermal Dose Units</td>
</tr>
<tr>
<td>TNO</td>
<td>Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Scientific Research)</td>
</tr>
<tr>
<td>TR</td>
<td>Temporary Refuge</td>
</tr>
</tbody>
</table>
1. 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 Quantified Risk Assessment (QRA) generally addresses 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 (engulfment, thermal radiation, and exposure of buildings): Section 2.
- Explosion (effects of overpressure): Section 3.
- Toxic gases (excluding smoke): Section 4.
- Oxygen depletion: Section 5.
- Smoke: Section 7.
- Cryogenic Effects: Section 8.
- Cold Water Immersion: Section 9.

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.

Different, more stringent, criteria from those given in this document may be required by regulatory bodies, particularly for offsite populations.

The focus of this datasheet is vulnerability to the consequences described in the Consequence Modelling datasheet [1]. Vulnerability to other potentially fatal events such as dropped loads, transportation and occupational accidents are not addressed here; information on these can be found in other datasheets [2], [3], [4], [5], [6].

1.2 Definitions

- **Fatality** is used in this datasheet to refer to the qualitative effect of the consequences of a major accident hazard, i.e. that there is an unquantified possibility of a death resulting from the accident.
- **Lethality** refers to the *quantitative* effect of the consequences of a major accident hazard, namely the fraction/percentage of the exposed population who would suffer fatality on exposure to a given consequence level.
- **Radiation** is always used here to refer to thermal radiation. The effects of ionising radiation are not considered in this datasheet.
- **Probit** is a function that relates lethality to the intensity or concentration of a hazardous effect and the duration of exposure. This is discussed further in Appendix C.
2. Fire and thermal radiation

2.1 Introduction

Depending on the duration, intensity and area of exposure, the effects of fire range from pain, through 1st, 2nd and 3rd degree burns, to fatality. 2nd degree burns may result in fatality in a small number of cases (1% lethality for average clothing); 3rd degree burns are likely to result in fatality (50% lethality for average clothing). The lethality is also dependent on which parts of the body suffer burns and the proportion of skin damaged.

As identified in the Consequence Modelling datasheet [1], 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 (inside the flame).
- Thermal radiation from the fire (outside the flame).
- Inside a building that is exposed to fire/radiation due to heat build-up or catching fire which may additionally lead to structural collapse.

The relationship between fire type and potential vulnerability can be illustrated as shown in Table 2-1.

**Table 2-1: Relationships between Fire Types and Potential Vulnerabilities**

<table>
<thead>
<tr>
<th>Fire type</th>
<th>Potential Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Engulfment</td>
</tr>
<tr>
<td>Flash fire</td>
<td>✓</td>
</tr>
<tr>
<td>Jet fire</td>
<td>✓</td>
</tr>
<tr>
<td>Pool fire</td>
<td>✓</td>
</tr>
<tr>
<td>Fireball/BLEVE</td>
<td>✓</td>
</tr>
</tbody>
</table>

* Situations with limited vulnerability due to the short duration of exposure and/or the protection offered by the building.
2.2 Quantitative information

2.21 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 become a fatality.

For the purposes of QRA, the following lethality levels are recommended for people outdoors (People indoors are considered separately in Section 2.7.):

- For engulfment due to jet fire, pool fire or fireball:
  - 100% lethality for workers or members of the public.

- For engulfment due to flash fire:
  - 100% lethality for members of the public.
  - 50% to 100% lethality, depending on ease of escape, for workers wearing fire resistant clothing made from fabrics meeting the requirements of NFPA 2112 [7] or equivalent.

Fatalities may occur from different consequences of the same accident. In such cases care should be taken to avoid double counting of fatalities. For example, the lethality of a jet fire which follows after a flash fire only applies to the survivors of the flash fire.

2.2.2 Thermal radiation criteria

The effects of thermal radiation depend primarily on the thermal radiation flux and the duration of exposure. However, the type of clothing worn, the ease of sheltering, and the individual exposed will also have an influence. Hence the information provided below provides guidance on the lethality levels that can be expected in typical situations alongside guidance on how other factors may influence these lethality levels.

Table 2-2 summarizes thermal radiation exposure effects over a range of radiation fluxes as outlined by the UK HSE [8].

Table 2-3 (taken from ANSI/API Standard 521 [9]) sets out permissible levels for thermal radiation criteria for workers who may be exposed to high levels of radiation such as from flares.
Table 2-2: Thermal radiation exposure effects [8]

<table>
<thead>
<tr>
<th>Thermal Radiation (kW/m²)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>Received from the sun at noon in summer</td>
</tr>
<tr>
<td>2</td>
<td>Minimum to cause pain after 1 minute</td>
</tr>
<tr>
<td>Less than 5</td>
<td>Will cause pain in 15 to 20 seconds and injury after 30 seconds exposure</td>
</tr>
<tr>
<td>Greater than 6</td>
<td>Pain within approximately 10 seconds; rapid escape only is possible</td>
</tr>
<tr>
<td>12.5</td>
<td>Significant chance of fatality for medium duration exposure. Wood may ignite after prolonged exposure. Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause failure in load bearing structures.</td>
</tr>
<tr>
<td>25</td>
<td>Likely fatality for extended exposure and significant chance of fatality for instantaneous exposure. Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperatures that can cause failure.</td>
</tr>
<tr>
<td>35</td>
<td>Significant chance of fatality for people exposed instantaneously. Cellulosic material will pilot ignite within one minute’s exposure.</td>
</tr>
</tbody>
</table>

Table 2-3: Recommended design values for thermal radiation criteria for personnel [9]

<table>
<thead>
<tr>
<th>Thermal Radiation (kW/m²)</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.46</td>
<td>Maximum radiant heat intensity at any location where emergency action by personnel is required. When personnel enter or work in an area with the potential for radiant heat intensity greater than 6.31 kW/m² [2000 Btu/h·ft²], radiation shielding and/or special protective apparel (e.g., a fire approach suit) should be considered. It is important to recognize that personnel with appropriate clothing can tolerate thermal radiation at 9.46 kW/m² [3000 Btu/h·ft²] for more than a few seconds.</td>
</tr>
<tr>
<td>6.31</td>
<td>Maximum radiant heat intensity in areas where emergency actions lasting up to 30 s can be required by personnel without shielding but with appropriate clothing.*</td>
</tr>
<tr>
<td>4.73</td>
<td>Maximum radiant heat intensity in areas where emergency actions lasting 2 min to 3 min can be required by personnel without shielding but with appropriate clothing.*</td>
</tr>
<tr>
<td>1.58</td>
<td>Maximum radiant heat intensity at any location where personnel with appropriate clothing can be continuously exposed.*</td>
</tr>
</tbody>
</table>

* Appropriate clothing consists of a hard hat, a long-sleeved shirt with cuffs buttoned, work gloves, long-legged trousers, and work shoes such that direct skin exposure to thermal radiation is minimized.
2.3 Thermal dose criteria

For short exposures, thermal radiation dose units (TDU) are an appropriate way of combining levels of radiation with exposure times:

\[
\text{Dose (TDU)} = I^{4/3}t
\]

where: \( I \) is incident thermal flux (kW/m\(^2\)), and
\( t \) is the duration of exposure (s).

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

The dose (TDU) required to reach selected levels of harm to humans are reported by the UK HSE [8]; for both infrared radiation associated with hydrocarbon fires and ultraviolet radiation associated with nuclear explosions. Table 2-4, replicated from [8], provides the more appropriate, lower, values associated with infrared radiation together with the source references.

Table 2-4: Thermal radiation doses for selected harm levels

<table>
<thead>
<tr>
<th>Thermal Radiation Range Minimum</th>
<th>Dose (TDU)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>108 - 127</td>
<td>DNV/Scandpower [10]</td>
</tr>
<tr>
<td></td>
<td>86 - 103</td>
<td>HSL [11]</td>
</tr>
<tr>
<td>Significant Injury/First Degree Burns</td>
<td>c 80</td>
<td>Metha et al [12]</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>Tsao &amp; Perry [1979] [13]</td>
</tr>
<tr>
<td></td>
<td>80 - 130</td>
<td>HSL [11]</td>
</tr>
<tr>
<td>Second degree burns/1% lethality for average clothing</td>
<td>270-310</td>
<td>Stoll &amp; Green [14]</td>
</tr>
<tr>
<td></td>
<td>c 350</td>
<td>Metha et al [12]</td>
</tr>
<tr>
<td></td>
<td>730</td>
<td>Arnold et al [15]</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>HSL [11]</td>
</tr>
<tr>
<td>Third degree burns/50% lethality for average clothing</td>
<td>c 500</td>
<td>Metha et al [12]</td>
</tr>
<tr>
<td></td>
<td>2000-3000</td>
<td>DNV/Scandpower [10]</td>
</tr>
<tr>
<td></td>
<td>870 - 2600</td>
<td>HSL [11]</td>
</tr>
</tbody>
</table>

The UK HSE [16] also provide combinations of radiation intensity and exposure times for the onset of lethality and 50\% lethality. These are given in Table 2-5 along with the equivalent number of thermal dose units calculated using the above equation.

Table 2-5: Thermal radiation doses for onset of lethality and estimated 50\% lethality

<table>
<thead>
<tr>
<th>Radiation Intensity (kW/m(^2))</th>
<th>Onset of Lethality</th>
<th>Estimated 50% Lethality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exposure Time (secs)</td>
<td>Dose (TDU)</td>
</tr>
<tr>
<td>12.5</td>
<td>32</td>
<td>928</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>981</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>1015</td>
</tr>
</tbody>
</table>

The above data show that there are wide ranges of values quoted in the literature.
Given that workers on offshore installation and onshore processing sites will typically have clothing with a higher standard of fire protection, a dose criteria of 1000 TDU for the onset of lethality and 2000 TDU for 50% lethality is recommended. The literature (e.g., [8]) also indicates 3200 TDU should be used for 100% lethality.

The duration of exposure required to reach these lethality levels is dependent on the radiation level. Figure 2.1 shows the relationship between these for 1000 TDU (onset of lethality), 2000 TDU (50% lethality) and 3200 TDU (100% lethality). This indicates, for example, that an exposure of around 35-40 seconds at 20 kW/m² will result in a 2000 TDU (50% lethality) whereas less than 20 seconds exposure at 35 kW/m² will have the same result. Given that a typical time taken to escape from the immediate vicinity of the flame is often taken as 20 seconds, a value of 35 kW/m² to 37.5 kW/m² may be used for the 50% lethality level.

![Figure 2-1: Relationship between incident radiation level and exposure time for selected thermal doses](image)

### 2.4 Probits

A probit approach can be used instead of the dose criteria described in Section 2.3. In this approach, the probability of fatality, or probit, takes the form

\[ Y = a + b \ln(TDU) \]

The literature details various values for parameters a and b. Table 2.6 provides the most commonly used values of a and b and the dose required to result in 1% and 50% lethality or probits (referenced in [8]).
Table 2-6: Thermal radiation probits [8]

<table>
<thead>
<tr>
<th>Source</th>
<th>Probit parameters</th>
<th>Lethal Dose (TDU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Eisenberg et al [17]</td>
<td>-14.9</td>
<td>2.56</td>
</tr>
<tr>
<td>Tsao &amp; Perry [13]</td>
<td>-12.8</td>
<td>2.56</td>
</tr>
<tr>
<td>TNO [18]</td>
<td>-15.3</td>
<td>3.02</td>
</tr>
<tr>
<td>Lees [19]</td>
<td>-10.7</td>
<td>1.99</td>
</tr>
</tbody>
</table>

The Eisenberg probit [17] is based on unadjusted data from nuclear radiation incidents.

Tsao and Perry [13] revised Eisenberg’s model [17] to account for the difference between infrared and ultraviolet radiation to make it more appropriate for hydrocarbon fires. The thermal dose required for a given lethality level is generally lower for hydrocarbon fires than for nuclear explosions due to differences in wavelength and skin absorption.

