DETERMINATION OF SAFETY DISTANCES

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DETERMINATION OF SAFETY DISTANCES

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1 Introduction

This document establishes for the first time the basic principles to calculate appropriate safety distances for the industrial gas industry. It is intended that future EIGA working groups use this document as an aid to writing or revising any codes of practice which involve specifying separation distances for safe equipment layout. This will ensure a consistent and technically sound approach in future work. It is recommended that a process safety specialist is co-opted as a member of these working groups to perform the risk and consequence calculations described in this note. Although computer models and example calculations are given, it is expected that future improvements in near field dispersion modelling and failure rate data would be used by the specialist.

2 Scope and purpose

2.1 Scope

The work process can be used for equipment required for the storage and processing of all industrial, medical and speciality gases. These may be in cryogenic liquid, pressurised liquid or gaseous phase. Offsite transport and pipelines are not specifically addressed.

2.2 Purpose

The primary objective of this document is to define a philosophy to determine suitable separation distances for all equipment, pipework and storage to allow member companies to develop consistent standards across the industry.

3 Definitions

3.1 Definitions in risk assessment

Effect: Immediate or delayed result of an exposure to a hazard

Event: The realisation of a hazard

Frequency: An expression of how often a considered occurrence takes place in a given time

Hazard: An inherent property of a substance, agent, source of energy or situation having the potential of causing undesirable consequences and/or effect.

Probability: An expression of the chance that a considered occurrence will take place.

Risk: The combination of a stated effect and its probability of occurring.

3.2 Definition of safety distance

Within this document, the safety distance is the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident.
4 Basis of approach

The safety distance from a piece of equipment is to provide a minimum separation which will mitigate the effect of any likely event and prevent it from escalating into a larger incident. The safety distance will also provide protection for the equipment from foreseeable external impacts (e.g. roadway, flare) or activities outside the control of the operation (e.g. plant or customer station boundary).

The safety distance is not intended to provide protection against catastrophic events or major releases and these should be addressed by other means to reduce the frequency and/or consequences to an acceptable level.

The safety distance is a function of the following:

- The nature of the hazard (e.g. toxic, flammable, oxidising, asphyxiant, explosive, pressure etc.).
- The equipment design and the operating conditions (e.g. pressure, temperature) and/or physical properties of the substance under those conditions.
- Any external mitigating protection measures (e.g. fire walls, diking, deluge system etc.) which reduce the escalation of the incident.
- The "object" which is protected by the safety distance i.e. the harm potential (e.g. people, environment or equipment).

The provision of adequate distance or separation zones around equipment is a fundamental consideration for safe layout. By understanding the protection afforded by increasing the safety distance, one can optimise the safety protection of a piece of equipment. In most cases the safety distance to provide protection from all possible events is not practicable. Therefore an assessment of the frequency of the event and the potential consequence is necessary to understand which risks can be reasonably mitigated by a safety distance. If the safety distance is too large, additional mitigating or prevention measures should be considered and the safety distance re-calculated. Figure 1 shows a typical example for a pressure vessel and connecting pipework.

**SAFETY DISTANCES**

![Safety Distances Diagram]

1. Minor Leaks (e.g. valve or fittings)
2. Vent to atmosphere
3. Line break
4. Vessel Failure

Ft: Threshold frequency
4.1 Summary of method

- Identify the hazard sources and events (e.g. release of gas) taking into account the likelihood.
- Calculate the effects on neighbouring objects taking into account mitigating factors.
- Determine the safety distance to each object to meet the minimum hazard criteria.
- Consider additional prevention or mitigating factors and re-calculate safety distance.

5 Selection of events

5.1 Criteria for determining the individual harm exposure threshold value

The harm exposure threshold frequency should have a legitimate basis, which is accepted by authorities and the general public at large. A legitimate basis could be provided for when this threshold value is based on facts of life and could be related to the natural death probability or natural fatality risk.

This natural fatality risk is for most industrial countries about the same. This natural fatality risk varies only marginally downwards with time. The slight improvement with time reflects mostly the improved living and working conditions.

It is accepted philosophy that the risk from a hazardous activity should not be significant when compared with risk in everyday life. The lowest natural fatality risk of an individual lies between the ages of around 5 and 15 years, and it is this rate that should be used as a root base from which the harm exposure threshold value is derived.

The Dutch government in preparing their national risk management policy "Premises for Risk Management" 1988-9 used a base death rate of $1 \times 10^{-4}$ per annum for their population in the age range 10 to 14 years. UK Heath and Safety Executive advice on risk criteria includes use of UK data of $2.8 \times 10^{-4}$ per annum for 5 to 14 year olds (Central Statistical Office 1987).

Accounting for variations between sources, the present natural minimum individual fatality risk should be taken as $2 \times 10^{-4}$ per annum. This frequency taken for westernised industrialised populations at large entails all harm exposures, which could be broken down in the large segments - occupational - traffic - home/leisure, each of them contributing to one third of the harm exposure.

Derived from the above the individual fatal risk potential for determining safety distances should not be higher than $0.7 \times 10^{-4}$ per annum.

The criteria proposed to determine the harm exposure threshold chosen as half of the above fatal risk frequency as a reflection of the mitigation provided for in our industrial gas industry and to improve over the present European fatal accident rate.

Thus the individual harm exposure threshold (to be defined as $F_t$) for determining safety distances is thus proposed as

$$F_t =< 3.5 \times 10^{-5} \text{ per annum.}$$

For events where the risk of harm is below $F_t$, no safety distance criteria need be established. For deviations which are likely to occur during the life of the equipment or occur during normal operation (e.g. venting) then the safety distance should be calculated or mitigation provided to produce a no harm effect.

Defining the "harm criteria" as being approximately a 1% chance of individual risk of serious injury or fatality, then for less likely events but with a frequency determined to be higher than the threshold
value \( F_l \) the safety distance is calculated to the harm criteria given in Section 6 up to a frequency of 100 \( F_l \). Since the harm criteria is set at a 1% risk of serious injury or fatality, it follows that deviations above a frequency of 100 \( F_l \) may contribute to an unacceptable individual fatal risk frequency. Therefore for deviations above 100 \( F_l \) the criteria for the safety distance should be the no harm effect as given in Section 6 (the "no harm criteria").

This can be illustrated by means of Figure 2 below.

![Figure 2](image)

5.2 Methodology to identify harm potential

5.2.1 Introduction

The objective is to identify foreseeable events - called deviations - from industrial gas processes and equipment, which have direct harm potential to other entities be it neighbouring equipment, activities or persons. In addition deviations with potential for harm to the industrial gas process from external sources need also to be defined. All of the identified deviations will then be subjected to the criteria laid down for defining the safety distances in order to obtain those values that should be assigned to justifiable safety distances.

Equipment and processes can be thoroughly reviewed for deviation scenarios using several suitable identification techniques. Some of them are indicated further on in this Section.

5.2.2 Basic requirements for deviation review to determine harm potential

In order to conduct a deviation review the following is required:

1. Information on physical/chemical properties of the gases under review.
2. Construction drawing/flow sheet of the system process equipment or component under review.
3. A review team, made up of experienced and qualified persons with preferably multi-discipline background (production, safety, engineering, depending on the complexity of the review).
5.2.3 Harm/effect checklist technique

This technique is based on the knowledge of actual previous accidents and incidents in our industry. The root causes of the sources of the Industrial Gas Industry accidents causing the harm is given in Table 1: Harm effect list.

### TABLE 1

**Harm effect checklist**

**Relevant to the definition of a safety distance**

<table>
<thead>
<tr>
<th>Environmental and mankind</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen enrichment</td>
<td>Heat of radiation</td>
</tr>
<tr>
<td>Oxygen deficiency</td>
<td>Heat of conduction</td>
</tr>
<tr>
<td>Fog – visibility</td>
<td>Heat of convection</td>
</tr>
<tr>
<td>Snow/ice - mechanical stress, slip/fall</td>
<td>Flame impingement</td>
</tr>
<tr>
<td>Toxic/harmful substance exposure</td>
<td>Cold of conduction</td>
</tr>
<tr>
<td>Corrosive substance exposure</td>
<td>Cold of convection</td>
</tr>
<tr>
<td>Water/soil contamination</td>
<td>Cold by impingement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kinetic</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Striking objects</td>
<td>Electric current</td>
</tr>
<tr>
<td>Missiles</td>
<td>Arc flash</td>
</tr>
<tr>
<td>Shock waves</td>
<td>Static electricity</td>
</tr>
<tr>
<td>Automotive motion</td>
<td>Electronic interference</td>
</tr>
<tr>
<td>Vibration</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Others</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UV radiation</td>
<td></td>
</tr>
<tr>
<td>Metal corrosion</td>
<td></td>
</tr>
<tr>
<td>Material (plastic) ageing</td>
<td></td>
</tr>
<tr>
<td>Chemical reaction/contamination</td>
<td></td>
</tr>
</tbody>
</table>

The type of equipment and components involved in such accidents and the type of leak/event are provided for in Table 2: List of leak sources and leak scenarios. The sources of leaks are often common sources and safety distances determined on the basis of tables are intended to safeguard against or mitigate harm of such leaks but do generally not safeguard against catastrophic leaks.

