METHODOLOGY FOR DETERMINATION OF SAFETY AND SEPARATION DISTANCES

Doc 75/21 Rev 1

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Prepared by AHG-S.9 of Safety Advisory Council

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Table of Contents

Tables

Figures

Amendments to 75/07

Section	Change
	Editorial to align style with EIGA style manual
All	Rewrite to reflect current practices
	Appendix A rewritten with updated modelling

NOTE Technical changes from the previous edition are underlined

Rev 1 Amendments to 75/21

Section	Change
5.1, 6	Update to harm, no harm criterion wording for clarity

1 Introduction

This publication describes the basic principles to calculate appropriate safety and separation distances for the industrial gases industry. It is intended that EIGA members use this publication as an aid to writing or revising any publications that involve specifying safety and separation distances for safe equipment layout.

Historically, the term safety distance has been used for an effect-based distance. This is consequence based and gives conservative safety distances. Because of increasing density of industrial installations, there is a need for more realistic safety distances. This has led to risk-based safety distances.

Determination of safety and separation distances is a subject that requires detailed knowledge of risk and consequence modelling and as such this publication should only be used by specialists with this knowledge.

2 Scope and purpose

2.1 Scope

The work process can be used for the equipment required for industrial and medical gases. These can be in cryogenic liquid, pressurised liquid or the gaseous phase.

This publication is intended to be applied to new installations and may be used for both existing, and modifications to existing, installations to assess safety and separation distances.

Offsite transport and pipelines are not specifically addressed.

2.2 Purpose

The primary objective of this publication is to define a philosophy to determine suitable separation distances for all equipment, pipework and storage to allow EIGA member company experts to develop consistent standards across the industry and avoid escalation scenarios. In a similar way, the safety and separation distances are given to protect personnel. Member company experts using this publication should be familiar with the risk assessment methods, criteria and process modelling described in this publication.

The prescribed methodology is one option for defining safety distances and the attached example shows that this approach reflects a conservative methodology. EIGA member companies might choose other methodologies, such as:

- basic spacing tables;
- consequence based; or
- fully risk based.

Local legislation shall take precedence over this publication.

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

3.2.1 Definitions in risk assessment

3.2.1.1 Effect

Immediate or delayed result of an exposure to a hazard.

3.2.1.2 Event

Realisation of a hazard.

3.2.1.3 Frequency

Expression of how often a considered occurrence takes place in a given time.

3.2.1.4 Hazard

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

3.2.1.5 Probability

Expression of the chance that a considered occurrence will take place.

3.2.1.6 Projectile

Debris that is ejected by energy release.

3.2.1.7 Risk

Product of the likelihood and consequence of a given hazardous scenario.

3.2.1.8 Safety distance

Minimum separation between a hazard source and a human, that will mitigate the effect of a foreseeable incident.

3.2.1.9 Separation distance

Distance that will mitigate the effect of a foreseeable incident and prevent a minor incident escalating into a larger incident due to damage to equipment or environment.

3.2.2 Pressure

In this publication bar shall indicate gauge pressure unless otherwise noted i.e., (bar, abs) for absolute pressure and (bar, dif) for differential pressure.

4 Basis of approach

The safety distance is to provide a minimum separation that will mitigate the effect of any foreseeable event. The separation distance will also provide protection for the equipment from foreseeable external impacts such as roadway, flare or activities outside the control of the operation, for example a plant or customer station boundary and prevent it from escalating into a larger incident. In order to do so, the following steps shall be followed:

1. Identify the hazard sources and events, for example release of gas, taking into account the likelihood.
2. Calculate the effects on neighbouring objects and population taking into account mitigating factors.
3. Determine the safe distance to each object or population to meet the minimum hazard criteria.
4. Consider additional prevention or mitigating factors and re-calculate safe distance.

As discussed in 5.1, the safety and separation distances are not intended to provide protection against catastrophic events or major releases, 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, for example toxic, flammable, oxidising, asphyxiant, explosive and overpressure.
- The equipment design and the operating conditions, for example pressure and temperature and / or physical properties of the substance under those conditions.
- Any external mitigating protection measures, for example fire walls, blast walls, dyking, deluge system, that reduces the escalation of the incident.
- The object that is protected by the safety distance; that is the harm potential, including for example, people, exposure time, 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 of such an assessment for a pressure vessel and connecting pipework.