The TNO “Green Book” [18] probit model uses the functions developed by Tsao and Perry to develop a probit for 2nd degree burns.

The Lees probit model [19] has been developed for fatal injury from burns and in this probit a modified version of the normal dose is used:

\[ Y = -17.944 + 3.019 \ln(TDU) \]

Where \( \Phi \) is a factor accounting for variations in exposed skin area (0.5 for normally clothed population and 1.0 if clothing has been ignited). This means that the rate at which the dose accumulates increases after the clothing has been ignited and is assumed to occur after an unfactored thermal dose of 3600 TDU. The probit is non-conservative relative to the TNO and Tsao & Perry probits because it is derived from earlier work which used a predominantly ultraviolet radiation source.

More information is available in the HSE report 129/1997 [20].

Information on the use of probits and their conversion to lethality is given in Appendix C.

None of these probits are optimal for use in risk studies considering the effect of hydrocarbon fires on workers wearing protective clothing. This is because they either relate to ultraviolet radiation, the effect on bare skin or result in 2nd degree burns rather than fatalities.

It is proposed that a variation on the TNO curve is used whereby the “a” parameter is adjusted to give 50% lethality for 2000 TDU. This is then compatible with the dose criteria given in Section 2.3.

This gives the following modified TNO probit for workers wearing appropriate PPE:

\[ Y = -17.944 + 3.019 \ln(TDU) \]

Figure 2-2 shows graphs of lethality versus exposure time for the probits given in Table 2-6 alongside the proposed IOGP probit listed above for a radiation level of 20 kW/m².
This shows there are significant differences between the probits. This, in turn, could result in large differences in the number of fatalities calculated. For example, for an exposure time of 35 seconds, the Lees probit gives 2% lethality whereas the Tsao & Perry probit gives 94% lethality.

Figure 2-3 shows the relationship between time of exposure and lethality for a range of incident radiation levels using the TNO probit for naked skin (dashed lines) and the modified TNO probit for protected skin (solid lines).

**Figure 2-2:** Comparison of thermal radiation probits at 20 kW/m²

**Figure 2-3:** Lethality versus exposure time for selected radiation levels
2.5 Detailed calculation guidance

Lethality is related to the thermal dose which in turn is related to the level of radiation a worker may receive while egressing from the location where the fire exists. The level of radiation will normally decrease as the worker increases their separation. It may also be the case that the size of the fire and its emissive power changes with time. The degree of shielding offered by walls and pieces of equipment will also have an influence but may be difficult to quantify in a typical study. The effectiveness of protective clothing does not influence the thermal dose received by the clothes but will influence the radiation experienced by the skin. This can be accounted for by the choice of probit.

Consideration needs to be given to the degree of shielding offered by clothing. Where there is confidence that adequate PPE will be worn such that only small areas of facial skin are exposed then it is appropriate to use the “Modified TNO” probit described in Section 2.4. In all other cases, and particularly in the case of members of the public, the Tsao and Perry probit is recommended.

The thermal radiation dose for time varying levels of radiation is given by

\[ TDU = \int t^{4/3} \cdot dt \]

In the example shown in Table 2-7, two worker groups with protective clothing are exposed to three different levels of radiation which are constant over a defined period of time.

**Table 2-7**: Example calculation for radiation fatalities

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th></th>
<th>Group 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number in Group</strong></td>
<td>5</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>Radiation Level (kW/m²)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Level</td>
<td>40</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>Duration (secs)</strong></td>
<td>5</td>
<td>15</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Dose (TDU)</strong></td>
<td>684</td>
<td>814</td>
<td>431</td>
<td></td>
</tr>
<tr>
<td><strong>Dose (TDU)</strong></td>
<td></td>
<td></td>
<td></td>
<td>543</td>
</tr>
<tr>
<td><strong>Dose (TDU)</strong></td>
<td></td>
<td></td>
<td></td>
<td>543</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1929</td>
<td></td>
<td>1037</td>
<td></td>
</tr>
</tbody>
</table>

Using the modified TNO probit in Section 2.4 this gives:

- Probit = -17.944 + 3.019 \( \ln(1929) \) = 4.89 for group 1, and
- Probit = -17.944 + 3.019 \( \ln(1037) \) = 3.02 for group 2.

Using the tables in Appendix C, these equate to lethality probabilities of 0.457 and 0.024 respectively.

The estimated number of fatalities is then \((5 \times 0.457) + (10 \times 0.024) = 2.521\).

A more accurate assessment may be achieved by using a greater number of categories.
2.6 Practical calculation guidance

It may not be practicable to calculate the fatalities in a typical risk assessment dealing with a large number of scenarios and workers in different locations. In this case a simplified approach is considered acceptable.

The usual approach is to define one or more regions where the radiation level exceeds a certain value and assume certain levels of lethality within it. Various references give values for the radiation level above which 100% lethality is expected. For example, the UK HSE recommend a value of 35 kW/m² for “immediate fatalities to all personnel local to the fire”. Other sources quote lower values, but these are dependent on the time of exposure. Using the Modified TNO probit given in Section 2.4 a radiation level of 35 kW/m² equates to a 50% lethality with 17.5 seconds of exposure. This approach removes the requirement to consider the change in radiation levels as personnel move to a safer location.

The lethality levels associated with differing levels of radiation adopted by one IOGP member are given in Table 2-8 and illustrated in Figure 2-4. The number of radiation bands can be increased or decreased depending on the required level of accuracy. This can include a single step approach where lethality is set to unity above the critical radiation level and zero below that level.

**Table 2-8: Thermal radiation lethality levels example (IOGP Member)**

<table>
<thead>
<tr>
<th>Thermal Radiation Range</th>
<th>Lethality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>37.5 kW/m²</td>
<td>Inside Fire</td>
</tr>
<tr>
<td>20 kW/m²</td>
<td>37.5 kW/m²</td>
</tr>
<tr>
<td>12.5 kW/m²</td>
<td>20 kW/m²</td>
</tr>
<tr>
<td>5 kW/m²</td>
<td>12.5 kW/m²</td>
</tr>
<tr>
<td>0</td>
<td>5 kW/m²</td>
</tr>
</tbody>
</table>

**Figure 2-4: Probability of Lethality With Radiation Zones (IOGP Member)**
A typical approach is to assume a uniform distribution of people over the areas affected. Using the above lethality rates and hypothetical areas as an example, if 10 workers are uniformly distributed in an area of 800 m², the estimated number of fatalities can be calculated as shown in Table 2-9.

### Table 2-9: Example fatality calculation for radiation

<table>
<thead>
<tr>
<th>Radiation Level (kW/m²)</th>
<th>Area (m²)</th>
<th>Proportion of Area</th>
<th>People in Area</th>
<th>Lethality Rate</th>
<th>No. Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;37.5</td>
<td>50</td>
<td>0.0625</td>
<td>0.625</td>
<td>1</td>
<td>0.625</td>
</tr>
<tr>
<td>20 - 37.5</td>
<td>70</td>
<td>0.0875</td>
<td>0.875</td>
<td>0.9</td>
<td>0.788</td>
</tr>
<tr>
<td>12.5 - 20</td>
<td>100</td>
<td>0.125</td>
<td>1.25</td>
<td>0.3</td>
<td>0.375</td>
</tr>
<tr>
<td>5 - 12.5</td>
<td>150</td>
<td>0.1875</td>
<td>1.875</td>
<td>0.03</td>
<td>0.0563</td>
</tr>
<tr>
<td>&lt;5</td>
<td>430</td>
<td>0.5375</td>
<td>5.375</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>1.844</strong></td>
<td></td>
</tr>
</tbody>
</table>

The radiation levels and lethality rates for different zones will depend on the size of the flame, and therefore the contours, since this will affect the distance a worker will travel and the time spent within each radiation zone. A more complex calculation could be used to reflect the travel speed expected in a given zone dependent on available escape routes. This increases the complexity of a risk assessment when multiple release points, hole sizes, release orientation and area type are taken into consideration. An example is presented in Table 2-10 where the time to escape from a congested area is greater and leads to longer exposure times.

### Table 2-10: Example of radiation lethality rates by release rate and area type

<table>
<thead>
<tr>
<th>Radiation Level (kW/m²)</th>
<th>&lt;1 kg/s</th>
<th>1 – 10 kg/s</th>
<th>&gt;= 10 kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open</td>
<td>Congested</td>
<td>Open</td>
</tr>
<tr>
<td>&gt;37.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20 - 37.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>12.5 - 20</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>5 - 12.5</td>
<td>0</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td>&lt;5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note: the values in this table are for exemplar purposes and should be derived for a given installation based on its layout*

### 2.7 People inside buildings

Persons inside a building are likely to be able to take shelter and may only be subject to radiation for a short period of time. Lives of persons inside may be threatened if the building is not able to provide protection because it:

- Catches fire, either due to a directly impinging flame or to high levels of radiation
- Collapses due to weakening of the structure as its temperature increases
- Allows flame to penetrate the interior, or
- The heat from the fire is transferred through the walls and significantly heats up the interior
In addition, escape routes may be impaired preventing occupants from moving to a safe location.

Two types of ignition are recognized:
- 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 that thermal radiation levels of 35 kW/m² can cause ignition of wood and cellulosic material within a minute. However, this level of radiation would only be realized in very close proximity to the fire itself.

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 compared with the time to alert the people inside and evacuate them. Inability to escape may be because all available escape routes are impaired by high radiation levels. A criterion of 5 kW/m² is recommended.

The use of blast resistant modular (BRM) buildings may introduce an additional hazard from rapidly increasing temperature leading to insulation materials breaking down and off-gassing. This can occur quickly and prior to the ability to egress if external radiation is high.

Buildings constructed of combustible materials are unlikely to be used within a site processing hydrocarbons but, if they are, the buildings will be located in areas where risk assessments have identified that escape routes from the buildings would not be impaired by thermal radiation. The assessment of the time taken to impair a building due to thermal loads is out of the scope of this document. Sites should complete an assessment which identifies vulnerable buildings calculates the frequency of ignited releases which may result in radiation levels sufficient to damage the buildings and impair escape routes.

Similar to radiation level categories used for persons who are directly exposed, lethality values for those inside a building can be used. Table 2-11 gives examples of values used by one IOGP Member for specific building types.

**Table 2-11: Indoor thermal radiation lethality levels example (IOGP Member)**

<table>
<thead>
<tr>
<th>Thermal Radiation (kW/m²)</th>
<th>Lethality Indoor (No Specific Protection)</th>
<th>Lethality Indoor (Fire Protection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;= 37.5 kW/m²</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>12.5 – 37.5 kW/m²</td>
<td>0.3</td>
<td>0.0006</td>
</tr>
<tr>
<td>6.3 – 12.5</td>
<td>0.015</td>
<td>0.00003</td>
</tr>
<tr>
<td>&lt; 6.3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
2.8 Recommended data

Lethality for people exposed to thermal radiation

Where it is practical to take account of the time of exposure, the use of the Tsao and Perry probit and Modified TNO probit as described in Section 2.4 are recommended for unprotected skin and protected skin respectively.

Tsao & Perry probit \[ Y = -12.8 + 2.56 \ln(I^{4/3}t) \]

Modified TNO probit \[ Y = -17.944 + 3.019 \ln(I^{4/3}t) \]

The equivalent probit is then calculated using the tables in Appendix C.

Where a single duration of exposure is required for the purposes of immediate fatality calculation for situations where workers can reach a place of safety, it is suggested that a period of 20 seconds is used. Graphs of lethality versus radiation are shown in Figure 2-5 and values taken from these are given Table 2-12. The graph for “Protected Skin” relates to clothing, hats, boots and gloves complying with NFPA 2112 or equivalent [7]. Workers with non-compliant clothing should be assessed using the graph for unprotected skin.