### TABLE 2

**Checklist of leak sources and leak scenarios**

<table>
<thead>
<tr>
<th>Type of equipment/component</th>
<th>Type of leak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipework</td>
<td>Pinholes, pipe split</td>
</tr>
<tr>
<td>Flanges</td>
<td>Gasket failure (mechanical failure/burn out/brittleness). Thermal movement/material creep</td>
</tr>
<tr>
<td>Weld connection</td>
<td>Weld crack</td>
</tr>
<tr>
<td>Solder connection</td>
<td>Solder crack, solder melt</td>
</tr>
<tr>
<td>Union connection</td>
<td>Thermal movement, leak</td>
</tr>
</tbody>
</table>
Screw connection: Leak, sealant creep, material split
Hose connection: Seal leak, material split, human error
Valves: Stem leak, seat leak, bonnet/housing split, opened by impact
Hoses: Perforation, split
Instruments: Element rupture
Regulators: Diaphragm rupture/seal leak/downstream rupture (overpressure). Housing split/flash fire perforation (O₂)
Solenoid valves: Seat leaks
Pumps: Perforation by O₂ flash fire/seal leak
Cylinders: Perforation, rupture

When using the harm/effect and leak source lists as checklist it has been stated that up to 95% of the deviation scenarios will be captured (Ref: Rijnmond Report 1982)

The following sequence should be followed when performing the analysis:

1. Make inventory on (hazardous) substances.
2. Review and list their intrinsic hazards.
3. Make inventory on equipment/components used in system or process.
4. Identify hazard sources and possible exposed objects (people, equipment...)
5. Review above against harm/effect checklist by asking the question
   IS THE LISTED HARM APPROPRIATE FOR THE OBJECT UNDER CONSIDERATION AND CAN IT BE GENERATED?
   and check against leak source and leak scenarios list by asking the question
   WHICH EQUIPMENT OR COMPONENT IS A SOURCE OF HARM?
   and then
   WHAT LEAK SCENARIOS ARE POSSIBLE?
6. Proceed through all sources and exposed objects.
7. Include external sources (LPG storage, vehicles...) with the gas process equipment as objects by asking the question
   WHAT COULD BE A SOURCE OF HARM TO THE GAS PROCESS EQUIPMENT?

A worksheet is proposed in Section 5.4 to simplify the documentation of this and subsequent steps.
5.2.4 Other identification techniques

The harm/effect checklist can be complemented with other hazard identification techniques like

- What if/How can analysis
- FMEA, Failure Mode and Effect Analysis
- HAZOP, Hazard and Operability Study
- Event tree and fault tree analysis

What if/how can and FMEA methods both rely like the harm/effect checklist on knowledge and experience of the team. Both techniques are a good complementary technique to the harm/effect checklist method. The HAZOP is a systematic method, very time consuming in practice and might not necessarily provide more hazard identification than the other methods. The event tree and fault tree techniques can also be used for data prediction.


5.3 Methodology for the evaluation of the safety distance from the identified hazard events

The event tree in figure 3 shows the necessary steps for the evaluation of the safety distances required on a given equipment on which hazard sources and sensitive objects have been identified; the process is iterative. The method shall be applied on each couple (hazard source, object) previously defined. The screening of the foreseeable hazard events called "deviations" associated with the hazard sources and the objects shall be based firstly on probabilities and frequencies, then on harm criteria (see Section 6) as described hereafter.
For a given object, the successive questions to be answered concerning a possible hazard event or deviation are:

1. *What is the frequency $F_d$ of the concerned deviation?*

   (e.g., frequency of a specific pipe or valve leakage, modified by prevention device)

   $F_d$ may increase/decrease as a function of the potential source population (e.g., the number of valves on a given panel or the probability of delayed or immediate ignition).

2. *Is this frequency less than fixed individual harm exposure threshold frequency $F_t$?*

   (see proposed $F_t$ criteria in Section 2.1)

   If the answer is YES, the considered deviation is low enough to be excluded from the calculation of the safety distance, so examine another deviation.

   If the answer is NO, the next question is:

3. *Is there a geometric risk reduction to take into account, that is to say a probability $P_g<1$ that the object would be exposed to the hazard source?*

   (e.g., the probability that a jet fire would point toward a specific piece of equipment is generally less than 1)

   If no geometric risk reduction is identified, $P_g=1$.

   Missiles case: the probability $F_d*P_g$ that a missile would reach a specific object is generally very low; consequently, a safety distance for the protection against missiles is not considered in this Technical Note.

4. *Is $F_d*P_g$ less that $F_t$?*

   If the answer is YES, the risk of reaching the object is low enough to eliminate the considered deviation from the calculation of the safety distance, so go through another deviation (this can mean consider the same object but another source).

   If the answer is NO, the next questions is:

5. *Is there any mitigating measure, whose probability of failure $P_m<1$ is known?*

   (e.g., a deluge system can protect a piece of equipment from a damaging heat flux. See section 5)

   If there is no mitigating measure likely to eliminate the damage caused by the considered deviation or if it is inoperative $P_m=1$.

6. *Is $F_d*P_g*P_m$ less than $F_t$?*

   If the answer is YES, the considered deviation is associated with a sufficient mitigation to be excluded from the calculation of a safety distance, so examine another deviation.

   If the answer is NO, the next question is:

7. *Is $F_d*P_g*P_m$ less than $100*F_t$?*

   If the answer is YES, taking into account geometric risk reduction and reliability of mitigating measure(s), the considered deviation is rather unlikely to cause the feared damage. This allows to choose distance the calculated distance $X_d$ related to effects defined as “harm criteria”.


If the answer is NO, in spite of geometric risk reduction and mitigation, the feared damage frequency remains too high compared to the fixed threshold frequency \( F_t \). Therefore, the recommended safety distance shall be the calculated distance \( X_d \) related to "no harm".

In both cases, the last question is:

8. *Is this distance \( X_d \) acceptable as a safety distance linked to the considered object?*

If the answer is YES, go through another deviation iteratively until all the identified deviations have been examined and the corresponding safety distances determined. The largest distance will be the safety distance linked to the considered object.

Then, repeat the process with another object and the associated possible deviations to find another safety distance linked to this other object. Carry on the process with other identified sources...and so on until all the identified objects have been examined and the linked safety distances determined. The largest distance will be the FINAL safety distance.

If the answer is NO, the feared damage frequency has to be reduced. This can be done using:

- an alternative prevention, thus reducing the considered deviation frequency \( F_d \)
- or the alternative mitigation, thus reducing the probability of mitigation inefficient \( P_m \)

With the process complete, there will be a list of safety distances related to types of objects.

5.4 Worksheet for evaluation of hazard events frequency

Section 5.2 gives the method proposed to identify foreseeable harm events, and section 5.3 establishes how the frequency of the anticipated event (the deviation) should be used to determine whether a safety distance is to be linked from the event to the considered object.

Appendix D at the end of this document is a worksheet laid out expressly to complete this methodology systematically.

The technique (after carrying out items 1-3 in Section 5.2) is to

1. Specify the SOURCE (heading A).
2. Categorise the OBJECTS being considered with this source (heading B).
3. Using the harm/effect checklist (Table 1), enter the appropriate harm for the listed object(s).
4. Determine the equipment that can be the source of this harm (Table 2) and the type of deviation involved.
5. Estimate a value for \( F_d \) and enter the necessary multipliers for population of the leak source and any conditional probabilities.
6. Complete the methodology in Section 5.3 to determine whether safety distance calculations are required.
7. Return to (4) and examine another leak scenario or equipment source.

It is suggested that for any harm event the deviations ought to be examined in order from the highest estimated value of \( F_d \), since in this way once a value of \( F_d \times P_g \times P_m \) below the harm exposure threshold has been reached no less frequent events need be examined.

Worked examples of the methodology including filled-in worksheets are given in the Appendices.

For some harm/effects, objects can be grouped (e.g. individuals with plant fence line -general public for fires), otherwise a new worksheet should be started for each source/object combination.

It can be seen that frequency event estimation is an important part of the methodology. Ideally a group or organisation examining a particular type or configuration of equipment should have some plant specific data on the failure rates for the components in the system. However this is unlikely to be the case in many circumstances, in which case published generic data has to be examined for suitability for use for the scenarios in Table 2.
Published major data sources include:

- Institute of Electronic and Electrical Engineers (USA) "Guide to...Reliability Data for Nuclear Power Generating Stations" IEEE Standard 500 (1982).

These all generally suffer by being non-specific as to the type and quality of the process industries sourced, often contain a lot of old information not applicable for modern equipment or management standards, and also may no distinguish between size of the event in the sample.

For this reason the worked examples in the Appendixes examined the following published references, which not only gave failure rate data for the types of event considered in the above methodology but also indicated a distribution of the data between sizes of the event (e.g."small", "large" and "rupture").

- Safety and Research Directorate of UKAEA Report SRD/HSR/R488 "An initial prediction of the BLEVE frequency of a 100 Te Butane storage" Blything and Reeves 1988 (Appendix 1)

Example frequencies for leak terms from these sources are given in Appendix C with comparative values from various EIGA members in-house data sources. The adopted values are those frequencies used in the examples in Appendices A & B.

6 Criteria for harm potential

The object of safety distances is to provide protection by ensuring that the effects of an event do not cause a risk of injury to people or failure of equipment. In order to calculate a safety distance an assumption has to be made for the threshold level of the effect that can cause a defined severity of failure or injury.

For the purpose of calculating a safety distance, this severity can be defined for people at two levels required by the method of analysis presented in Section 2. A “harm” criteria is one that would cause severe distress, a high probability of a need for medical attention, likelihood of serious injury or a probability of fatal injury. A “no harm” criteria is one that nearly all individuals could be exposed to without experiencing or developing irreversible or other serious health effects, or symptoms that could impair their abilities to take protective action.