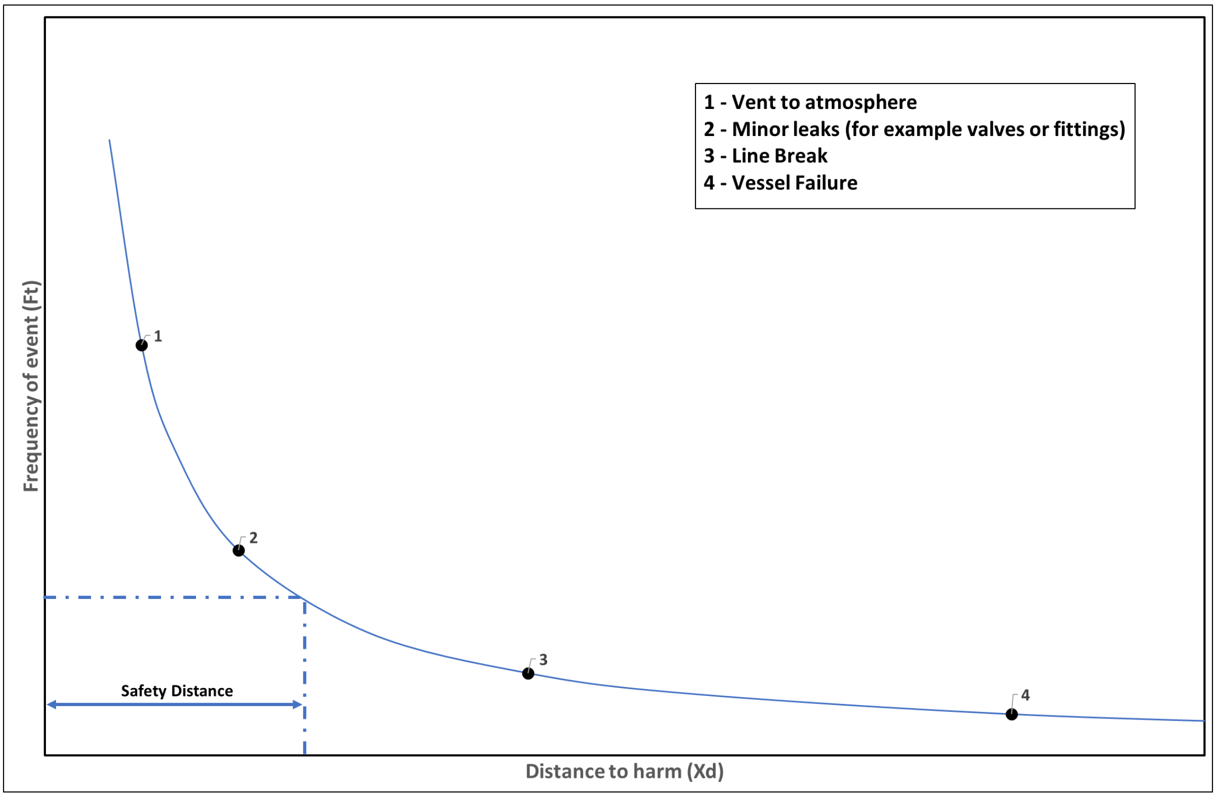

Figure 1 – Safety distance for pressure vessel and connecting pipework

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 generally accepted by authorities and the general public at large to reflect their specific requirement and processes, EIGA companies are invited to define their own criteria. Broadly accepted publicly available values are presented here after.

The risk from a hazardous activity should not be significant when compared with risk in everyday life.

The individual harm exposure threshold, defined as Ft, for determining safety distances is proposed as:

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

For events where the risk of harm is below Ft, no safety distance criteria is required. For deviations, which are likely to occur during the life of the equipment or occur during normal operation, for example venting, then the safety distance should be calculated, or mitigation provided to produce a no harm effect.

In Section 6, harm and no harm criteria are discussed in detail. Harm criterion corresponding to a probability of fatality of 1% and no harm criterion corresponding to a probability of fatality of 0.1% are proposed if not defined otherwise by member companies. For less likely events with a frequency between Ft and 100 x Ft harm criterion shall be applied. For more frequent events with a frequency > 100 x Ft no harm criterion shall be applied.

This can be illustrated by Figure 2.