![Figure 2-5: Lethality versus radiation level for 20 seconds exposure](image-url)
### Table 2-12: Lethality versus radiation level for 20 seconds exposure

<table>
<thead>
<tr>
<th>Radiation (kW/m²)</th>
<th>Lethality (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unprotected Skin</td>
<td>Protected Skin</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>6.6</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>18.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>53.8</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>80.4</td>
<td>17.2</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>93.0</td>
<td>41.6</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>97.8</td>
<td>65.9</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>99.3</td>
<td>82.8</td>
<td></td>
</tr>
</tbody>
</table>

It is recommended that in screening studies an approach using bands of radiation levels similar to the example shown in Table 2-8 is used. This should be based on the relevant probit.

**Lethality for people engulfed by flame**
- Jet fire, pool fire or fireball: 100%
- Flash fire
  - Members of the public: 100%
  - Workers wearing fire resistant clothing meeting the requirements of NFPA 2112 [7] or equivalent: 50% - 100%

**Lethality for people inside buildings**
- People inside a building from which escape is not practical and which catches fire: 100%
- Prolonged exposure to elevated levels of heat inside a building: Refer to Section 6.

**Impairment of escape routes and embarkation areas**

Lower levels of radiation may also impair the ability of workers to move to a safe location or evacuate an offshore installation. The levels will depend on many factors such as the provision of protective clothing, the expected duration of exposure and the severity of conditions in the workers current location. Various values have been suggested but the consensus complies with the values suggested by the UK HSE [8].

- Impairment of escape routes for workers with protective clothing complying with NFPA standards [7]: 6 kW/m².
- Impairment of escape routes for workers without protective clothing complying with NFPA standards [7]: 5 kW/m².
- In addition to the above two criteria, an escape route may be considered to be impaired if the thermal dose acquired by traversing the route exceed 290 TDU as given in [11].
- Impairment of TEMPSC embarkation areas: 4 kW/m².
3. Explosions

3.1 Introduction

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 categorized 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 each of 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 greater than 1 barg. However, other effects, such as secondary effects and thermal injuries, are predominant such that casualties with only direct blast injuries make up a small part of an exposed group.

3.2 Quantitative information

The UK HSE [8] quote a probit for blast overpressure fatalities

$$Y = 5.13 + 1.37 \ln(P)$$

Where the Pressure, \( P \), is expressed in barg.

This can be used to generate the graph in Figure 3-1 which indicates 1% lethality at around 0.35 bar, 50% at 0.9 bar and 95% at 3 bar. These can be taken as appropriate for primary effects where there is limited possibility of fatality from being hit by fragments of debris or being thrown against a stationary object. Application of this probit will be inappropriate in most settings where the effect of projectiles, impact with stationary objects or being in a structure which is damaged may be the main cause. In such settings fatalities are likely to occur at lower overpressures.
The level of overpressure resulting in defined probabilities of injury or lethality vary greatly in the literature from operators and regulatory standards and are not necessarily traceable back to the original reference or related to the setting in which they may be applied. Figure 3-2 presents a selection of values found in the literature and operators’ technical guidance for offshore QRA and congested regions. Points of the same colour are taken from the same data set. This illustrates a wide range of values adopted but also a consensus that the threshold for fatalities is around 0.2 bar and above 0.5 bar 100% lethality can be assumed. This correlation is represented by the solid black line and applies to the specific location of a worker. Different lethalities may apply in different locations of large modules where variations in overpressure are predicted. For smaller modules it is usual to assume the same overpressure applies to all parts of that module.

Figure 3-1: Explosion lethality from direct effects as a function of overpressure

Figure 3-2: Lethality versus overpressure [offshore]
Similarly, Figure 3-3 shows a collection of data points relating to lethalities for onshore explosions where there is less likelihood of being struck by projectiles or impacting solid objects. Again, it can be seen that although there are outlying values, there is a broad consensus for the threshold for fatalities being around 0.2 bar but with overpressures in the region of 3 bar being required for 100% lethality. The solid black line represents the suggested correlation which can be applied for onshore scenarios for cases where people are in open areas away from plant structure.

![Figure 3-3: Lethality versus overpressure (onshore)](image)

The duration of the blast may also be important. Figure 3-4, adapted from [10], for example, indicates that the overpressure with a duration of 1 msec required to result in 50% lethality is approximately 10 bar but the overpressure with a duration of 10 msecs is approximately 3 bar. However, the duration of a large hydrocarbon gas explosion will typically be in the region 100 – 200 msecs [21]. Curves in this region give overpressures for 50% fatality of around 2.8 bar (280 kPa).
3.3 Detailed calculation guidance

The overpressures calculated in the explosion analysis, particularly if undertaken using CFD, may be for a series of very specific scenarios with regards to the release location of the gas, the release rate and release orientation, all of which have a bearing on the change of size and location of the gas cloud with time. The size of the non-homogeneous gas cloud, combined with the location of the ignition source, will have a bearing on the overpressures generated at different locations.

Ideally, the lethality at each location where people are exposed to the blast should be calculated for each of the n scenarios and the overall risk calculated using this lethality multiplied by the frequency of that scenario.

\[
L_T = \frac{\sum_{i=1}^{n} L_i f_i}{\sum_{i=1}^{n} f_i}
\]

Where

- \(L_T\) is the overall lethality averaged over all the scenarios,
- \(L_i\) is the lethality for a given scenario which is itself a function of overpressure, and
- \(f_i\) is the frequency of that scenario.

This process would normally be overly complex for all but the most detailed risk assessments and a more practical approach is suggested in Section 3.4.
3.4 Practical calculation guidance

In most offshore risk assessments, the explosion overpressure at a given point is normally expressed in the form of a probabilistic exceedance curve. This reflects the distribution of overpressures which may be experienced depending on the size of the gas cloud when ignited, its proximity to stoichiometric conditions, the degree of confinement and the degree of congestion.

Care should be taken to ensure that the overpressures used in the exceedance curves are compatible with those related to the fatalities; for example, are they side-on pressures or reflected pressures? Note that the values given in Table 3-2 for directly exposed workers are side-on (free field) pressures. The overpressures calculated in the explosion analysis will vary throughout the installation. A simplified, and conservative, approach is to adopt the most adverse exceedance curve as applying to the local area or module. A more complex analysis may split the area/module into different regions.

Typically, the overpressures used are representative values covering a module or area in an offshore installation where all workers in that area are assumed to be exposed to the same level. In onshore studies the area which the overpressure affects may be divided up into different regions and the population within a region is assumed to be evenly distributed.

As an example, Figure 3-5 shows a hypothetical probabilistic overpressure exceedance curve and lethality curve. The lethality due to overpressure given an ignition can be calculated by the convolution of the two functions. A practical approach in a numerical calculation is to divide the overpressure spectrum into ranges, evaluate the probability within that range and determine a representative lethality for that range. In this example, the probability, given ignition, of an overpressure between 0.3 and 0.4 barg is 0.0625 and the average lethality within this range is 0.5. This gives a contribution of 0.0625 × 0.5 = 0.031. The overall calculation is shown Table 3-1.

![Figure 3-5: Probability of Exceedance and Lethality By Overpressure - Example](image-url)
Table 3-1: Lethality calculation example

<table>
<thead>
<tr>
<th>Overpressure Range (barg)</th>
<th>Proportion Within Range</th>
<th>Lethality</th>
<th>Contribution to Lethality Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 0.1</td>
<td>0.5</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>0.1 - 0.2</td>
<td>0.25</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>0.2 - 0.3</td>
<td>0.125</td>
<td>0.167</td>
<td>0.021</td>
</tr>
<tr>
<td>0.3 - 0.4</td>
<td>0.0625</td>
<td>0.500</td>
<td>0.031</td>
</tr>
<tr>
<td>0.4 - 0.5</td>
<td>0.03125</td>
<td>0.833</td>
<td>0.026</td>
</tr>
<tr>
<td>0.5 - 0.6</td>
<td>0.015625</td>
<td>1</td>
<td>0.016</td>
</tr>
<tr>
<td>0.6 - 0.7</td>
<td>0.015625</td>
<td>1</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>0.109</strong></td>
</tr>
</tbody>
</table>

This approach can be further simplified by adopting a single value criterion whereby an overpressure lower than the fatality criterion is assumed to result in 0% lethality and values above are assumed to result in 100% lethality. In this case the calculation is reduced to determining the probability of exceeding the critical overpressure.

3.5 People inside buildings

Building damage assessment results can be used to estimate the potential vulnerability of building occupants. The primary hazards to personnel located indoors are building collapse and flying debris. The likelihood of death depends on the extent of the damage to the component parts of the building. This is dependent not only on the strength and duration of the explosion but also on the type and robustness of the construction and the amount of glazing.

Occupant vulnerability has been correlated to building damage for some building types. Two sets of relationships between lethality level and over-pressure are presented below: Figure 3-6 replicates the graph presented in API RP 752 [1st edition] [22]. Figure 3-7 replicates that from the CIA Guidance [3rd edition] [23]. Both differentiate between building construction types.

![Figure 3-6: Overpressure – lethality relationships from API 752 [22]](image)

1 This diagram does not appear in the 3rd edition of the standard but is still considered to be relevant.
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 [24] has superseded API RP 752 [22] with regard to locating portable buildings (building type B1). This does not provide a comparable graphical relationship. However, guidance on both a simplified method and detailed analysis is provided.

![Figure 3-7: Overpressure – lethality relationships from CIA guidance [23]](image)

**Figure 3-7:** Overpressure – lethality relationships from CIA guidance [23]

Building Types
- Hardened structure building: special construction, no windows
- Typical office block: four storey, concrete frame and roof, brick block wall panels
- Typical domestic building: two-storey, brick, walls, timber floors
- 'Portacabin' type timber construction, single storey

The correlations given in [22] and [23] (i.e., Figure 3-6 and Figure 3-7) are presented in a common axes in Figure 3-8.
Figure 3-8: Lethality versus overpressure correlations for various building types

Further information on overpressures required to damage or destroy buildings are given in [25].

3.6 Recommended data

Table 3-2 summarizes the recommended lethality versus overpressure for various settings. Refer to Section 3.5 for guidance on vulnerability of persons inside buildings.

Table 3-2: Recommended overpressure lethality relationships

<table>
<thead>
<tr>
<th></th>
<th>Open Areas</th>
<th>Confined and/or Congested Areas</th>
<th>Offshore in Adjacent or Protected Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overpressure (barg)</td>
<td>Lethality</td>
<td>Overpressure (barg)</td>
<td>Lethality</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.6</td>
<td>0.35</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[^{2}\] The blast duration is also relevant in assessing the structural response.
\[^{3}\] The overpressure to be considered is the load on the barrier which may be greater than the free field overpressure when reflection is taken into account.
\[^{4}\] The factor of 1.2 may be used in the absence of more specific analysis to assess the ratio of the overpressure required to cause sufficient damage to result in fatalities.
4. Toxic gases

4.1 General

Various approaches are used to determine the consequences of toxic gases (not including smoke, which is addressed separately in Section 7):

- Immediate Danger to Life or Health (IDLH) is the maximum concentration from which escape is possible within 30 minutes without any irreversible health effects.
- Emergency Response Planning Guidelines (ERPG) are used (in the USA and elsewhere) to plan emergency response to an incident, knowing the likely ranges of health effects resulting from the incident and consequent numbers of casualties.
- Probit approaches 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).
- Specified Level of Toxicity (SLOT) Dangerous Toxic Load (DTL) is usually defined as the dose that results in highly susceptible people being killed, a substantial portion of the exposed population requiring medical attention and severe distress to the remainder exposed (commonly referred to as LD1 or LD1.5).
- SLOD (Significant Likelihood of Death) DTL is defined as the dose to typically result in 50% lethality (LD50) within an exposed population and is the value typically used for group risk of death calculation onshore.

The IDLH (“Immediate Danger to Life or Health”) concentration has been seen to be used as the limiting value for the onset of fatalities. However, this is very conservative when used within the QRA process. IDLHs are more suitable for use as a workplace risk management tool or as an impairment criteria 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.