Where suitable effect criteria meeting the above definitions have been proposed in accepted references, these should be adopted. If none are available, then as an approximation values of 1% probability of fatality to a general population for "harm" and 0.1% probability of fatality for "no harm" are suggested.

For equipment it would be an effect level that causes a failure which would lead to escalation of the event (a significant increase in the harm potential).
6.1 Thermal Effects

6.1.1 Fires

Fires primarily cause failure or harm by direct flame contact or radiation causing a rise in temperature leading to material failure or burning. Basic criteria can therefore be limiting thermal radiation levels or flame impingement.

For people, various radiation levels have been proposed as criteria for harm. It is suggested that for radiation from sustained credible fires a value of 9.5 kW/m$^2$ is used (Pain threshold reached after 8s; second degree burns after 20s: World Bank "Manual of Industrial Hazard Assessment Techniques" 1985). Where a flash fire of a flammable gas cloud could occur the maximum extent of the cloud to the Lower Flammable Limit (LFL) should be taken as the hazard range.

For "no harm" corresponding values of 1.6 kW/m$^2$ (No discomfort for long exposure: World Bank) and 50% of LFL should be used.

For equipment, a value of 37.5 kW/m$^2$ (Sufficient to cause damage to process equipment: World Bank) is suggested. Where equipment is protected e.g. by insulation, a more detailed calculation may be required. The rise in temperature of the material and reduction in yield strength should be compared to the loads imposed. The limiting criteria is when these become equal i.e. yield could occur.

Similarly, although direct flame impingement can initially be taken as causing equipment failure, this more sophisticated approach of calculated heat transfer can show that failure is not likely to happen.

6.1.2 Explosions

Possible effects of explosions on humans include blast-wave overpressure effects, explosion wind effects, impact from fragments or debris, collapse of buildings and heat-radiation effects. The TNO "Green Book" (Committee for the Prevention of Disasters "Methods for the determination of possible damage to people and objects resulting from the releases of hazardous material " CRP 16E,1989) discusses this issue in some detail.

Fortunately, by use of the methodology in Section 5 there will very seldom be instances where blast hazards have to be taken into account in determining safety distances to "harm" or "no harm". It is proposed that the following values for peak side-on overpressure be adopted if required:

- Harm to people: 7 kPa (threshold of injury causation by building damage, masonry wall collapse, cladding behaving as missiles)
- Harm to equipment: 20 kPa (onset of damage to heavy machines, storage tanks, steel frame buildings etc) (Both criteria from structural damage as World Bank or TNO Green Book data)
- No harm to people: 2 kPa (as "safe distance" by Gugan "Unconfined Vapour Cloud Explosions" (1979) after Clancy (1972)).

6.1.3 Cryogenic

In the same way that a rise in temperature can cause harm, a reduction in temperature can cause material failure or harm to people. A vapour or gas cloud has insufficient heat capacity to significantly affect equipment, however it may cause harm to people. It is suggested that a "harm" criteria could be a cloud temperature below -40°C, with "no harm" at 0°C (from BCGA Technical Report TR1(1984) "A method for estimating the off site risk from bulk storage of liquefied oxygen"). However the effects criteria suggested for oxygen enrichment/deficiency below will probably dominate in any calculation.

As with flames, direct impingement of cryogenic liquids on unprotected or unsuitable materials, or equipment can be taken as a basic criteria of harm.
6.2 Oxygen Enrichment or Deficiency

The release of oxygen or inerts, in gaseous or liquid phase can cause potential harm, although the only direct effect is the possible asphyxiation of people.

6.2.1 Enrichment

The hazard of oxygen enrichment is the increase in flammability of materials. Ease of ignition, burning rate and fire spread increases with increased oxygen concentrations. The onset of this enhancement is seen at 25% oxygen level in the atmosphere and reaches its maximum from approximately 40% oxygen concentrations. This increased oxygen concentration is only a secondary hazard as there has to be a fuel supply and source of ignition before the hazard is realised. Taking account of various factors such as burning rates, reaction times etc. a total oxygen concentration above 35% should be considered the “harm” criteria, and 25% O2 for “no harm” as described in Section 4.1 of the EIGA Position Paper PP-14 “Definitions of Oxygen Enrichment/Deficiency Safety Criteria used in IHC Member Associations” (published August 2006).

6.2.2 Deficiency

The displacement of oxygen from the atmosphere will not usually harm equipment but can cause a hazard by inhibiting combustion processes i.e. boilers, vehicles, or by asphyxiation of people. These effects are seen as hazardous beyond 16% oxygen with certainty of fatality below 10%. A total oxygen concentration of 12.5% should be taken as the criteria for “harm” and 17% for “no harm” as described in Section 4.2 of the EIGA Position Paper PP-14 referenced above.

6.3 Toxic effects

The severity of adverse human effects caused by acute (i.e. relatively short-term) exposures to toxic material depends both on the intensity (concentration) and the duration (time) of the exposure. The concept of toxic doserepresents this relationship (for any specific gas) as

\[ \Sigma c^n t = \text{constant} \]

where \( c \) is a concentration, \( t \) is the exposure time, and \( n \) is an exponent accounting for the manner in which the gas produces a toxic effect. (For the specific cases where \( n=1 \), this relationship is Haber’s Law.)

Where data exists it is proposed that "the lethal dose for fatality to 1% of the exposed population" (LD\(_{01}\)) or "the lowest reported lethal dose" LD\(_{LO}\) are used for the "harm" level criteria for people, with LD\(_{001}\) or 0.1 LD\(_{LO}\) for the "no harm" level.

In practice little valid data of this form exists. One method of assessing the consequence of an event is the direct effect model, which predicts effects on people or structures based on predetermined criteria (e.g. death is assumed to result if an individual is exposed to a certain concentration of toxic gas for a specified length of time).

Many useful measures are available to use as criteria for the likelihood of serious injury or death. However these should be adjusted to take account of the likely exposure times.

For "harm" criteria values can be taken from:

- Emergency Reponse Planning Guidelines for Air Contaminants ERPG Level 3 from the American Industrial Hygiene Association
- Immediately Dangerous to Life or Health (IDLH) from the US National Institute for Occupational Safety and Health
- For "no harm" levels it is proposed to use ERPG Level 2 (AEGL2) for acceptable exposure levels. The ERPG -2 is the maximum airborne concentration below which, it is believed, nearly all
individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. If ERPG-2 values are not available then an equivalent concentration should be used. Useful sources for these are nationally determined guides such as Occupational Exposure Standards in the UK (EH40)

- Threshold Limit Values in the US
- MAK values in Germany

These values will need to be multiplied by a factor to allow for short term exposure.

In reality the consequences may not take the form of discrete functions but may instead conform to probability distribution functions. A statistical method of assessment is the Probit method. For about 20 commonly used substances there is some information on dose-response relationships that can be applied to a probit function to quantify the proportion of fatalities within a population subject to a given exposure.

For these substances it is proposed that the "harm" level be a calculated probit value of 2.67, and the "no harm" level be set at a probit of less than 2.

Parameters for probit equations exist for (among others) ammonia, chlorine, and carbon monoxide. Sources for these parameters are:

- Committee for the Prevention of Disasters "Methods for the determination of possible damage to people and objects resulting from the releases of hazardous material" CRP 16E - the Netherlands "Green Book" Voorburg 2nd Ed 1992.

7 Calculation of hazardous effects

In order to calculate the hazardous effects, one needs to consider the series of physical effects that could occur.

- rate of release of the substance (including flashing, aerosol and evaporation effects)
- gas dispersion
- fires or explosions
- exposure to toxics

7.1 Rate of Release

Discharge of a flammable or toxic material from its containment is usually the initiating event for most acute incidents. This could arise from a crack or fracture of vessels or piping, from open valves or from emergency vents. The discharge may be gas, liquid or two-phase flashing liquid releases.

The estimate of release rate and quality of the discharge become important inputs into dispersion models. The actual duration of the release must also be determined for subsequent consequence estimation. The total quantity released may be greater or less than vessel volumes or inventory because of interconnecting pipework, shutoff valves, depressurisation vents etc.

The check list of leak sources (Table 2) in Section 5 should be used for initiating events, any of which can give rise to different discharges. For example:

Gas
- Hole in pipe or vessel containing gas under pressure
- Emergency relief discharge (vapour only)
- Boiloff or evaporation from liquid pool
Liquid
- Hole in atmospheric storage tank, vessel or connecting pipe under liquid head
- Hole in pipe or vessel containing pressurised liquid below its normal boiling point

Two phase
- Hole in pipe or vessel containing pressurised liquid above its normal boiling point
- Emergency relief discharge (e.g. runaway reactor containing viscous or foamy material)

Models for calculating discharge rates from holes in vessels and pipes are reasonably simple and straightforward for gas and liquid discharges. They can be obtained from standard references such as Perry or the Crane Co. handbook if not included in the dispersion and effects computer programmes discussed below.

Gas discharge from pressure relief valves can be calculated from the initiating event placing a demand on the relief device (e.g. estimating a vent rate in case of external fire) but more simply for the purpose of determining separation differences can be set at the rated relief valve capacity for a short term release. Valve capacities or methods of determining them are usually available on the device vendor data sheets.

However treatment of two-phase and two-phase flashing flow is more complex. Superheated liquids will flash when they are released into the atmosphere. In addition, some of the liquid portion will remain suspended as an aerosol in the vapour cloud due to the sudden release of pressure and the violent boiling of the liquid. The remainder of this liquid portion will rain out onto the ground and form a liquid pool, which may then boil-off so rapidly that all the discharge enters the vapour cloud almost immediately, regardless of the flash fraction. On the other hand, the quantity of liquid may be so large that due to cooling the vaporisation rate cannot match the rate of liquid rain out and a continuous plume will follow the initial vapour cloud.