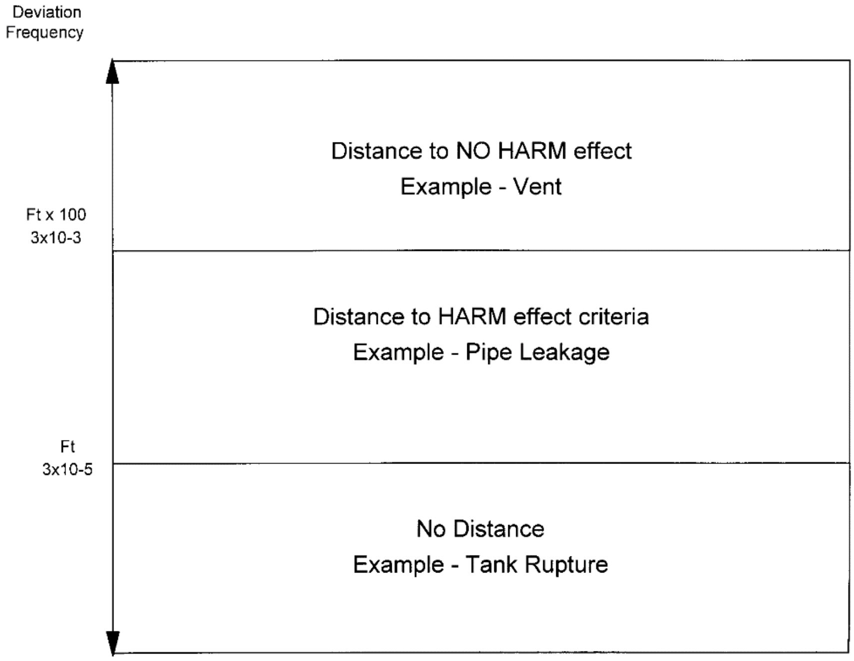

Figure 2 – Harm vs no harm criteria

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 shall also be defined, for example, flammable gas storages and chemical or refinery industries. All of the identified deviations shall 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 of the following is required:

- information on physical / chemical properties of the gases under review;
- construction drawing / flow sheet of the system process equipment or component under review;
- layout / plot plan; and
- 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 the industrial gas industry.

Some contributing factors to industrial gas accidents are given in Table 1.

Table 1 – Contributing factors checklist relevant to the definition of a safety distance

Environmental and mankind	**Thermal**
Oxygen enrichment	Heat of radiation
Oxygen deficiency	Heat of conduction
Fog – visibility	Heat of convection
Toxic / harmful substance exposure	Flame impingement
Corrosive substance exposure	Cold of conduction
Water / soil contamination	Cold of convection
Kinetic	Cold by impingement
Falling objects	**Electric**
Projectiles	Arc flash
Shock waves (over pressure from gas or liquid)	Static electricity
Struck by moving vehicle	Electronic interference
Vibration	
Others	
UV radiation	
Metal corrosion	
Material (plastic) ageing	
Chemical reaction / decomposition	
Chemical contamination	
Cold embrittlement	

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

Table 2 – Checklist of leak sources and leak scenarios

Type of equipment / component	Type of leak
Pipework	Pinholes, pipe rupture
Flanges	Gasket failure (mechanical failure / burnout / brittleness). Thermal movement / material creep
Weld connection	Weld crack or porosity
Solder connection	Solder crack or porosity, solder melt
Union connection	Thermal movement, leak
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, rupture
Instruments	Element rupture
Regulators	Diaphragm rupture / seal leak / downstream rupture (overpressure). Housing split / flash fire perforation (oxygen)
Solenoid valves	Seat leaks
Pumps	Perforation by oxygen flash fire / seal leak
Cylinders	Perforation, rupture

When using the harm / effect and leak source lists as a checklist, it has been stated that up to 95% of the deviation scenarios will be captured (for more information see Rijnmond Report) [1].[1]

The sequence to be followed when performing the analysis should be:

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[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

1. Make an inventory on (hazardous) substances.
2. Review and list their intrinsic hazards.
3. Make an inventory of equipment / components used in system or process.
4. Identify hazard sources and possible exposed objects such as people and equipment.
5. Review above against harm / effect checklist by asking the questions:

   Which equipment or component is a source of harm?

   What leak scenarios are possible?
6. Proceed through all sources and exposed objects.

5.2.4 Other identification techniques

The harm / effect checklist can be complemented or substituted with:

- What if / How can analysis;
- Failure Mode and Effects Analysis (FMEA);
- Hazard and Operability Study (HAZOP);
- Event tree and fault tree analysis; or
- Quantitative Risk Analysis (QRA).

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 below.