Neither IDLH nor ERPG values are recommended for major hazard QRAs, however both are useful as indicators of the hazard effects of toxic materials and can often be used in the assessment of safety distances for emergency response planning in areas where many people may need (or require help) to escape in a timely manner. Workplace exposure limits for a large number of materials is given in [26].

Probit functions have been developed for a wide range of toxic materials. They can be used to provide fine resolution in lethality estimates, especially for third party (offsite) risks from onshore facilities, using the results of atmospheric dispersion models (see Consequence Modelling datasheet [1]). However, it should be noted that this does not imply accuracy in the estimates given the level of uncertainty. Probits recommended below are those published by recognized bodies, such as TNO and the UK HSE, and used by regulators.

Although not covered in detail in this datasheet, the anaesthesia effects of hydrocarbon vapours may also need to be considered in some release scenarios.
4.2 Methodologies

The SLOT DTL and the SLOD DTL techniques have been proposed and developed by the UK HSE as alternatives to the probit approach. Both are calculated as:

\[ \text{DTL} = C^n t \]

where: 
- \( C \) is the concentration in ppm, and 
- \( t \) is the exposure duration in minutes

Table 4-1 provides values for SLOT and SLOD for selected substances from [8]. These can also be used to derive parameters \( a \) and \( b \) for a probit that gives the same dose for \( L_{1.5} \) (taken as 3% lethality rate giving a probit value of 3.1192) and \( L_{50} \) (probit value 5). These are calculated as follows:

\[ a = 5 - \left( \frac{1.8808 \ln(SLOD)/\ln(SLOD) - \ln(SLOT))}{\ln(SLOD) - \ln(SLOT)} \right), \quad \text{and} \]
\[ b = 1.8808/\ln(SLOD) - \ln(SLOT) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>SLOT</th>
<th>SLOD</th>
<th>n</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>( 3.78 \times 10^8 )</td>
<td>( 1.03 \times 10^9 )</td>
<td>2</td>
<td>-33.94</td>
<td>1.88</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>40125</td>
<td>57000</td>
<td>1</td>
<td>-53.67</td>
<td>5.36</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>( 1.5 \times 10^{40} )</td>
<td>( 1.5 \times 10^{41} )</td>
<td>8</td>
<td>-72.44</td>
<td>0.82</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>( 2 \times 10^{12} )</td>
<td>( 1.5 \times 10^{13} )</td>
<td>4</td>
<td>-23.32</td>
<td>0.93</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>( 4.66 \times 10^4 )</td>
<td>( 7.45 \times 10^5 )</td>
<td>2</td>
<td>-7.30</td>
<td>0.68</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>12000</td>
<td>21000</td>
<td>1</td>
<td>-11.26</td>
<td>1.53</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>96000</td>
<td>( 6.24 \times 10^5 )</td>
<td>2</td>
<td>-8.41</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note that the values for SLOT, SLOD and \( n \) are as reported in [8]. The values for \( a \) and \( b \) have been calculated from these.

Figure 4-1 shows the probit for carbon monoxide as an example with the SLOT and SLOD points indicated.

**Figure 4-1:** Exemplar probit (carbon monoxide) based on SLOT and SLOD doses
Probits are available from other sources, in particular from RIVM [27] and the CCPS [28]. The probits reported by CCPS are also reported by the HSE in [19] and Lees in [8]. The probits in the RIVM guidance are similar to those in the “Purple Book” [29] and “Green Book” [18] and where differences exist, those in the RIVM guidance take precedence since this is a later publication. It is important to note that the probits in the Purple Book are applicable to concentrations measured in mg/m$^3$ rather than ppm. To obtain the equivalent probits in ppm the “a” parameter is modified using the equation:

$$a = a' + b \cdot n \cdot (\ln(M_w) - \ln(24.45))$$

where $a'$ is the parameter related to concentrations in mg/m$^3$, and $M_w$ is the molecular weight of the substance. The parameters $b$ and $n$ remain unchanged.

**Example**

The probit for hydrogen sulphide in the RIVM guidance [27] is

$$Y = -11.5 + 1 \cdot \ln(C^{1.9} \cdot t)$$

where $C$ is measured in mg/m$^3$

The molecular weight of hydrogen sulphide is 34.08

Hence,

$$a = -11.5 + 1 \cdot 1.9 \cdot (\ln(34.08) - \ln(24.45)) = -10.87$$

And the probit is

$$Y = -10.87 + 1 \cdot \ln(C^{1.9} \cdot t)$$

where $C$ is measured in ppm

The CCPS/AICHE and RIVM probit parameters are presented in Table 4-2

<table>
<thead>
<tr>
<th>Material</th>
<th>CCPS/AICHE Probits</th>
<th>RIVM Probits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>Ammonia</td>
<td>-35.9</td>
<td>1.85</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>-37.98</td>
<td>3.7</td>
</tr>
<tr>
<td>Chlorine</td>
<td>-8.29</td>
<td>0.92</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>-31.42</td>
<td>3.008</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>-15.67</td>
<td>2.1</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>-35.87</td>
<td>3.354</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>-13.79</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The lethality rates for a given substance may vary significantly depending on which of the probits presented in Table 4-1 and Table 4-2 are used. Using 20,000 ppm ammonia as an example as shown in Figure 4-2 it is seen that the calculated lethality at 5 minutes varies from 10% to 86%.

\[^5\] Probits for carbon dioxide are not presented in the RIVM or CCPS/AICHE report
Table 4-3 provides a comparison of the calculated concentration (in ppm) required for 1% lethality for 10 minutes and 30 minutes exposure using the various probits and Table 4-4 provides the equivalent concentrations for 30 minutes exposure.

Table 4-3: Comparison of concentrations for 1% and 50% lethality for 10 minutes exposure

<table>
<thead>
<tr>
<th>Material</th>
<th>10 minutes - 1% Lethality</th>
<th>10 minutes - 50% Lethality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSE</td>
<td>RIVM</td>
</tr>
<tr>
<td>Ammonia</td>
<td>5460</td>
<td>3986</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>3692</td>
<td>1961</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>73688</td>
<td>-</td>
</tr>
<tr>
<td>Chlorine</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>594</td>
<td>350</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>492</td>
<td>1259</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>897</td>
<td>401</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>78</td>
<td>85</td>
</tr>
</tbody>
</table>
Table 4-4: Comparison of concentrations for 1% and 50% lethality for 30 minutes exposure

<table>
<thead>
<tr>
<th>Material</th>
<th>30 minutes - 1% Lethality</th>
<th>30 minutes - 50% Lethality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HSE</td>
<td>RIVM</td>
</tr>
<tr>
<td>Ammonia</td>
<td>3152</td>
<td>2301</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>1231</td>
<td>654</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>64233</td>
<td>-</td>
</tr>
<tr>
<td>Chlorine</td>
<td>-</td>
<td>67</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>451</td>
<td>196</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>284</td>
<td>796</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>299</td>
<td>193</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>45</td>
<td>63</td>
</tr>
</tbody>
</table>

4.3 Example calculations

The calculation of lethality is a three stage process:

1) Calculate the dose based on the concentration and time of exposure
2) Calculate the probit value
3) Calculate the lethality based on the probit.

As an example, consider the calculation of lethality for a person exposed to a concentration of ammonia of 15,000 ppm for 10 minutes using the RIVM probit.

Dose, \( DTL = C^2 t \times 10 = 2.25 \times 10^9 \)

Probit, \( Y = a + b \cdot \ln(DTL) = -16.21 + 1 \cdot \ln(2.25 \times 10^9) = 5.324 \)

Lethality = 0.627 (from table in Appendix C)

The reverse process can also be used to determine a concentration required to result in a given lethality and a time of exposure.

As an example, the concentration of ammonia required to result in a lethality of 50% for a 5 minute exposure using the RIVM probit is calculated by;

Probit, \( Y = 5 \) (from table in Appendix C)

Dose, \( DTL = \exp[(Y - a)/b] = \exp((5 - (-16.21))/1) = 1.63 \times 10^9 \)

Concentration, \( C = [DLT/t]^{1/n} = (1.63 \times 10^9/5)^{1/2} = 18039 \) ppm

Likewise, a time of exposure given a lethality and concentration can be calculated. As an example, the exposure time to ammonia at 25,000 ppm required to result in a lethality of 80% using the RIVM probit is calculated by;

Probit, \( Y = 5.84 \) (from table in Appendix C)

Dose, \( DTL = \exp[(Y - a)/b] = \exp((5.84 - (-16.21))/1) = 3.77 \times 10^9 \)

Exposure time, \( t = DTL/C^n = 3.77 \times 10^9/(25,000^2) = 6.04 \) minutes
In the above examples, a constant concentration over the period of exposure is assumed. Where the concentration varies, the dose should be calculated by integrating the concentration over time.

\[ DTL = \int_0^t C^n \, dt \]

### 4.4 Hydrogen sulphide

Other than toxic products from combustion of hydrocarbons the most likely toxic gas present in oil and gas production hydrocarbon fluids is hydrogen sulphide (H\(_2\)S). The effects likely to be experienced by humans exposed to various concentrations of H\(_2\)S are described in Table 4-5 which replicates the information presented in [30]. However, as noted above the effects and lethality levels for many substances vary greatly between different sources and this is the case with hydrogen sulphide. In particular, the value of the exponent \( n \) used in calculating the dose varies between probits. In the probits described above the value is 4 when used in the HSE’s SLOT/SLOD approach indicating that a doubling of the concentration gives a 16 fold increase in the dose for a given exposure time. In comparison, the value for the RIVM probit is 1.9 giving a 3.7 fold increase in dose when doubling concentration. For the CCPS/Lees probit the value is 1.43 giving a 2.7 fold increase.

Table 4-5: Effects of exposure to hydrogen sulphide [30]

<table>
<thead>
<tr>
<th>H(_2)S Concentration</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00011 – 0.00033</td>
<td>Typical background concentrations</td>
</tr>
<tr>
<td>0.01-1.5</td>
<td>Odour threshold (when rotten egg smell is first noticeable to some). Odour becomes more offensive at 3-5 ppm. Above 30 ppm, odour described as sweet or sickeningly sweet.</td>
</tr>
<tr>
<td>2 - 5</td>
<td>Prolonged exposure may cause nausea, tearing of the eyes, headaches or loss of sleep. Airway problems (bronchial constriction) in some asthma patients.</td>
</tr>
<tr>
<td>20</td>
<td>Possible fatigue, loss of appetite, headache, irritability, poor memory, dizziness.</td>
</tr>
<tr>
<td>50-100</td>
<td>Slight conjunctivitis (&quot;gas eye&quot;) and respiratory tract irritation after 1 hour. May cause digestive upset and loss of appetite.</td>
</tr>
<tr>
<td>100</td>
<td>Coughing, eye irritation, loss of smell after 2-15 minutes (olfactory fatigue). Altered breathing, drowsiness after 15-30 minutes. Throat irritation after 1 hour. Gradual increase in severity of symptoms over several hours. Death may occur after 48 hours.</td>
</tr>
<tr>
<td>100-150</td>
<td>Loss of smell (olfactory fatigue or paralysis).</td>
</tr>
<tr>
<td>200-300</td>
<td>Marked conjunctivitis and respiratory tract irritation after 1 hour. Pulmonary edema may occur from prolonged exposure.</td>
</tr>
<tr>
<td>500-700</td>
<td>Staggering, collapse in 5 minutes. Serious damage to the eyes in 30 minutes. Death after 30-60 minutes.</td>
</tr>
<tr>
<td>700-1000</td>
<td>Rapid unconsciousness, &quot;knockdown&quot; or immediate collapse within 1 to 2 breaths, breathing stops, death within minutes.</td>
</tr>
<tr>
<td>1000-2000</td>
<td>Nearly instant death</td>
</tr>
</tbody>
</table>

Table 4-6 shows the concentrations required for various exposure times to provide SLOT and SLOD doses using the HSE values.
Table 4-6: SLOT and SLOD concentrations for various H₂S exposure times

<table>
<thead>
<tr>
<th>Inhalation Exposure Time</th>
<th>H₂S Concentration in Air (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLOT: 1-5% Fatalities</td>
</tr>
<tr>
<td>60 min</td>
<td>427</td>
</tr>
<tr>
<td>30 min</td>
<td>508</td>
</tr>
<tr>
<td>20 min</td>
<td>562</td>
</tr>
<tr>
<td>10 min</td>
<td>669</td>
</tr>
<tr>
<td>5 min</td>
<td>795</td>
</tr>
<tr>
<td>1 min</td>
<td>1189</td>
</tr>
</tbody>
</table>

The dose required to incapacitate a human may be rather less than that required to result in a fatality. Whether the incapacitation ultimately results in death may be dependent on the prospect of the person being rescued or provided with an alternative source of air. This is particularly relevant for hydrogen sulphide where, as given in Table 4-5, a concentration of 700 – 1000 ppm can result in unconsciousness within a time period which ranges from a few breaths to 10 minutes. Assuming this concentration remains present, the person exposed will eventually become a fatality. The time of exposure to 700 ppm of H₂S to result in a lethality of 0.5 using the probits described above varies between 16 and 64 minutes. This is reduced to 9 to 15 minutes at a concentration of 1000 ppm and 1 to 4 minutes at a concentration of 2000 ppm. In practice it may not be possible for a rescue team to recover a victim. It may therefore be appropriate to regard 700 ppm as a fatal concentration and the probit or SLOD approach only applied to concentrations below 700 ppm.