Calculation of two-phase release rates and the proportion of liquid resulting can be complex although the mechanism has been much studied. The AIChE DIER S literature is a good all-round source of information on pressure relieving systems. However for small release events directly from a vessel or a long pipe it may be sufficient to calculate the release rate as all liquid, and determine the vapour fraction from isenthalpic flash calculations with an adjustment for entrained droplets. (2 - 3 times the adiabatic flash is often quoted empirically.) Alternatively after determining the liquid release rate, merely assume that all remaining liquid rapidly evaporates into the gas stream to give a worst vapour case.

7.2 Gas dispersion

When a flammable and/or toxic gas is released, the resulting vapour cloud will be diluted by air entrainment. The rate of dilution is controlled by several factors which include chemical properties, the release rate, meteorological conditions and terrain. There are also various release scenarios, such as, evaporation from liquid pools, high momentum releases from the opening of a relief valve, low momentum releases from conservation vents, instantaneous releases from catastrophic rupture or process equipment, and continuous releases. For these reasons, there is no one universal dispersion model to handle all types of releases; the appropriate model must be chosen for the particular release.

Computer models have been developed to predict the dispersion process in terms of time duration and distance. There are 3 descriptive terms used to determine the suitability of a particular model:

- Type of Release: Continuous (Plume) or Instantaneous (Puff)
- Momentum: Low or High
- Buoyancy: Emission gas density relative to air.

When a toxic and/or flammable gas of neutral buoyancy is released into the air with very low or no momentum (velocity), the vapour cloud will be completely wind-driven. This type is dispersion is
modelled using a Gaussian model. Specific models of much greater complexity are available if the gas is heavier than air, but the Gaussian models are often used because of their simplicity for these applications. Some examples are:

- The evaporation of oxygen from a large liquid pool.
- Discharge from Reversing Heat Exchangers on an ASU

An emission from a pressurised system will provide an initial high momentum that will affect the distance travelled and the dispersion rate of the release.

A jet model should be used to predict a dispersion when the release has initial momentum and is continuous. A general rule for deciding when to use a jet model is that if an initial velocity can be calculated the jet model should be used.

At some distance from the release point however, the velocity falls so low that the movement of the gas is no longer determined by the momentum of the jet but by velocity of the wind. The models in use today generally include this transition.

### 7.2.1 Buoyancy

Special plume rise models exist to deal with continuous elevated releases of dense gas. Initially the jet momentum may cause the gas to rise but then it sinks due to its excess density. If the initial gas density is high enough, the plume may reach the ground, and slumping effects ("cloud pancaking") come into effect as well as momentum and wind effects. If the gas is released with little or no momentum at or near grade as is common for a cryogenic spill, so-called "box" or "slab" models are used for effects, which assume constant concentrations in the plume in any cross-section downwind. Again transition to a Gaussian model is usual in any computation method.

A diagram indicating the logic for determining the dispersion process for any release is given
Below is a summary of some of the more commonly used computer based dispersion models available and when they should be employed.

Publically Available Code

- ALOHA: Low momentum, dense or neutrally buoyant gas (NOAA, EPA)
- DEGADIS: Dense gas jets or low momentum dense gas releases
- HGSYSTEM/SLAB: (Various US research sources generally available on request)
- ISC: Industrial Source Complex Model generally used for routine bouyant air pollutant modeling - includes downwash and building effects (US EPA)

Proprietary Commercial Code

- WHAZAN: Computerisation of World Bank Manual individual calculation methods for buoyant, neutral or dense gas releases (DNVTechnica)
- PHAST: All gas or liquid release cases (DNV Technica)
- SUPERCHEMS: All releases (Arthur D Little)
- TRACE: Gas releases (SAFER Corp./Du Pont)

It is important to note the major areas where understanding of calculation techniques is still limited, e.g. dispersion at or near buildings, concentration fluctuations within plumes, wind shifts and terrain steering effects, effects close to the source, variable source rates or qualities. Improvements in models are continuing, therefore care should be taken in evaluating the models available at the time of any analysis, and then selecting the most appropriate for the release conditions.

7.3 Calculation principles for thermal effects

For the calculation of thermal effects the following kinds of fires must be considered:

- pool fire
- flash fire
- jet flame
- fireball or BLEVE

The effect of heat on an object may be caused by:

- heat convection
- heat radiation

Heat convection may occur if a flame and/or hot vapour have contact with the surface of the object or a jet flame is directed to the object. Then the particles of the flame/vapour transmit a part of their heat to the surface of the installation.

Heat convection has to be taken into account if the heat source is under or right near the installation. Then heat convection must be a part of the calculation as well as the heat radiation.

Heat radiation is a transmission of heat via radiation and may heat up the installation even if the seat of fire is separated several meters from the installation.

The effect of heat convection is influenced by:

- temperature and heat capacity of flame and combustion products
- laminar or diffuse flame or flow of vapour
• flow regime (turbulent/laminar)
• soot (carbon)
• duration of fire
• weather (wind)

The effect of heat radiation is influenced by:

• dimension of the fire
• mean surface emission flux
• duration of heat emission
• weather (temperature, fog)
• angle between installation and fire
• orientation of object
• distance between fire and object

For the purpose of Safety Distance Calculation it may not be necessary to take all of them into a computation and for this reason the models recommend simplified equations.

For the calculation of separation distances between source and object the following steps are necessary:

1. If the fire occurs due to a leak, the leak rate and quantity of flammable substances must be evaluated by the gas emission models mentioned before. Then the dimensions of the flame and the incident heat flux may be estimated, taking into consideration the properties of the flammable substance, duration of fire, direction of flame etc. If ignition is assumed to be delayed, then the gas dispersion models should be employed to establish either the area covered by a flammable cloud (continuous release - flash fire) or the mass of flammable material within the cloud (instantaneous or short-term release - fireball or BLEVE).

2. The permissible heat flux on the object is established (refer to Section 3).

3. If there are further safety precautions (insulation, deluge system etc.) their possible influence on the thermal effect must be a part of the calculation.

More detailed computation of the separation distances based on the maximum permissible installation temperature and the transmission of heat through the outer wall (and insulation) and the maximum permissible temperature of the gas within the installation may be required.

Some examples for possible mean flame flux are given:

• hydrocarbon pool fire 60 kW/m²
• LPG (well aerated) pool fire 120 kW/m²
• timber 170 kW/m²
• turbulent gas jet flame 250 kW/m²
• LPG torch flame (RV release) 450 kW/m²

Models for calculation of heat radiation include

• API RP 521 1990 (Simplied model and Brzustowski & Sommer)
• Strahlungsmodell Becker/Huth/Muller 1991 TU Bd.32 (1991) Nr. 4
• IVA's notice No. 238, 1981, Sweden

Various computer codes incorporating such models are

• SUPERCHEMS Arthur D Little
• EFFECTS TNO
• WHAZAN DNV Technica
• PHAST DNV Technica
7.4 Calculation principles for explosion effects

Explosions can be classified into Unconfined Vapour Cloud Explosions (which has equivalence to a flash fire except that the consequence considered is the shock wave produced rather than the thermal radiation as previous), physical explosions (where the stored energy of the system is released by rupture), and confined explosions (where a rapid chemical reaction takes place inside the vessel or process). The result is usually examined in terms of a shock wave although projectiles can be a major threat from physical or confined explosions.

An accurate calculation of the potential explosion effects is only possible if all the influences are included by methods such as Computational Fluid Dynamics, particularly if it is an explosion in connection with obstacles and/or confinement. However in the context of separation distance selection, explosion events should be so rare as not to require more than general consideration of harm/no-harm effects.

The following empirical models are available:

- **TNT equivalence model**
  The proportion of available energy of the explosive gas cloud is estimated and converted to an equivalent quantity of TNT. Then the pressures can be estimated from TNT.

- **TNO model ("Yellow Book")**
  The model calculates the maximum peak overpressure from quantities involved and the flame spread velocities. The flame spread rate depends on the reactivity of the gas (low: Ammonia, Methane; medium: Propane; high: Hydrogen, Acetylene).

There is a current model which recognises the mechanism by which a combustion process in a gas release runs up to detonation through feedback of the turbulence induced by combustion in confined spaces.

- **Multi-energy Method**
  The model accounts for the energy of only that proportion of the gas release that is in the confined area under consideration, and takes account of the degree of congestion or confinement of the igniting gas.

Separate subsequent sub-explosions in unconnected spaces from the same flame path are possible - hence the model title.

Models for calculation of explosion effects are found as follows:

- **TNT equivalence model:**
  WHAZAN: DNV Technica
  PHAST: DNV Technica
  SUPERCHEMS: Arthur D Little

- **TNO model:** TNO Yellow Book Committee for the prevention of Disasters (1979) publ. Wiekema Netherlands


7.5 Toxic gas effects

Toxic effect models are employed to assess the consequences to human health as a result of exposure to toxic gases. Mitigation of these consequences by sheltering or evasive action is an important consideration in determining overall effects.
For estimation of separation distances, the first step is to determine concentration-time information for toxic gas clouds from the dispersion models. The dispersion modelling MUST include selection of an "averaging time" appropriate to the toxic dose criteria being considered. Probit models can then be used to develop exposure estimates for situations involving continous emissions (approximately constant concentrations over time downwind) or puff emissions (concentrations varying with time). Alternatively the distances to the timeadjusted direct effect model criteria (OES, ERPG) can be gauged from the dispersion information.