Rather than adopting a single value, an approach taken by one IOGP Member based on an internal toxicology report [31] is a series of steps as follows:

- 650 ppm results in 1% lethality
- 950 ppm results in 50% lethality
- 1100 ppm results in 100% lethality

For lower concentrations over a longer period the SLOT and SLOD approach is appropriate. In most studies the period of exposure is assumed greater than 10 minutes and in these cases probits fitted to the SLOT and SLOD values are appropriate.

An alternative probit for H₂S has been proposed by the Energy Resources Conservation Board of Alberta Canada [32]. This has the equation:

\[ Y = -29.15 + 1.443 \ln(C^{3.5} t) \]

Which gives much more severe lethality levels than is calculated using the probits referenced above.
4.5 Carbon dioxide

Hazards related to carbon dioxide are likely to become more common due to the development of carbon capture and storage schemes. Although, carbon dioxide has not traditionally been classified as toxic, exposure to significant concentrations result in fatalities from a number of mechanisms. Information of the toxic effects of carbon dioxide are given in [33] and [34].

The UK HSE [8] quote the effects given in Table 4-7.

**Table 4-7: Effects of exposure to carbon dioxide** [8]

<table>
<thead>
<tr>
<th>CO₂ Concentration (ppm)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>45000</td>
<td>Reduced concentration capability for more than 8 hours exposure, adaptation possible</td>
</tr>
<tr>
<td>55000</td>
<td>Difficulty breathing, headache and increased heart rate after 1 hour.</td>
</tr>
<tr>
<td>65000</td>
<td>Dizziness, and confusion after 15 minutes exposure</td>
</tr>
<tr>
<td>70000</td>
<td>Anxiety caused by breathing difficulty effects becoming severe after 6 minutes exposure</td>
</tr>
<tr>
<td>100 000</td>
<td>Approaches threshold of unconsciousness in 30 minutes</td>
</tr>
<tr>
<td>120 000</td>
<td>Threshold of unconsciousness reached in 5 minutes</td>
</tr>
<tr>
<td>150 000</td>
<td>Exposure limit 1 minutes</td>
</tr>
<tr>
<td>200 000</td>
<td>Unconsciousness occurs in less than 1 minute</td>
</tr>
</tbody>
</table>

The HSE [8], [35] have quoted values for SLOT and SLOD for carbon dioxide as follows:

\[
\text{SLOT} = 1.5 \times 10^{40} \\
\text{SLOD} = 1.5 \times 10^{41}
\]

The exponent, n, applied to the concentration for the purposes of calculating the DTL is 8. This large value indicating that the sensitivity of lethality is much greater for changes in concentration than for changed in exposure time.

The probit derived from the SLOT and SLOD is:

\[
Y = -72.44 + 0.817 \ln(DTL)
\]

This is consistent with values presented by HSE in [36] which is reproduced in Table 4-8.

**Table 4-8: SLOT and SLOD concentrations for various CO₂ exposure times**

<table>
<thead>
<tr>
<th>Inhalation Exposure Time</th>
<th>CO₂ Concentration in Air (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLOT: 1-5% Fatalities</td>
</tr>
<tr>
<td>60 min</td>
<td>63 000</td>
</tr>
<tr>
<td>30 min</td>
<td>69 000</td>
</tr>
<tr>
<td>20 min</td>
<td>72 000</td>
</tr>
<tr>
<td>10 min</td>
<td>79 000</td>
</tr>
<tr>
<td>5 min</td>
<td>86 000</td>
</tr>
<tr>
<td>1 min</td>
<td>105 000</td>
</tr>
</tbody>
</table>
Figure 4-3 shows the lethality versus time for various concentrations of CO₂ exposure using this probit. High concentrations are required before adverse effects are experienced but beyond that point relatively small increases in concentration lead to rapidly increasing lethality rates.

![Figure 4-3: Lethality versus time for various CO₂ concentrations using the probit derived from HSE SLOT and SLOD doses](image)

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 following relationship is presented in [8] which it attributes to [37]:

\[
\text{Breathing Volume Rate (l/min) = exp(0.2496 \times \%CO₂ + 1.9086)}
\]

This is shown graphically in Figure 4-4.
At dose levels below those which may result in fatalities, carbon dioxide may incapacitate a worker leaving them unable to escape without assistance. The effect of CO₂ can be expressed as the fraction, $F_{CO₂}$, of the incapacitating dose by integrating the following expression:

$$\frac{dF_{CO₂}}{dt} = \frac{1}{\left(\exp\left(6.1623 - 0.5189CO₂\right)\right)}$$

Where

$$\frac{dF_{CO₂}}{dt}$$

is the rate of change in fractional incapacitating dose per minute, and

- $CO₂$ is the concentration of CO₂ (%) in air, and
- $t$ is time measured in minutes,

Concentrations of less than 3% are considered to have no effect on incapacitation.

If the concentration of CO₂ is constant, the fractional incapacitating dose varies linearly with time as shown in Figure 4-5.
Figure 4-5: Variation in fractional incapacitating dose for selected concentrations of CO₂

Example

If the concentration of CO₂ is 7%. The rate of change of fractional dose is

\[
\frac{df_{\text{CO₂}}}{dt} = \frac{1}{(\exp[6.1623 - 0.5189 \times 7])} \\
= 0.0797/\text{min}
\]

At this rate the fractional incapacitating dose is reached in \(1/0.0797 = 12.6\) minutes

The incapacitating dose and the use of SLOT and SLOD probits for CO₂ human vulnerability represent conservative approaches to risk assessments. In a population of healthy young volunteers, the inhalation of 7.5% CO₂ was well tolerated with no significant cognitive issues for up to 60 minutes. Based on these results, allowing for a margin of safety, a 5% CO₂ concentration is recommended as a reasonable guide for the onset of impairment to the ability to escape/evacuate after 60 minutes exposure, applicable to a general population. A lower value of 4% is recommended for areas with a high number of highly vulnerable individuals (e.g., hospitals). For detailed studies, a toxicology health subject matter expert should be consulted.

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4.6 Sulphur dioxide

Sulphur dioxide is an irritant gas which is commonly produced upon combustion of fossil fuels containing hydrogen sulphide or due to the thermal decomposition of sulphur containing compounds. SO$_2$ may cause tightening of the airways and individuals with asthma may be significantly more sensitive to its effects. Exposure to high concentrations may be fatal due to asphyxiation caused by blockage of the upper respiratory tract resulting from the irritation. Table 4-9 provides some information taken from Table 2-2 of the U.S. Department of Health and Human Services’ Toxicological Profile for Sulphur Dioxide [38] on the health effects of various concentrations below those which are likely to result in fatalities.

Table 4-9: Effects of exposure to sulphur dioxide – summarized from [38]

<table>
<thead>
<tr>
<th>SO$_2$ Concentration (ppm)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.1</td>
<td>Bronchoconstriction in sensitive exercising asthmatics</td>
</tr>
<tr>
<td>3</td>
<td>Easily detected odour</td>
</tr>
<tr>
<td>6 - 12</td>
<td>May cause nasal throat irritation</td>
</tr>
<tr>
<td>20</td>
<td>Definite irritation to eyes, chronic respiratory system developed at this level, respiratory protection is necessary</td>
</tr>
<tr>
<td>50 - 100</td>
<td>Maximum tolerable exposures for 30-60 minutes</td>
</tr>
</tbody>
</table>

The UK HSE [16] suggest a LC$_1$ concentration of 965 ppm for a 5 minute exposure and a LC$_{50}$ concentration of 1576 ppm for a 30 minute exposure.

4.7 Combined effect of toxic gasses

The combined effect of more than one toxic gas being inhaled should also be considered. The recommended approach is to calculate the sum of the fractions of exposure of each gas when measured against the limiting value estimated for the period under evaluation (i.e. the fraction of the incapacitating dose).

The total effective dose, $D_{tot}$, can be taken as being the additive effects of the various component doses ($D_1$, $D_2$, etc.) divided by their respective limits ($L_1$, $L_2$, etc.):

$$D_{tot} = \frac{D_1}{L_1} + \frac{D_2}{L_2} + \frac{D_3}{L_3} + \cdots + \frac{D_n}{L_n}$$

4.8 Detailed calculations

A detailed assessment of toxic lethality would involve a number of steps:

1) Calculate the time dependent concentration profile at the relevant locations.
2) Calculate the dose the population at these locations are subjected to. This may also involve taking account of the people moving to different levels of concentration during the period of analysis.
3) Calculate probits.
4) Calculate lethalties.
5) Multiply the lethality by the population at each location to obtain an estimate of the fatalities.
4.9 Practical calculations

The process outlined in Section 4.8 may be overly complex for integration into a typical QRA. A more common approach may be;

- Estimate the time that a person may be exposed to the gas before being able to shelter from it or move to a safe location.
- Use this and an appropriate probit to calculate the concentration required to result in a lethality of 0.5.
- Assume everyone within the contour representing this contour becomes a fatality and those outside survive.

Intermediate levels of complexity could involve sub-dividing the analysis into a number of concentration-lethality bands.

4.10 Recommendations

The following recommendations are made for the choice of probit:

- For studies of facilities falling under the UK regulatory regime, the probits based on HSE SLOT and SLOD values are recommended.
- If a regulatory regime has specified probits, then these probits should be used.
- For all other studies, the RIVM probits are recommended. However, note that the Dutch regulator is allowing the use of the UK HSE probit for carbon dioxide rather than the RIVM probit.
- If practical within the context of the study, a toxicologist should be consulted to advise on the most appropriate probit to use in a specific scenario.

Consideration should be given to the dose required to incapacitate an individual since if it is not practical to rescue them shortly afterwards, they are likely to continue to inhale the gas and result in a fatality. This is particularly relevant to Hydrogen Sulphide.
5. Oxygen depletion

The UK HSE [8] present typical physiological effects on humans from oxygen depletion as given in Table 5-1. The symptoms described are also dependent on duration of exposure so these require a period for these symptoms to manifest.

Table 5-1: Effects of oxygen depletion [8]

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

Oxygen constitutes approximately 20.9% 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:

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

Where \( \frac{dF_{O_2}}{dt} \) is the rate of change in fractional incapacitating dose per minute, and \( O_2 \) is the oxygen concentration [%] in air.

If the concentration of \( O_2 \) is constant, the fractional incapacitating dose varies linearly with time as shown in Figure 5-1.
**Figure 5-1:** Variation in fractional incapacitating dose for selected concentrations of $O_2$

**Example**

If the concentration of $O_2$ is 10%. The rate of change of fractional dose is

$$\frac{dF_{O_2}}{dt} = \frac{1}{(\exp [8.13 - 0.54 (20.9 - 10)])}$$

$$= 0.106/\text{min}$$

At this rate the fractional incapacitating dose is reached in $1/0.106 = 9.4$ minutes
The body’s ability to regulate its temperature depends on its ability to shed excess heat. This is dependent on the temperature and humidity of the surroundings. Exposure to high air temperature may cause heat stress resulting in a fatal outcome.

In an emergency where personnel are required to muster in a confined space the temperature of the air may rise as a result of hot gasses ingress to that space, conductivity of heat through the area’s bounding walls or from heat generated by equipment and the personnel themselves. This may lead to physiological effects such as difficulty in breathing or increased core temperature leading to collapse.

Table 6-1 indicates some physiological effects of elevated ambient air temperatures on humans based on full-scale fire tests and presented in [10].

**Table 6-1**: Effects of elevated temperature on humans

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Physiological Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>127</td>
<td>Difficult breathing</td>
</tr>
<tr>
<td>140</td>
<td>5-min tolerance limit</td>
</tr>
<tr>
<td>149</td>
<td>Mouth breathing difficult, temperature limit for escape</td>
</tr>
<tr>
<td>160</td>
<td>Rapid, unbearable pain with dry skin</td>
</tr>
<tr>
<td>182</td>
<td>Irreversible injury in 30 seconds</td>
</tr>
<tr>
<td>203</td>
<td>Respiratory systems tolerance time less than four minutes with wet skin</td>
</tr>
</tbody>
</table>

These temperatures are only likely to be achieved inside a building or refuge when the temperature of the surrounding walls is above the impairment criteria for the location. Workers would most likely have evacuated before this point is reached.

It is assumed that for temperatures below 70°C the situation inside a confined area will be uncomfortable but not fatal. Above this temperature humans may become incapacitated. The HSE [8] and DNV/Scandpower [10] quote the following relationship between air temperature and average time to incapacitation.

\[
t = 5.33 \times 10^9/T^{3.66}
\]

Where \( t \) is the exposure time to incapacitation (minutes), and \( T \) is the ambient temperature (°C).

The relationship is shown in Figure 6-1.
Figure 6-1: Relationship between air temperature and time to incapacitation

A method for the evaluation and interpretation of the thermal stress experienced in a hot environment is available in ISO 7933. [39].
7. Smoke

Smoke from hydrocarbon fires contains several gases which if inhaled can lead to incapacitation and ultimately, if not rescued, death. The main contributor is carbon monoxide, which will lead to the formation of carboxyhaemoglobin in the bloodstream of persons inhaling the smoke. The effects of carbon dioxide, sulphur dioxide and oxygen depletion also contribute. In addition, the temperature of the smoke gives rise to heat stress. Hence, the direct effect of smoke needs to consider the combined effects of these constituents: see Section 7.3.

Once personnel are mustered in the TR offshore, they continue to be vulnerable through smoke ingress. Reduction in visibility within a TR may render it impaired and instigate an evacuation. The analysis is primarily concerned with calculating the fractional dose from the various effects and summing these to obtain the time at which workers may become incapacitated. It is generally assumed that when conditions in the TR are such that workers are in danger of becoming incapacitated, they will attempt to evacuate or escape and incur the risks associated with those actions. If workers remain in the TR they would become unconscious and potentially fatalities. This Section provides guidance on the combination of factors which may lead to this situation.

This time dependent variation in the concentrations of CO, CO₂, SO₂ and O₂ need to be determined as a prerequisite to the vulnerability calculations. This will involve analysis of the concentration of smoke at the source of the fire, the dilution as it moves towards the TR, or other muster area, and the rate at which the smoke ingresses that location. These aspects are covered in [1].

7.1 Effects of carbon monoxide exposure

The UK HSE [8] present typical physiological effects on humans from exposure to carbon monoxide as given in Table 7-1.

**Table 7-1: Effects of carbon monoxide exposure [8]**

<table>
<thead>
<tr>
<th>CO concentration</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 ppm</td>
<td>Headache after 15 minutes, collapse after 30 minutes, death after 1 hour</td>
</tr>
<tr>
<td>2000 ppm</td>
<td>Headache after 10 minutes, collapse after 20 minutes, death after 45 minutes</td>
</tr>
<tr>
<td>3000 ppm</td>
<td>Maximum &quot;safe&quot; exposure for 5 minutes, danger of collapse in 10 minutes.</td>
</tr>
<tr>
<td>6000 ppm</td>
<td>Headache and dizziness in 1 to 2 minutes, danger of death in 10 to 15 minutes</td>
</tr>
<tr>
<td>12800 ppm</td>
<td>Immediate effect, unconscious after 2 to 3 breaths, danger of death in 1 to 3 minutes</td>
</tr>
</tbody>
</table>
Figure 7-1 shows graphs of probability of lethality for the concentrations in Table 7-1 based on the recommended probit for carbon monoxide given in Section 4. These would suggest that the exposure times for “danger of death”, if equated to lethalities close to 1, are similar for the lower concentrations (1500 – 3000 ppm) but that the concentration required for death in “1 to 3 minutes” may be higher.

Figure 7-1: Lethality for selected carbon monoxide concentrations

Guidance on the concentration of CO generated in various types of fire are given in [40].

7.2 Carboxyhaemoglobin formation

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 O₂), 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 effect on persons who smoke is greater because they will have a higher level of COHb prior to the effect of smoke inhalation.

There are two main models for calculating the time dependent variation in COHb; the model attributed to Stewart et al [41] and alternative proposed by Coburn, Forster, and Kane which is reported in [8] and [42].
7.2.1 Stewart model

The rate of change (per second) of the carboxyhaemoglobin level (COHb \%) is given by the following equation based on the work of Stewart et al [41]:

\[
\frac{dC_{\text{COHb}}}{dt} = \frac{(100 - C_{\text{COHb}})}{100} \times 3.37 \times 10^{-5} \times (CO \times 10^{-4})^{0.036} \times BR \times 1000
\]

where \ CO is the concentration of CO in \%,
\ BR is the breathing rate in m³/s.

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 CO₂ as discussed in Section 4.5 and given by the equation:

Breathing Volume Rate (l/min) = \exp(0.2496 \times \%CO₂ + 1.9086)

Breathing Volume Rate (m³/s) = \exp(0.2496 \times \%CO₂ + 1.9086) / 60000

Examples

For a carbon monoxide concentration of 5000 ppm (0.5\%) and a carbon dioxide concentration typical of atmospheric conditions of 420 ppm (0.042\%), the breathing rate is

\[
\exp(0.2496 \times 0.042 + 1.9086) / 60000 = 1.136 \times 10^{-4} \text{ m}^3/\text{sec}
\]

With an initial concentration of 0.15\% (typical for a non-smoker), the initial rate of increase in COHb\% is

\[
\frac{dC_{\text{COHb}}}{dt} = \frac{(100 - 0.15)}{100} \times 3.37 \times 10^{-5} \times 5000^{1.036} \times 1.136 \times 10^{-4} \times 1000
\]

\[
= 0.026\% /\text{sec}
\]

At this rate the level of COHb at 30 minutes would be 0.15 + 1800 \times 0.026 = 46.9\%. However, the rate of increase is also dependent on the existing level of COHb, e.g., at 50\% COHb the rate of increase is halved relative to the initial rate. The curve in Figure 7-2 generated using a numerical integration indicates that the level of COHb at this time would be 37.5\%.

If the concentration of CO₂ is also high this will affect the breathing rate and hence the rate of increase of COHb. For the same level of CO but in combination with a CO₂ concentration of 20000 ppm (2\%), the breathing rate is increased to

\[
\exp(0.2496 \times 2 + 1.9086) / 60000 = 1.852 \times 10^{-4} \text{ m}^3/\text{sec}
\]

The initial rate of increase in COHb\% is

\[
\frac{dC_{\text{COHb}}}{dt} = \frac{(100 - 0.15)}{100} \times 3.37 \times 10^{-5} \times 5000^{1.036} \times 1.852 \times 10^{-4} \times 1000
\]

\[
= 0.042\% /\text{sec}
\]

The result, as shown in Figure 7-2, is that the level of COHb builds up more quickly.
7.2.2 Coburn Forster Kane model

The Coburn Forster Kane model, as detailed in [42] can be expressed as

\[
\text{COHb} = \frac{\left( \frac{\text{CO}(1 - \delta)}{1316} \right) - \delta (\beta V_{\text{CO}} - \alpha D) + \beta V_{\text{CO}}}{\alpha}
\]

Where COHb is the final COHb blood concentration, CO is the concentration of CO breathed in ppm, D is the initial COHb blood concentration (usually taken as 0.0015 \(\text{ml CO/ml blood}\)), \(V_{\text{CO}}\) is the rate of endogenous CO production (taken as 0.007 ml/min), \(\alpha\) is the partial pressure of oxygen in capillaries (mmHg), \(\delta\) is the CO/O2 affinity for haemoglobin [the Haldane constant], and \(\beta\) is the oxyhaemoglobin concentration (ml/ml blood).

Taking typical values of 100 mmHg for \(P_{\text{O}_2}\), 218 for \(\delta\) and 0.2 ml/ml blood for \(O_2\text{Hb}\) give a value for \(\alpha\) of 2.29.
\[
\beta = \frac{1}{D_L} + \frac{P_L}{V_A}
\]

Where \(P_L\) is the dry barometric pressure of the lungs (713 mmHg)
\(D_L\) is the diffusion rate of carbon monoxide through the lungs, and
\(V_A\) is the ventilation rate for workers.

\[
\delta = \exp(-\alpha V_b / \beta)
\]

\(V_b\) is the blood volume (typically 5500ml for an average male), and
\(t\) is the time of exposure in minutes.

The UK HSE [16] uses the value of 2.29 for \(\alpha\) and 0.04 for \(\beta\). However, experiments commissioned by an IOGP member have been carried out on stressed mustering offshore workers which gave values of 72.4 ml/min/mmHg for \(D_L\) and 16430 ml/min for \(V_A\). Note that this value for \(V_A\) is significantly larger than the breathing rate used in Section 7.2.1 and reflects the increase in a working environment compared with being at rest. Using these values gives a value of 0.0572 for \(\beta\) and this is recommended.

**Example**

For a carbon monoxide concentration of 5000 ppm (0.5%) and using the default values above for an exposure period of 30 minutes

\[
\delta = \exp((-30 \times 2.29)/(5500 \times 0.0572)) = 0.80358, \quad \text{and}
\]

\[
\text{COHb} = \frac{\left[ \left( \frac{5000(1 - 0.73178)}{1316} \right) - 0.73178((0.0572 \times 0.007) - (2.29 \times 0.0015)) + (0.04 \times 0.007) \right]}{2.29}
\]

\[
= 32.7\%
\]

### 7.2.3 Comparison of models

Using CO concentrations of 500, 1000, 1500 and 2000 ppm together with recommended values for other parameters as given in Section 7.2.1 and Section 7.2.2 gives graphs of variation of COHb as shown in Figure 7-3.
7.2.4 Effects of carboxyhaemoglobin

Table 7-2 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 incapacitation becomes more certain within a relatively short period and recovery may not be possible. Death is increasing likely above levels of 60%. 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 7-2: Effects of COHb in blood [8]

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

For the purposes of risk assessment it is recommended that a person should be assumed to be incapacitated if their level of COHb reaches 15%.

The Coburn Foster Kane model can be rearranged to calculate the time to impairment for a given constant CO concentration as follows.

\[
t = -\frac{V_h \beta \log(\delta)}{\alpha}
\]

Where,

\[
\delta = \frac{CO - 1316(COHb A - V_{CO} \beta)}{1316(V_{CO} \beta - AD) + CO}
\]

A graph of time to impairment at a COHb of 15% is shown in Figure 7-4.