Effect calculations using probit methodology are included in the DNV Technica consequence modelling packages WHAZAN and SAFETI.

8 Prevention and mitigation factors

The risk of an event is a product between probability and consequences.

The design, manufacture and operation of a system have the aim to eliminate risks. Nevertheless it is self evident that an absolute safety does not exist.

The minimum of requirements ensuring an optimum of safety at an economically justifiable level is given by regulations, recommendations or codes of practice.

Separation distances calculated starting from theoretical or statistical premises could be considerable. From practical points of view it may be necessary to reduce them, without reducing the level of safety. This is possible by the use of additional safety measures, also known as prevention or mitigation factors.

Due to the different levels of basic requirements in different countries it is difficult to separate the "normal" from the "additional" measures.

Nevertheless normal requirements mean that the installations are designed, manufactured and installed in accordance with recognised codes.

The installation shall be operated by personnel fully trained in operating and emergency procedures.

The maintenance including periodic inspection shall be performed according to national regulations and manufacturer's recommendations.

Considering all these requirements as "normal" in the following are listed some examples of possible "additional" mitigation factors.

The mitigation factors can be taken into consideration when calculating safety distances by:

- reducing the probability of the event - PREVENTION
- reducing the consequences of the event - MITIGATION

8.1 Factors reducing the probability of the event

Use of fittings with a high reliability.

Use of valves without gland sealings; instead of gland sealings which must periodically be tightened it is possible to use bellows sealed or membrane valves.

Maximise use of welded or soldered connections for fittings and pipes.

Redundant components, e.g. the use of two safety valves or of a safety valve and a bursting disc, the use of 2 quick-acting shut off valves.

100% non destructive testing of circular welds of pipelines.

Double-wall vessels with leakage indicator on the interspace.
Tankers provided with anti-tow-away devices to ensure that they do not move before the flexible hose between tanker and stationary system is removed.

Regular frequent inspection of flexible hoses.

8.2 Factors reducing the consequences of the event

Use of remote controlled, automatic or manual quick-acting emergency isolating valves. Flow rate limiters.

Provision of a collecting basin ("bund") for storage vessels (capacity consistent with the vessels' capacity).

Protection walls of fire resistant material; if adequately dimensioned the protection wall can represent a boundary limit for the separation distance.

Provision of gas warning devices, which may also trigger protective devices (alarm, shut off etc.).

Fire detection devices automatically initiating a sprinkler system.

Personal protective equipment.

Provision of shelters, gas escape masks

Emergency response training
APPENDIX A
DETERMINATION OF SAFETY DISTANCE ON A LIQUID OXYGEN COLD CONVERTER AT CUSTOMER PREMISES

Description of Installation

A 33000 litre capacity liquid oxygen tank is used to supply gaseous oxygen into the customer premises. The required minimum supply pressure is 8 barg; consequently the tank pressure buildup regulator is set at 8 barg with the tank regulator set at 10 barg so that pressure in the supply line will normally vary between these values. The tank pressures safety valve is set at 16 barg with an additional bursting disc set at 24 barg. The pressure safeties are under the tank at 1 metre elevation. Ambient vaporisation of LOX is at a capacity of 300Nm3/hr for 8 hours per day and a 5 day week. The tank is expected to operate between 90% and 18% of gross capacity with an estimated 25 refills per annum. Refilling is by pump from a tanker at a rate of 25000 litres per hour. The tank is a vertical vacuum/perlite insulated vessel of external dimensions 11 metres high by 2.6 metres diameter. The installation is within the customer premises.

Identified Harm Potential

Fire hazard by oxygen enrichment*
Fire hazard from use of oxygen incompatible materials
Material embrittlement by exposure to cryogenic temperatures
Overpressure potential due to vaporisation of trapped liquid

*Potential for oxygen enrichment will be examined in the harm/effect worksheet.

Adopted criteria:

No Effect 25 %vol. O₂
Harm Effect 35 %vol. O₂

Equipment Inventory and Components (see following figure A)

(Only components in subsequent analysis itemised)

6. Main safety valve (bronze, threaded connection) 15mm
10. Rupture disc (brass, threaded connection) 15mm
11. Gas vent globe valve (bronze, silver soldered to 25mm ss.pipe) 25mm
15. Liquid withdrawal valve (bronze, silver soldered) 25mm
16. Three-way valve manifold (brass, compression fitting) 25mm
19. Liquid fill line (st.steel, soldered to valve #23/welded to tank) 25mm
26. Line to vaporiser (copper, silver soldered to unions) 25mm
27. Vaporiser-aluminium finned tubes (alum.bends, welded to tubes) 20mm
28. Liquid withdrawal connection (st.steel, welded to tank/soldered to fitting) 25mm
33. Hose (st.steel, welded to coupling) 50mm
34. Trailer fill connection (bronze, union connection) 50mm
**HARM/EFFECT WORKSHEET**

Source: LOX customer storage (in operation 24 hours per day - assume worst effect for 100% time)

Object 1: Neighbouring buildings/equipment (ignitable)  
Target deviation limit <3.5 x 10^{-5}  
No distance req'd

Object 2: Plant boundary/fence (assembly of people)  
Target deviation limit >3.5 x 10^{-3}  
Distance to no effect req'd

Object 3: Customer personnel outside installation boundary  
Target deviation limit Remainder  
Distance to harm limit criteria