Figure 7-4: Time to 15% COHb versus CO concentration

7 Assuming recommended parameters
In practice, the CO concentration will vary with time and more complex numerical analysis will be required.

### 7.3 Combined effects of carbon monoxide, carbon dioxide, and oxygen depletion and heat

The time to incapacitation due to smoke is dependent on the combined effect build-up of carboxyhaemoglobin, heat stress, oxygen depletion and toxicity of the products of the combusting material. If the combusting gas contains significant amounts of Hydrogen sulphide (H\textsubscript{2}S), the products of combustion will include sulphur dioxide (SO\textsubscript{2}) and this may also ingress the TR.

The combined effect of these smoke constituents and heat stress (see Section 5) can be considered to give an incapacitating dose, $F_{\text{Tot}}$, calculated as follows:

$$F_{\text{Tot}} = F_{\text{COHb}} + F_{\text{Temp}} + F_{\text{O}_2} + \sum F_{\text{Toxic}}$$

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

$F_{\text{COHb}}$ is recommended to be calculated as COHb/0.15.

The fraction of incapacitating dose for each constituent is obtained by integration taking account of the variation in concentration with time.

For example, if the fractional doses of COHb, O\textsubscript{2} depletion, heat stress, CO\textsubscript{2} and SO\textsubscript{2} experienced by a person are 0.5, 0.05, 0.1 and 0.2 and 0.15 respectively

$$F_{\text{Tot}} = 0.5 + 0.05 + 0.1 + 0.2 + 0.15 = 1.0$$

And the person would be considered to be incapacitated and the location impaired.

Note that carbon monoxide should not be considered separately as a toxic component since its effect is accounted for through the build-up of COHb. In practice it is likely that the COHb fractional dose will dominate the total contribution.

In a QRA the individual and combined contributions are typically calculated on a time dependent basis in order to estimate the time at which a location becomes impaired.

### 7.4 Recommendations

Incapacitation of individuals and impairment of locations should be calculated using the combined fractional doses of the various effects.

The recommended method for calculating COHb build-up is the Coburn Foster Kane equation given in Section 7.2.2.

The impairing level of COHb is 15%.

Irrespective of the duration of exposure, a concentration of H\textsubscript{2}S in excess of 700 ppm should be considered fatal unless rescue can take place in a short period of time.
8. Cryogenic exposure

Accidental releases of liquids at very low temperatures, such as may occur from LNG or other liquified gas releases, may result in fatalities. This may be due to one of two mechanisms:

- Asphyxiation due to the displacement of oxygen by vaporising liquid
- Severe cold burns

The effect of oxygen depletion is covered in Section 5.

The effect of cold burns is mentioned in documents such as the Sandia report on the safety implications of LNG spills over water [43], AIChE guidance [44]. In each case reference to cold burns is in the context of its potential to cause injury in the event of LNG liquid contacting bare skin rather than death. Cold burns may also result from exposure to the evaporated vapour immediately above a pool. Releases from the vapour side of LNG vessels should also be considered since it is possible that breathing LNG vapours at extremely low temperatures would lead to cold burns to the lungs which may lead to fatalities. Direct contact with metal at cryogenic temperatures can damage skin tissue more rapidly than exposure to cold vapor. This can be a factor with platform ladders and handrails used in access and escape.

LNG liquid and evaporated vapour immediately above the pool are at a constant temperature corresponding to the normal boiling point, -160°C for LNG. After mixing with air the temperature rises and at around -113°C the vapour is lighter than air and becomes less of a threat.

Appropriate protective clothing protects against cryogenic burns but does not mitigate against cryogenic vapour inhalation.

Fatalities from cold burns could result from prolonged exposure to cryogenic liquid or cold vapour but guidance on the correlation between liquid temperature, extent of body coverage, exposure time and lethality is not readily available. In screening studies, it may be assumed that if any part of a person’s unprotected skin is impacted by cryogenic liquid they will become a fatality. However, this is very conservative, and a more appropriate set of assumptions would take extent of coverage and exposure time into consideration.

The recommended approach is to relate the probability of fatality to the temperature contours calculated from a consequence assessment. This provides a more direct link between the consequence assessment and the calculation of fatalities rather than basing it on the degree to which cryogenic liquid or vapour contacts skin. This is a similar approach to that taken in Section 2.6 for radiation.

AIChE guidance [44] presents a table on the effects of LNG spills at various temperatures. The criteria relating to human vulnerability are reproduced in Table 8 1.
Table 8-1: Suggested threshold temperatures for LNG cryogenic spills [44]

<table>
<thead>
<tr>
<th>Exposure Temperature (°C)</th>
<th>Phase</th>
<th>Escape Impaired</th>
<th>Impairment Probability</th>
<th>Contact Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>-160</td>
<td>Liquid Pool</td>
<td>Yes</td>
<td>99%</td>
<td>Immediate liquid cryogenic burns. Permanent damage to skin</td>
</tr>
<tr>
<td>-160</td>
<td>Vapour</td>
<td>Yes</td>
<td>50% - 70%</td>
<td>Cryogenic inhalation and damage to skin possible for short duration exposure</td>
</tr>
<tr>
<td>-113</td>
<td>Vapour</td>
<td>Yes</td>
<td>&lt; 10%</td>
<td>Cryogenic inhalation may be possible with long exposure duration</td>
</tr>
<tr>
<td>-73</td>
<td>Vapour</td>
<td>No</td>
<td>&lt; 1%</td>
<td>Some cryogenic inhalation</td>
</tr>
</tbody>
</table>

Other cryogenic liquids will boil at other temperatures, e.g., ethane at -89°C and propane at -42°C

Based on the above and generalising for all cryogenic liquids and vapours the following criteria are recommended.

Personnel outdoors exposed to liquid pools:
- Any personnel within liquid pools colder than -60°C are assumed to become fatalities. The combined effect of severe cold burns and shock would make escape unlikely.
- Personnel outside cold liquid pools or in pools above -20°C are assumed to be able to escape and hence suffer no fatalities.
- Between -60°C and -20°C the fatality rate is assumed to vary linearly.
- Cryogenic effects from any associated vapour cloud that is evolved are evaluated as described below. If ignited, fatalities from thermal effects are predicted to occur in the same way as for any flammable liquid.
- If ignited, fatalities from thermal effects are predicted to occur in the same way as for any flammable liquid.

Personnel outdoors exposed to jets and clouds of cold fluids:
- Engulfment in vapour below -180°C results in fatality.
- Engulfment in vapour above -70°C are considered to be survivable.
- 60% lethality is assumed at -160°C and 10% at -113°C. Between these values, and those given above, the lethality can be obtained by linear interpolation.
- If ignited, fatalities from thermal effects are predicted to occur in the same way as for any flammable liquid.

The lethality/temperature relationships in Figure 8-1
Figure 8-1: Lethality of personnel outdoors for cryogenic liquids/sprays and gas/vapour

The lethality of releases which are a mixture of liquid and vapour can be obtained by interpolating between the two lethality values in proportion to the relative mass release rates.

Personnel indoors are assumed to be protected against the effects of releases which occur outside the building.

The following should also be noted:

- Releases of dense phase carbon dioxide may result in the generation of dry ice projectiles which can endanger a worker in line with the release direction.
- Personnel not affected by the immediate effects of a cryogenic release may be prevented from mustering because of the potential for the obscuration of escape routes due to the condensation of humidity in the air.
9. Cold water immersion

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
- Availability of rescue facilities

The UK HSE have published a review of probable survival times for immersion in the North Sea [45]. This was carried out in 1996 but remains relevant. It states that while research prior to the review had focussed upon death by hypothermia, the dominant threat is from drowning. Nevertheless, the effects of cold water are debilitating and increase the probability of drowning.

Fatalities may result soon after immersion as the result of cold shock which cause the escapee to inhale water. If this period is survived and if the worker is provided with suitable buoyancy and insulation, they are likely to survive for a number of hours.

Several mathematical models are available, but the report concludes that the Wissler model [46] “appears to be broadly accepted for predicting time to rectal temperatures of 34°C in calm, resting conditions”. At this temperature it is assumed that an immersed person would be incapable of self-help and have a high risk of drowning. The “standard man” used in these assessments falls within the thinnest 2% of the offshore population. He is assumed to be of average fitness, is uninjured, and is not in a distressed psychological state or prone to panic.

The model estimates survival times for five different classes of clothing:

- Working clothes only
- Membrane suit with 1 litre leakage
- Membrane suit with dry clothing
- Insulated suit with 1 litre leakage
- Insulated suit with dry clothing

Membrane suits are designed to keep the wearer dry but have limited insulation properties. Survival suits are intended to keep the wearer warm but are not necessarily watertight. The curves are shown in Figure 9-1 and have been reproduced from [45].
These times are representative for “calm” water defined as Beaufort 0 – 2. For wind speeds greater than this it is suggested that the survival time is halved to account for the physical effort that is required in turbulent sea conditions. It should be noted that the probability of wind speeds in Beaufort 0–2 is relatively low in most areas of the world so the reduced time for survival will apply in most cases.

It is also suggested in [45] that if a suit leaks it will decrease buoyancy and that this should be modelled as a further reduction of 10%.

It is recommended that separate account is taken of the likelihood of drowning due to the initial cold shock and that this will occur shortly after immersion and before a rescue can be affected. Probabilities for this occurring are a matter of judgement and will be dependent on the water temperature and sea state. Suggested values are 0.1 for water temperatures below 10°C and 0.05 between 10°C and 20°C.
Example 1:
A group of uninjured survivors are immersed in moderate seas associated with Beaufort wind force 4 with a sea temperature of 5°C. They are wearing non-leaking membrane suits with lifejackets.

There is an initial threat posed by the inhalation of water due to the sudden shock of immersion which results in the inability to control breathing. At this temperature an estimated lethality of 0.1 is applied. If the initial immersion is survived it is assumed from Figure 9.1 that the core temperature of the “standard man” will fall to 34°C in 2 hours for calm water conditions. However, in sea conditions associated with Beaufort wind force 4 this will be reduced to 1 hour.

Example 2:
The same conditions apply for the standard man but in this case the suits leak and reduce the insulation value of the clothing worn beneath it. From Figure 9.1 the predicted time to cooling to 34°C is reduced to around 75 minutes for calm conditions. However, this is reduced by 50% to account for the Beaufort 4 sea conditions and a further 10% to account for the loss of buoyancy effect (combined value of 55%). This gives a survival time of approximately 34 minutes.

Example 3:
The standard man is immersed in water at a temperature of 10°C and is wearing a leaking insulated suit. This temperature is at the lower end of the range where a lethality of 5% may be appropriate. From Figure 9.1 it is seen that the survival time is 8 hours. If the sea state is such that the 50% factor applies, this would be reduced to 4 hours and further reduced to around 3½ hours in the event to account for loss of buoyancy due to suit leakage.

Further details on the calculation of in-water fatalities are contained in the Evacuation, Escape and Rescue RADD document. [47]
10. Guidance on use of data

10.1 General validity

The criteria set out in Sections 2 to 9 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 those discussed explicitly in this datasheet, their effects should be incorporated in the analysis, e.g., by using the probits for those materials.

10.2 Uncertainties

Individuals’ vulnerabilities to all the potential causes of injury/fatality discussed in this document 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] which affects the time of exposure
- 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 these factors should be considered for their relevance and impact when using the criteria.
11. Recommended data sources for further information

For all of the impairment criteria except cold water, the HSE document [8] provides a good general summary of vulnerabilities and physical effects of the hazards discussed in Sections 2 to 9. It draws on a range of other published studies referenced within it.

Supplementary references are as follows:

- **Fire**  
  API [9]
- **Explosion**  
  API [48]
- **Toxic gases**  
  RIVM [27] and HSE [49]
- **Heat Stress**  
  ISO 7933 [39]
- **Smoke**  
  U.S. Department of Health [42], Stewart et. al. [41], SFPE [50] and Purser [51]
- **Cold Water**  
  HSE (Robertson and Simpson) [45]
12. References


Appendix A: 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 and/or toxic gas
- Explosion or structural collapse resulting in the TR being breached or otherwise ceasing to be habitable

A.1 Smoke ingress

Smoke ingress to the TR also results in heat build-up. CO₂ build-up and oxygen depletion are also enhanced through respiration. 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 and that this can be modelled using a constantly stirred tank reactor (CSTR) model.