Object 4: Servicer personnel inside installation boundary

<table>
<thead>
<tr>
<th>Event</th>
<th>Harm/Effect</th>
<th>Harm Generating Device</th>
<th>Description of Deviation</th>
<th>Prevention</th>
<th>Estimation of Frequency of Event (per yr)</th>
<th>Geometrical Effect</th>
<th>Mitigation</th>
<th>Consequence Calcn Req'd</th>
</tr>
</thead>
</table>
| 1.1   | Oxygen enrichment | 1.ian Safety Valve (Drwg item 6) | Vent to atmosphere above 25% | Type of valve Periodic calibration | Short duration opening, \( \lambda > 1 \) /yr  
Justification: normal event  
Long duration opening: frequency \( \lambda \) depending on the opening causer | \( F_d > 1 \)  
\( P_g = 1 \) | Blowing down, but not applicable to all vessels  
therefore \( P_m = 1 \) | No effect distance |
| 1.2   | Oxygen enrichment | | Periodic vacuum measurement | | \( F_d = 1 \times 5.2 \times 10^{-4} \)  
\( \lambda = 5.2 \times 10^{-4} / y r : vacuum \ loss \ by \ leak \ into \ annular \ space \)  
(For vacuum loss in fire \( \lambda = 3.3 \times 10^{-5} / y r \)  
therefore not considered) | \( F_d \times P_g = 5.2 \times 10^{-4} \)  
\( F_d \times P_g \times P_m = 5.2 \times 10^{-4} \) | Harm effect distance |
| 1.3   | Oxygen enrichment | | Long duration vent after malfunction of pressure building regulator | | \( F_d = 7 \times 10^{-3} \)  
Pressure buildup fails open | \( F_d \times P_g = 7 \times 10^{-3} \)  
\( F_d \times P_g \times P_m = 7 \times 10^{-3} \) | No effect distance |
<p>| 1.4 | Large duration vent after overfilling | Opening of overflow valve (full trycock valve Drwg item 24) | ( F_d = N \times 3 \times 10^{-3} ) | ( F_d \times P_g = N \times 3 \times 10^{-3} ) | Operator stops filling before tank is hydrostatically full in 90% of cases ( P_m = 1 ) ( F_d \times P_g \times P_m = 1.5 \times 10^{-3} ) (large customer) ( F_d \times P_g \times P_m = 7 \times 10^{-3} ) (small customer) | Harm effect distance |
| 2.1 | 2. Bursting disk (Drwg item 10) | Premature rupture | Periodic replacement | One disk in service Premature Rupture ( \lambda = 1 \times 10^{-3}/yr ) | ( P_g = 1 ) Mitigation as for safety valve ( P_m = 1 ) ( F_d \times P_g \times P_m = 1 \times 10^{-3} ) | Harm effect distance |
| 2.2 | Justified rupture | | | Pressure increase that should be released by a short duration venting Safety valve fails to open ( \lambda = 5.0 \times 10^{-4}/yr ) | ( F_d \times P_g = 5.0 \times 10^{-4} ) Pressure increase is observed and action taken in 50% of cases ( P_g \times P_m = 0.5 ) ( F_d \times P_g \times P_m = 8.6 \times 10^{-4} ) | Harm effect distance |
| 2.3 | Justified rupture | | | Pressure increase by overfilling due to human error (omission of procedure) ( F_d = N \times 3 \times 10^{-3} ) N = 25 (small customer) N = 50 (large customer) | ( F_d \times P_g = N \times 3 \times 10^{-3} ) Operator stops filling after tank hydrostatically full in 99 cases on 100 ( P_m = 0.01 ) ( F_d \times P_g \times P_m = 1.5 \times 10^{-3} ) (large customer) ( F_d \times P_g \times P_m = 2.5 \times 10^{-4} ) (small customer) | Harm effect distance |</p>
<table>
<thead>
<tr>
<th>3.1</th>
<th>3. Hose failure</th>
<th>Towaway liquid hose rupture</th>
<th>( \lambda = F_d = 3.5 \times 10^{-5} )</th>
<th>( F_d \times P_g = 3.5 \times 10^{-5} )</th>
<th>( F_d \times P_g \times P_m = 3 \times 10^{-5} )</th>
<th>No distance req'd</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>Large leak</td>
<td>Periodic replacement</td>
<td>Hose failure: Large leak ( \lambda = 5.0 \times 10^{-2} ) /yr Time in use: 50 deliveries \times 50 minutes (large customer) 25 deliveries \times 40 minutes (small customer) ( F_d = 50 \times 60 \times 5 \times 10^{-2} / (60 \times 24 \times 365) = 2.9 \times 10^{-4} ) (large customer) ( F_d = 25 \times 40 \times 5 \times 10^{-2} / (60 \times 24 \times 365) = 9.5 \times 10^{-5} ) (small customer)</td>
<td>( F_d \times P_g = 2.9 \times 10^{-4} ) (large customer)</td>
<td>Operator stops filling. Fails to stop in 10% of cases ( F_d \times P_g \times P_m = 2.9 \times 10^{-5} ) (large customer)</td>
<td>No distance req'd</td>
</tr>
<tr>
<td>3.3</td>
<td>Small leak</td>
<td></td>
<td>( \lambda = 5.0 \times 10^{-1} ) Considering the time in use ( F_d = 2.9 \times 10^{-34} ) (large customer) ( F_d = 9.5 \times 10^{-4} ) (small customer)</td>
<td>( F_d \times P_g = 2.9 \times 10^{-3} ) (large customer)</td>
<td>Operator stops filling. Fails to stop in 5% of cases ( F_d \times P_g \times P_m = 1.5 \times 10^{-4} ) (large customer)</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td>3.4</td>
<td>Small leak in fill couplings</td>
<td>2 couplings</td>
<td>( \lambda = 3.3 \times 10^{-2} ) ( F_d = 2 \times 3.3 \times 10^{-2} ) x time in use = ( 50 \times 60 \times 6.6 \times 10^{-2} / (60 \times 24 \times 365) = 3.8 \times 10^{-4} ) (large customer)</td>
<td>( F_d \times P_g = 3.8 \times 10^{-4} ) (large customer)</td>
<td>Operator stops filling. Fails to stop in 5% of cases ( F_d \times P_g \times P_m = 1.9 \times 10^{-5} ) (large customer)</td>
<td>No distance req'd</td>
</tr>
<tr>
<td>4.1</td>
<td>4. Liquid valve</td>
<td>Gland leak (drwg item 23,15,5,7)</td>
<td>( \lambda = 1.0 \times 10^{-2} / yr ) ( F_d = 4.0 \times 10^{-2} )</td>
<td>( F_d \times P_g = 4.0 \times 10^{-2} )</td>
<td>( F_d \times P_g \times P_m = 4.0 \times 10^{-2} )</td>
<td>No effect distance</td>
</tr>
<tr>
<td>5.1</td>
<td>5. Gaseous valve</td>
<td>Gland leak (drwg item 25,1,9,11,32)</td>
<td>( \lambda = 1.0 \times 10^{-2} / yr ) ( F_d = 5.0 \times 10^{-2} )</td>
<td>( F_d \times P_g = 5.0 \times 10^{-2} )</td>
<td>( F_d \times P_g \times P_m = 4.0 \times 10^{-2} )</td>
<td>No effect distance</td>
</tr>
<tr>
<td>Section</td>
<td>Type</td>
<td>Leak</td>
<td>Rate</td>
<td>Joints</td>
<td>Fd</td>
<td>Calculation</td>
</tr>
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<tr>
<td>6.1</td>
<td>6. Joints and unions</td>
<td>Small leak</td>
<td>$\lambda = 3.3 \times 10^{-2}$/yr</td>
<td>10 joints</td>
<td>3.3 x 10^{-1}</td>
<td>$F_d \times P_g = 3.3 \times 10^{-1}$</td>
</tr>
<tr>
<td>6.2</td>
<td>Large leak</td>
<td>$\lambda = 4 \times 10^{-3}$/yr</td>
<td>10 joints</td>
<td>4 x 10^{-2}</td>
<td>$F_d \times P_g = 4 \times 10^{-2}$</td>
<td>4 x 10^{-2}</td>
</tr>
<tr>
<td>6.3</td>
<td>Break</td>
<td>$\lambda = 5 \times 10^{-4}$/yr</td>
<td>10 joints</td>
<td>5 x 10^{-3}</td>
<td>$F_d \times P_g = 5 \times 10^{-3}$</td>
<td>5 x 10^{-3}</td>
</tr>
<tr>
<td>7.1</td>
<td>7. Welded and brazed fittings</td>
<td>Small leak</td>
<td>$\lambda = 9 \times 10^{-5}$/yr</td>
<td>30 welded or brazed joints</td>
<td>2.7 x 10^{-3}</td>
<td>$F_d \times P_g = 2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>8.1</td>
<td>8. Stainless steel pipe</td>
<td>Small leak</td>
<td>$\lambda = 7.5 \times 10^{-6}$/yr/m</td>
<td>Diameter =25mm Length = 10m</td>
<td>7.5 x 10^{-5}</td>
<td>$F_d \times P_g = 7.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>8.2</td>
<td>Large leak</td>
<td>$\lambda = 2 \times 10^{-6}$/yr/m</td>
<td>Diameter =25mm Length = 10m</td>
<td>2 x 10^{-5}</td>
<td>$F_d \times P_g = 2 \times 10^{-5}$</td>
<td>2 x 10^{-5}</td>
</tr>
<tr>
<td>9.1</td>
<td>9 Copper pipe</td>
<td>Small leak</td>
<td>$\lambda = 7.5 \times 10^{-6}$/yr/m</td>
<td>Diameter =25mm Length = 10m</td>
<td>7.5 x 10^{-5}</td>
<td>$F_d \times P_g = 7.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>10.1</td>
<td>10. Copper brazings</td>
<td>Small leak</td>
<td>$\lambda = 9 \times 10^{-5}$/yr</td>
<td>30 brazed joints</td>
<td>2.7 x 10^{-3}</td>
<td>$F_d \times P_g = 2.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>11.1</td>
<td>11. Aluminium bends on vaporiser</td>
<td>Small leak</td>
<td>$\lambda = 9 \times 10^{-5}$/yr</td>
<td>60 bends, 120 welds, Diameter =20mm Length = 10m</td>
<td>1.1 x 10^{-2}</td>
<td>$F_d \times P_g = 7.5 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
SAFETY DISTANCE CALCULATIONS FOR SCENARIOS SELECTED FROM HARM/EFFECT WORKSHEET

(Carried out using PHAST software v6.51 Meteo condition - 2 m/s wind, very stable (worst case))

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Effect Calculation</th>
<th>Release Position</th>
<th>Release Section</th>
<th>Pressure (barg)</th>
<th>Flowrate (kg/s)</th>
<th>Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bursting Disc Rupture</td>
<td>Harm Effect</td>
<td>Horizontal height = 1m above ground</td>
<td>15mm ID 100% section</td>
<td>24</td>
<td>1.55</td>
<td>2</td>
</tr>
<tr>
<td>Safety Valve Continuous Release</td>
<td>No Effect</td>
<td>Horizontal height = 1m above ground</td>
<td>15mm ID 100% section</td>
<td>16</td>
<td>1.04</td>
<td>6</td>
</tr>
<tr>
<td>Delivery Line Small Liquid Leak</td>
<td>Harm Effect</td>
<td>Horizontal height = 0.1m above ground</td>
<td>50mm ID 2% section</td>
<td>10</td>
<td>1.04</td>
<td>3</td>
</tr>
<tr>
<td>Joint/Valve Small Liquid Leak</td>
<td>No Effect</td>
<td>Horizontal height = 1m above ground</td>
<td>25mm ID 2% section</td>
<td>10</td>
<td>0.26</td>
<td>4</td>
</tr>
</tbody>
</table>
APPENDIX B
SAFETY DISTANCES FOR A GASEOUS HYDROGEN TRANSFILL AND STORAGE SYSTEM

Description of system

A 45 barg stationary hydrogen storage vessel is used to supply hydrogen into the customer process. Gas is drawn down daily to a minimum residual pressure of 10 barg in the storage. The storage is replenished by delivery from 200 barg tubetrailers, which refill by equalising pressure with the storage through an 8mm hose connection. Replenishment takes half an hour after which the depleted trailer is removed by the driver. The storage tank is protected by one of a pair of pressure safety valves with a rated capacity of 0.28 kg/sec of hydrogen (sized for worst case overpressure event). The trailer manifold is provided with a regulator of 3.5mm effective orifice to vent any excess pressure generated in transit from the fill site.

Identified Harm Potential

Flame impingement
Heat of radiation

Adopted Criteria

<table>
<thead>
<tr>
<th>No Effect</th>
<th>Harm Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash fire 50% LEL;</td>
<td>Flash fire to LEL;</td>
</tr>
<tr>
<td>Radiation 1.6 kw/m²</td>
<td>Radiation 9.5 kw/m² (people)</td>
</tr>
<tr>
<td></td>
<td>12.5 kw/m² (equipment)</td>
</tr>
</tbody>
</table>

Equipment Components (see following figure B)

- Trailer has 9 tubes connected to manifold by 3.5mm NB valves
- Manifold is connected to the trailer panel by 15mm NB flange
- Trailer fill valves are 10 mm NB
- Hose is 8mm NB
- Piping, valves and fittings on tank are 12mm NB. The tank pipe connection is flanged.
- The tank has a 500mm manway.
- All connections are screwed or union couplings.

Worksheet Descriptions

- Worksheet 1 examines sources of harm generated by unloading the 200 bar tube trailer.
- Worksheet 2 examines the static storage at 45 bars
- Worksheet 3 iterates the effect generated by lighting off of the storage tank safety valve vent to determine possible vent elevations necessary to achieve the “no harm” effect.
### Source:
200 bar H₂ trailer system (decanted to 45 bar storage in 30 minutes daily)

<table>
<thead>
<tr>
<th>Event</th>
<th>Harm/Effect</th>
<th>Harm Generating Device</th>
<th>Description of Deviation</th>
<th>Prevention</th>
<th>Estimation of Frequency of Event (per yr)</th>
<th>Geometrical Effect</th>
<th>Mitigation</th>
<th>Consequence Calcn Req'd</th>
</tr>
</thead>
</table>
| 1.1   | Flame Impingement | 1. Trailer Valve Gland | Leak to atmosphere with ignition | Type of valve | 9 valves x 3.5mm bore  
Probability of ignition 50%  
Proportion of delayed ignitions 25%  
Small leak $\lambda = 0.1/yr$  
Large leak $\lambda = 0.01/yr$  
Duration $\frac{1}{2} \times \frac{1}{24}$ (fraction of time decanting) | Horizontal effect in one direction  
$45^\circ$ in $360^\circ$  
$P_g = 0.125$ | No mitigation | Harm effect distance |
| 1.2   | Jet flame from small leak |  
Flash fire from small leak | Fd = 9 x 0.1 x 0.5 x $\frac{1}{2} \times \frac{1}{24}$ = 9.3x10^-3 | Fd x Pg = 1.2 x 10^-3 | Fd x Pg x $P_m$ = 1.2 x 10^-3 | Harm effect distance |
| 1.3   | Jet flame from large leak | Fd = 9.3 x 10^-4 | Fd x Pg = 1.2 x 10^-4 | Harm effect distance |
| 1.4   | Flash fire from large leak | Fd = 2.3 x 10^-4 | Fd x Pg = 2.9 x 10^-4 | No distance req'd |
| 2.1   | Jet flame from a small leak (either size) | 2. Screwed fitting leak | Leak to atmosphere with ignition | Correct fitting selection | 10 fittings x 3.5mm bore  
10 fittings x 10mm bore  
Ignition as (1)  
Small leak $\lambda = 0.033$  
Large leak $\lambda = 4.0 \times 10^{-3}$/yr  
Rupture $\lambda = 5.0 \times 10^{-4}$/yr | Horizontal effect in any direction  
$P_g = 0.25$ | No mitigation  
$P_m = 1$ | Harm effect distance |
<p>| 2.2   | Jet flame from a large leak (either size) | Fd = 10 x 3.3 x 10^-2 x 0.5 x $\frac{1}{2} \times \frac{1}{24}$ = 3.4 x 10^-3 | Fd x Pg = 8.6 x 10^-4 | Fd x Pg x $P_m$ = 8.6 x 10^-4 | Harm effect distance |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Flash fire from a small leak (either size)</th>
<th>$Fd = 8.6 \times 10^{-4}$</th>
<th>$Fd \times Pg = 2.1 \times 10^{-4}$</th>
<th>Harm effect distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>Jet flame from a large leak (either size)</td>
<td>$Fd = 10 \times 4 \times 10^{-3} \times 0.5 \times \frac{1}{2} \times \frac{1}{24} = 4.2 \times 10^{-4}$</td>
<td>$Fd \times Pg = 1.0 \times 10^{-4}$</td>
<td>Harm effect distance</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>Flash fire from a large leak (either size)</td>
<td>$Fd = 1.0 \times 10^{-4}$</td>
<td>$Fd \times Pg = 2.6 \times 10^{-5}$</td>
<td>No distance req'd</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Jet flame from a rupture</td>
<td>$Fd = 10 \times 5 \times 10^{-4} \times 0.5 \times \frac{1}{2} \times \frac{1}{24} = 5.2 \times 10^{-5}$</td>
<td>$Fd \times Pg = 1.3 \times 10^{-5}$</td>
<td>No distance req'd</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>Flash fire from a rupture</td>
<td>$Fd = 1.3 \times 10^{-5}$</td>
<td>$Fd \times Pg = 3.2 \times 10^{-6}$</td>
<td>No distance req'd</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Hose failure</td>
<td>Leak to atmosphere with ignition</td>
<td>Periodic inspection and replacement</td>
<td>2 fittings x 8mm bore 1 x 8mm hose Ignition as (1) Fitting leaks as (2) Hose failure Small leak $\lambda = 0.1$/yr Large leak $\lambda = 0.01$/yr Rupture $\lambda = 0.001$/yr Horizontal effect in any direction $Pg = 0.25$</td>
<td>No mitigation $P_m = 1$</td>
</tr>
<tr>
<td>3.2</td>
<td>Jet flame from a small leak</td>
<td>$Fd = 0.166 \times 0.5 \times \frac{1}{2} \times \frac{1}{24} = 1.7 \times 10^{-3}$</td>
<td>$Fd \times Pg = 4.3 \times 10^{-4}$</td>
<td>Fd x Pg x Pm = 4.3 x 10^{-4}</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td>3.3</td>
<td>Flash fire from a small leak</td>
<td>$Fd = 4.3 \times 10^{-4}$</td>
<td>$Fd \times Pg = 1.1 \times 10^{-4}$</td>
<td>Harm effect distance</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Jet flame from a large leak</td>
<td>$Fd = 1.8 \times 10^{-2} \times 0.5 \times \frac{1}{2} \times \frac{1}{24} = 1.9 \times 10^{-4}$</td>
<td>$Fd \times Pg = 4.7 \times 10^{-5}$</td>
<td>Harm effect distance</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Flash fire from a large leak</td>
<td>$Fd = 4.7 \times 10^{-5}$</td>
<td>$Fd \times Pg = 1.2 \times 10^{-5}$</td>
<td>No distance req'd</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>Jet flame from a rupture</td>
<td>$Fd = 2.1 \times 10^{-5}$</td>
<td>$Fd \times Pg = 5.2 \times 10^{-6}$</td>
<td>No distance req'd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flange leak</td>
<td>Leak to atmosphere with ignition</td>
<td>Spiral wound gasket</td>
<td>1 flange x 15mm (Small) leak between bolts $\lambda = 1.7 \times 10^{-4}$/yr (Large) not tight all round $\lambda = 1.7 \times 10^{-5}$/yr Ignition as (1)</td>
<td>Horizontal effect perpendicular to flange $P_g = 0.1$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>4.1</td>
<td>Jet flame from a small leak</td>
<td>$F_d = 1.7 \times 10^{-4} \times \frac{1}{2} \times \frac{1}{24} = 1.7 \times 10^{-6}$</td>
<td></td>
<td>$F_d \times P_g = 1.7 \times 10^{-7}$</td>
<td>$F_d \times P_g \times P_m = 1.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>4.2</td>
<td>Flash fire from a small leak</td>
<td>$F_d = 4.2 \times 10^{-7}$</td>
<td></td>
<td>$F_d \times P_g = 4.2 \times 10^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>
### HARM/EFFECT WORKSHEET NUMBER 2

**Source:** 45 bar H₂ storage system (cycles between 45 bars and 10 bars in 24 hours - assume worst effect for 100% time)

**Object 1:** Neighbouring buildings/equipment  
Target deviation limit <3.5 x 10⁻⁵  
No distance req'd

**Object 2:** Plant boundary/fence (assembly of people)  
Distance to no effect req'd

**Object 3:** H₂ trailer station  
Remainder  
Distance to harm limit criteria

<table>
<thead>
<tr>
<th>Event</th>
<th>Harm/Effect</th>
<th>Harm Generating Device</th>
<th>Description of Deviation</th>
<th>Prevention</th>
<th>Estimation of Frequency of Event (per yr)</th>
<th>Geometrical Effect</th>
<th>Mitigation</th>
<th>Consequence Calcn Req'd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flame Impingement</td>
<td>1. Storage Valve Gland</td>
<td>Leak to atmosphere with ignition</td>
<td>Type of valve Hazardous area class.</td>
<td>10 valves x 12mm bore Probability of ignition 50% Proportion of delayed ignitions 25% Small leak λ = 0.1/yr Large leak λ = 0.01/yr</td>
<td>Horizontal effect in one direction 45° in 360°</td>
<td>No mitigation</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 10 x 0.1 x 0.5 = 0.5</td>
<td>Fd x Pg = 6.2 x 10⁻²</td>
<td>Fd x Pg x Pm = 6.2 x 10⁻²</td>
<td>No harm effect distance</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 10 x 0.1 x 0.5 x 0.25 = 0.125</td>
<td>Fd x Pg = 1.6 x 10⁻²</td>
<td>Fd x Pg x Pm = 1.6 x 10⁻²</td>
<td>No harm effect distance</td>
</tr>
<tr>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 5.0 x 10⁻²</td>
<td>Fd x Pg = 6.2 x 10⁻³</td>
<td>Fd x Pg x Pm = 6.2 x 10⁻³</td>
<td>No harm effect distance</td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 1.2 x 10⁻²</td>
<td>Fd x Pg = 1.6 x 10⁻³</td>
<td>Fd x Pg x Pm = 1.6 x 10⁻³</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 20 x 3.3 x 10⁻² x 0.5 = 0.33</td>
<td>Fd x Pg = 8.2 x 10⁻²</td>
<td>Fd x Pg x Pm = 8.2 x 10⁻²</td>
<td>No harm effect distance</td>
</tr>
<tr>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fd = 8.2 x 10⁻²</td>
<td>Fd x Pg = 2.1 x 10⁻²</td>
<td>Fd x Pg x Pm = 2.1 x 10⁻²</td>
<td>No harm effect distance</td>
</tr>
</tbody>
</table>
### Worksheet 2 cont...