The rate of change of CO concentration in the TR are evaluated as:

\[
\frac{d \text{Conc}_{\text{CO}}}{dt} = (\text{Conc}_{\text{CO}_{\text{in}}} - \text{Conc}_{\text{CO}_{\text{out}}})(\text{Vent Rate})
\]

Where:
- \( \frac{d \text{Conc}_{\text{CO}}}{dt} \) is the rate of change of CO concentration per second
- \( \text{Conc}_{\text{CO}_{\text{in}}} \) is the concentration of CO inside the TR
- \( \text{Conc}_{\text{CO}_{\text{out}}} \) is the concentration CO outside the TR, and
- \( \text{Vent Rate} \) is the TR ventilation rate (air changes per second)

The rate of change of CO₂ concentration in the TR is calculated as the sum of the contribution from smoke and that generated by the workers mustered in the enclosed space:

\[
\frac{d \text{Conc}_{\text{CO}_2}}{dt} = \left(\text{Conc}_{\text{CO}_2_{\text{in}}} - \text{Conc}_{\text{CO}_2_{\text{out}}}ight)(\text{Vent Rate}) + \frac{C \times N \times BR}{V}
\]

where:
- \( C \) is the concentration of CO₂ in exhaled air, assumed to be 3%
- \( N \) is the number of persons in the TR
- \( BR \) is an average individual's breathing rate [m³/s], and
- \( V \) is the TR volume [m³]
The O2 concentration in the TR is calculated as:

\[
\frac{d \text{ConcO}_2}{dt} = (\text{ConcO}_2\text{in} - \text{ConcO}_2\text{out})(\text{Vent Rate}) - \frac{P \times N \times \text{BR}}{V} 
\]

where \( P \) is the percentage of inhaled air that is converted from O2 to CO2, usually 3%

The initial concentrations are all taken to be zero, except O2 which is taken to be 20.9%.

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

\[
\frac{dT}{dt} = \frac{Q_1 + Q_2}{V\rho C} + (T_{\text{in}} - T_{\text{out}})(\text{Vent Rate}) 
\]

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)
- \( T_{\text{in}} \) is the temperature inside the TR
- \( T_{\text{out}} \) is the temperature outside the TR, and

and
- \( V\rho C \) is the heat capacity of the TR air (volume \( \times \) density \( \times \) specific heat capacity).

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 fractional incapacitating dose of COHb, CO2, O2 depletion, and temperature exceeds unity.

### A.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.

### A.3 Ingress of gas

In the same way that smoke may ingress a shelter, flammable and/or toxic gas may also accumulate. The build-up may be calculated using the CSTR model described in Section A.1.

Although it is conventional to assume a homogeneous dispersion of the flammable gas throughout the enclosed volume it is possible that some local areas will have an increased concentration bringing it into the flammable region while the average concentration is below this. Consequently, it is appropriate to consider that the TR is impaired if the average concentration exceeds a given fraction of lower flammable limit (LFL). A fraction of 60% is recommended.
For toxic gasses it may be appropriate to consider the TR to be impaired when the combination of concentration and exposure time reaches Acute Exposure Guideline Level 2 (AEGL-2). This is the airborne concentration (expressed as ppm or mg/m$^3$) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. Concentrations for various gasses may be obtained from on-line sources such as the United States Environmental Protection Agency (EPA) [52]. Table A-1 gives concentrations for various gasses taken from this.

**Table A-1:** AEGL-2 levels For selected gasses (ppm) [52]

<table>
<thead>
<tr>
<th>Material</th>
<th>10 mins</th>
<th>30 mins</th>
<th>1 hour</th>
<th>4 hours</th>
<th>8 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>220</td>
<td>220</td>
<td>160</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>420</td>
<td>150</td>
<td>83</td>
<td>33</td>
<td>27</td>
</tr>
<tr>
<td>Chlorine</td>
<td>2.8</td>
<td>2.8</td>
<td>2</td>
<td>1</td>
<td>0.71</td>
</tr>
<tr>
<td>Hydrogen Sulphide</td>
<td>41</td>
<td>32</td>
<td>27</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>95</td>
<td>34</td>
<td>24</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>20</td>
<td>25</td>
<td>20</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>

**A.4 Structural collapse**

Structural collapse and/or breach of the TR is addressed in the *Structural Risk for Offshore Installations* datasheet [53] and the *Vulnerability of Plant/Structure* datasheet [25].
Appendix B: Comparison of probits for selected substances and concentrations

These graphs are shown as examples for particular concentrations which give an indication of which probit is most conservative for a given exposure duration and to demonstrate the variability of results obtained with the use of different probits. However, it should be noted that equivalent graphs for other concentrations would not necessarily indicate the same probit as the most conservative.

Carbon Monoxide – 2,000 ppm

Chlorine – 500 ppm
Hydrogen Sulphide – 1,000 ppm

Sulphur Dioxide – 5,000 ppm
Hydrogen Fluoride – 10,000 ppm

Nitrogen Dioxide – 250 ppm
Appendix C: Probits

A probit is a function that relates lethality to the intensity or concentration of a hazardous effect and the duration of exposure.

\[ Y = a + b \ln V \]

where:  
- \( Y \) is the probit value  
- \( a, b \) are constants, and  
- \( V \) is the “dose”.

For toxic materials:

\[ V = (c^n t) \]

where  
- \( c \) = concentration,  
- \( n \) = constant, and  
- \( t \) = exposure duration.

For thermal radiation:

\[ V = (l^{4/3} t) \]

where  
- \( l \) = thermal radiation, and  
- \( t \) = exposure duration.

The time of exposure is normally measured in minutes for toxicity probits but may be seconds for thermal.

The lethality of the dose can be related to the probit

\[ \text{Lethality} = \left(-\text{erf}\left(\frac{5 - Y}{\sqrt{2}}\right) + 1\right)/2 \]

Where \( Y \) is the probit value.

The error function \( \text{erf}(z) \) is evaluated using the equation

\[ \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} \, dt \]
The following table shows the probit values for a given lethality percentage affected (lethality).

<table>
<thead>
<tr>
<th></th>
<th>0%</th>
<th>1%</th>
<th>2%</th>
<th>3%</th>
<th>4%</th>
<th>5%</th>
<th>6%</th>
<th>7%</th>
<th>8%</th>
<th>9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>-</td>
<td>2.67</td>
<td>2.95</td>
<td>3.12</td>
<td>3.25</td>
<td>3.36</td>
<td>3.45</td>
<td>3.52</td>
<td>3.59</td>
<td>3.66</td>
</tr>
<tr>
<td>10%</td>
<td>3.72</td>
<td>3.77</td>
<td>3.82</td>
<td>3.87</td>
<td>3.92</td>
<td>3.96</td>
<td>4.01</td>
<td>4.05</td>
<td>4.08</td>
<td>4.12</td>
</tr>
<tr>
<td>30%</td>
<td>4.48</td>
<td>4.50</td>
<td>4.53</td>
<td>4.56</td>
<td>4.59</td>
<td>4.61</td>
<td>4.64</td>
<td>4.67</td>
<td>4.69</td>
<td>4.72</td>
</tr>
<tr>
<td>40%</td>
<td>4.75</td>
<td>4.77</td>
<td>4.80</td>
<td>4.82</td>
<td>4.85</td>
<td>4.87</td>
<td>4.90</td>
<td>4.92</td>
<td>4.95</td>
<td>4.97</td>
</tr>
<tr>
<td>50%</td>
<td>5.00</td>
<td>5.03</td>
<td>5.05</td>
<td>5.08</td>
<td>5.10</td>
<td>5.13</td>
<td>5.15</td>
<td>5.18</td>
<td>5.20</td>
<td>5.23</td>
</tr>
<tr>
<td>60%</td>
<td>5.25</td>
<td>5.28</td>
<td>5.31</td>
<td>5.33</td>
<td>5.36</td>
<td>5.39</td>
<td>5.41</td>
<td>5.44</td>
<td>5.47</td>
<td>5.50</td>
</tr>
<tr>
<td>70%</td>
<td>5.52</td>
<td>5.55</td>
<td>5.58</td>
<td>5.61</td>
<td>5.64</td>
<td>5.67</td>
<td>5.71</td>
<td>5.74</td>
<td>5.77</td>
<td>5.81</td>
</tr>
<tr>
<td>80%</td>
<td>5.84</td>
<td>5.88</td>
<td>5.92</td>
<td>5.95</td>
<td>5.99</td>
<td>6.04</td>
<td>6.08</td>
<td>6.13</td>
<td>6.18</td>
<td>6.23</td>
</tr>
<tr>
<td>90%</td>
<td>6.28</td>
<td>6.34</td>
<td>6.41</td>
<td>6.48</td>
<td>6.55</td>
<td>6.64</td>
<td>6.75</td>
<td>6.88</td>
<td>7.05</td>
<td>7.33</td>
</tr>
</tbody>
</table>

Examples

A lethality of 33% has a probit value of 4.56.

A lethality of 86% has a probit value of 6.08.

Alternatively, the following table shows the lethality percentage for a given probit value.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>1</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.02%</td>
<td>0.03%</td>
<td>0.05%</td>
<td>0.07%</td>
<td>0.10%</td>
</tr>
<tr>
<td>2</td>
<td>0.13%</td>
<td>0.19%</td>
<td>0.26%</td>
<td>0.35%</td>
<td>0.47%</td>
<td>0.62%</td>
<td>0.82%</td>
<td>1.07%</td>
<td>1.39%</td>
<td>1.79%</td>
</tr>
<tr>
<td>3</td>
<td>2.28%</td>
<td>2.87%</td>
<td>3.59%</td>
<td>4.46%</td>
<td>5.48%</td>
<td>6.68%</td>
<td>8.08%</td>
<td>9.68%</td>
<td>11.51%</td>
<td>13.57%</td>
</tr>
<tr>
<td>4</td>
<td>15.87%</td>
<td>18.41%</td>
<td>21.19%</td>
<td>24.20%</td>
<td>27.43%</td>
<td>30.85%</td>
<td>34.46%</td>
<td>38.21%</td>
<td>42.07%</td>
<td>46.02%</td>
</tr>
<tr>
<td>5</td>
<td>50.00%</td>
<td>53.98%</td>
<td>57.93%</td>
<td>61.79%</td>
<td>65.54%</td>
<td>69.15%</td>
<td>72.57%</td>
<td>75.80%</td>
<td>78.81%</td>
<td>81.59%</td>
</tr>
<tr>
<td>6</td>
<td>84.13%</td>
<td>86.43%</td>
<td>88.49%</td>
<td>90.32%</td>
<td>91.92%</td>
<td>93.32%</td>
<td>94.52%</td>
<td>95.54%</td>
<td>96.41%</td>
<td>97.13%</td>
</tr>
<tr>
<td>7</td>
<td>97.72%</td>
<td>98.21%</td>
<td>98.61%</td>
<td>98.93%</td>
<td>99.18%</td>
<td>99.38%</td>
<td>99.53%</td>
<td>99.65%</td>
<td>99.74%</td>
<td>99.81%</td>
</tr>
<tr>
<td>8</td>
<td>99.87%</td>
<td>99.90%</td>
<td>99.93%</td>
<td>99.95%</td>
<td>99.97%</td>
<td>99.98%</td>
<td>99.99%</td>
<td>99.99%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>9</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Examples

A probit value of 4.1 corresponds to a lethality of 18.41%.

A probit value of 6.7 corresponds to a lethality of 95.54%.
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, but injury thresholds are identified where appropriate. It is part of IOGP’s Risk Assessment Data Directory series.