<table>
<thead>
<tr>
<th></th>
<th>Event Description</th>
<th>Formula</th>
<th>Distance</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>Jet flame from a large leak</td>
<td>( F_d = 20 \times 4 \times 10^{-3} \times 0.5 = 4.0 \times 10^{-2} )</td>
<td>( F_d \times P_g = 1.0 \times 10^{-2} )</td>
<td>No harm effect distance</td>
</tr>
<tr>
<td>2.4</td>
<td>Flash fire from a large leak</td>
<td>( F_d = 1.0 \times 10^{-2} )</td>
<td>( F_d \times P_g = 2.5 \times 10^{-3} )</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td>2.5</td>
<td>Jet flame from a rupture</td>
<td>( F_d = 20 \times 5 \times 10^{-4} \times 0.5 = 5.0 \times 10^{-3} )</td>
<td>( F_d \times P_g = 1.2 \times 10^{-3} )</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td>2.6</td>
<td>Flash fire from a rupture</td>
<td>( F_d = 1.2 \times 10^{-3} )</td>
<td>( F_d \times P_g = 3.1 \times 10^{-4} )</td>
<td>Harm effect distance</td>
</tr>
<tr>
<td>3.1</td>
<td>Flange leak Leak to atmosphere with ignition</td>
<td>Spiral wound gasket</td>
<td>1 flange x 12mm (Small) leak between bolts ( \lambda = 1.7 \times 10^{-4} \text{/yr} ) (Large) not tight all round ( \lambda = 1.7 \times 10^{-5} \text{/yr} ) Ignition as (1)</td>
<td>Horizontal effect perpendicular to flange ( P_g = 0.1 )</td>
</tr>
<tr>
<td>3.2</td>
<td>Flash fire from a small leak</td>
<td>( F_d = 0.00017 \times 0.5 = 8.5 \times 10^{-5} )</td>
<td>( F_d \times P_g = 8.5 \times 10^{-6} )</td>
<td>No distance req'd</td>
</tr>
<tr>
<td></td>
<td>Jet flame from a small leak</td>
<td>( F_d = 2.1 \times 10^{-5} )</td>
<td>( F_d \times P_g = 2.1 \times 10^{-6} )</td>
<td>No distance req'd</td>
</tr>
</tbody>
</table>
H2 Transfill safety distance results for scenarios selected from harm/effect worksheets 1 & 2

*(Carried out using PHAST software: Ave Meteo Conditions [little effect for jet releases]*
Small pipe or fitting leak 2% section; large pipe or fitting leak 20% section)

<table>
<thead>
<tr>
<th>DEVICE DEVIATION</th>
<th>DEVICE DEVIATION</th>
<th>CONSEQUENCE</th>
<th>SEPARATION FOR EQUIPMENT (M)</th>
<th>SEPARATION FOR PEOPLE (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Bar system</td>
<td>Valve gland</td>
<td>Small leak</td>
<td>Harm (jet or flash)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>Harm (jet)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10 mm fitting</td>
<td>Small leak</td>
<td>Harm (jet or flash)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>Harm (jet)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3.5 mm fitting</td>
<td>Small leak</td>
<td>Harm (jet or flash)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>Harm (jet)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Hose</td>
<td>Small leak</td>
<td>Harm (jet or flash)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>Harm (jet)</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEVICE DEVIATION</th>
<th>DEVICE DEVIATION</th>
<th>CONSEQUENCE</th>
<th>SEPARATION FOR EQUIPMENT (M)</th>
<th>SEPARATION FOR PEOPLE (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 Bar system</td>
<td>Valve gland</td>
<td>Small leak</td>
<td>No Harm (jet or flash)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>No Harm (jet)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Harm (flash)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>12 mm fitting</td>
<td>Small leak</td>
<td>No Harm (jet or flash)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large leak</td>
<td>No Harm (jet)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Harm (flash)</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Rupture</td>
<td></td>
<td>Harm (jet or flash)</td>
<td>8</td>
</tr>
</tbody>
</table>
**HARM/EFFECT WORKSHEET NUMBER 3**  
(WITH EFFECT OF CHANGES IN DESIGN CRITERIA)

Source: Vents  
Object 1: Operator  
Object 2: Plant boundary/fence (assembly of people)  
Object 3: $\text{H}_2$ storage  

<table>
<thead>
<tr>
<th>Event</th>
<th>Harm/Effect</th>
<th>Harm Generating Device</th>
<th>Description of Deviation</th>
<th>Prevention</th>
<th>Estimation of Frequency of Event (per yr)</th>
<th>Geometrical Effect</th>
<th>Mitigation</th>
<th>Consequence Calc Req'd</th>
<th>DISTANCE to object</th>
<th>TANCE object</th>
<th>(m) reqd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>1. Storage safety valve located at 3m elevation</td>
<td>Vent to atmosphere with ignition</td>
<td>Good operation Hazardous area class.</td>
<td>Frequent event $\lambda = 25/\text{yr}$ (tank may not be at min.pressure for 10% of 250 transfills) Probability of ignition 50% Small vent rate 80% Max vent rate 20%</td>
<td>High wind causes horizontal effect in any direction $P_g = 0.25$</td>
<td>99% chance trailer driver will intervene to stop tube trailer discharging $P_m = 0.01$</td>
<td></td>
<td>#1</td>
<td>#2</td>
<td>#3</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Jet flame from small vent rate</td>
<td>$F_d = 25 \times 0.8 \times 0.5 = 10$</td>
<td>$F_d \times P_g = 2.5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 6.2 kw/m²</td>
<td>&lt; 1.6 kw/m²</td>
<td>&lt; 35 kw/m²</td>
</tr>
<tr>
<td>1.2</td>
<td>Jet flame from max. vent rate</td>
<td>$F_d = 25 \times 0.2 \times 0.5 = 2.5$</td>
<td>$F_d \times P_g = 6.2 \times 10^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \ (\text{vert})$</td>
<td>$6 \ (\text{horiz})$</td>
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</tbody>
</table>

*RECALCULATE SEPARATION AS DISTANCE TO OBJECTS 1 & 2 ARE UNACCEPTABLE*

| 2.2 | 2. Storage safety valve located at 5m elevation | Jet flame from max. vent rate | $F_d \times P_g \times P_m = 6.2 \times 10^{-3}$ | No harm effect distance | 0 | 14** | 0 (vert) | 2(horiz) |
**FURTHER RECALCULATION NECESSARY?**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
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<tr>
<td><strong>3.2</strong></td>
<td><strong>4.2</strong></td>
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<tr>
<td>3. Storage safety valve located at 7.5m elevation</td>
<td>As 3.2 but for 10m elevation</td>
<td></td>
<td></td>
<td>Fd x Pg x Pm = 6.2x10^-3</td>
<td>No harm effect distance</td>
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<tr>
<td>Jet flame from max. vent rate</td>
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<td></td>
<td></td>
<td>No harm effect distance</td>
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# APPENDIX C

## FAILURE RATE DATA

<table>
<thead>
<tr>
<th>TYPE OF LEAK</th>
<th>MAGNITUDE</th>
<th>EfGA Memb.</th>
<th>Cadwallader</th>
<th>SRD R488</th>
<th>Cox, Lees &amp; Ang</th>
<th>Prugh</th>
<th>Adopted Value</th>
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<tr>
<td>100mm Pipe</td>
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<tr>
<td>small leak</td>
<td>6.00E-06</td>
<td>6.00E-06</td>
<td>1.50E-05</td>
<td>2.50E-06</td>
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<tr>
<td>large leak</td>
<td>3.00E-07</td>
<td>6.00E-07</td>
<td>1.50E-06</td>
<td>7.50E-07</td>
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<tr>
<td>break</td>
<td>3.00E-08</td>
<td>6.00E-08</td>
<td>1.50E-07</td>
<td>2.30E-07</td>
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<td>(per metre)</td>
<td></td>
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<td>Joints &amp; Unions</td>
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<td>3.30E-02</td>
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<td>1.00E-02</td>
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<td>1.00E-02</td>
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<td>3.40E-04</td>
<td>1.00E-03</td>
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<td>Flange</td>
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<tr>
<td>flange leak</td>
<td>2.60E-03</td>
<td>4.70E-06</td>
<td>3.00E-04</td>
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<tr>
<td>flange blowout</td>
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</tbody>
</table>

Frequency data in failures per item per year (except for pipe).
### APPENDIX D
### HARM/EFFECT WORKSHEET

Source: "Heading A"

Object 1: "Heading B"
- Target deviation limit $< 3.5 \times 10^{-5}$
- No distance req'd

Object 2: etc..
- $> 3.5 \times 10^{-3}$
- Distance to no effect req'd

Object 3: etc..
- Remainder
- Distance to harm limit criteria

<table>
<thead>
<tr>
<th>Event</th>
<th>Harm/Effect</th>
<th>Harm Generating Device</th>
<th>Description of Deviation</th>
<th>Prevention</th>
<th>Estimation of Frequency of Event (per yr)</th>
<th>Geometrical Effect</th>
<th>Mitigation</th>
<th>Consequence Calcn Req'd</th>
</tr>
</thead>
</table>