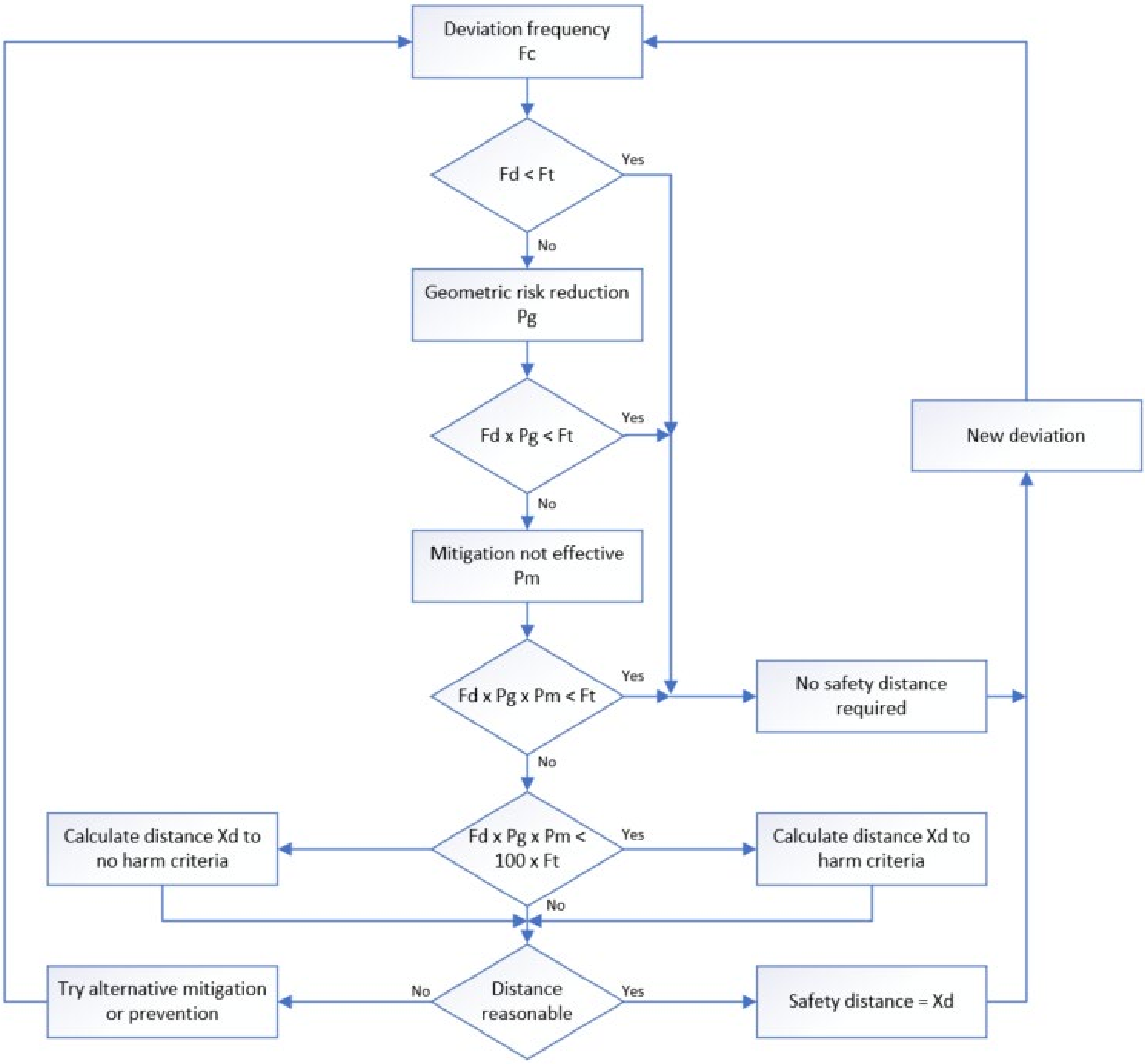

Figure 3 – Methodology for the evaluation of the safety distance

For a given object, the successive questions to be answered concerning a possible hazard event or deviation are:

1. What is the frequency Fd of the concerned deviation?

   (For example, frequency of a specific pipe or valve leakage, modified by prevention device)

   Fd may increase / decrease as a function of the potential source population (for example, 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 Ft?

   (See proposed Ft criteria in 5.1)

   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 Pg<1 that the object would be exposed to the hazard source?

For example, if the probability that a jet fire would point toward a specific piece of equipment is less than 1, a geometric risk reduction Pg=0.1 may be used.

Reduction is also possible for directional gas releases where modelling shows the affected zone is a specific limited area. For directed vents, like relief valves, a geometric risk reduction Pg=0.1 may be used. For liquid line or hose ruptures Pg=0.25 may be used.

If no geometric risk reduction is identified, Pg=1.

Projectile case: the probability Fd*Pg that a projectile would reach a specific object is generally very low; consequently, a safety distance for the protection against projectiles is not considered in this publication.

4. Is Fd*Pg less that Ft?

   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 considering 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 Pm<1 is known?

   For example, 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, Pm=1.

6. Is Fd*Pg*Pm less than Ft?

   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 Fd*Pg*Pm less than 100*Ft?

   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 selection of the calculated distance Xd 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 Ft. Therefore, the recommended safety distance shall be the calculated distance Xd related to no harm.

   In both cases, the last question is:

8. Is this distance Xd 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 requires reduction. This can be carried out using:

- an alternative prevention, thus reducing the considered deviation frequency (Fd); or
- alternative mitigation, thus reducing the probability of failure of mitigation measures (Pm).

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

5.4 Evaluation of hazard events frequency

Section 5.2 shows one of the potential methods 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.

It is suggested that for any harm event, the deviations should be examined in order from the highest estimated value of Fd, since in this way once a value of Fd*Pg*Pm below the harm exposure threshold has been reached, no less frequent events need be examined.

For some harm / effects, objects can be grouped, for example 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 is examined for suitability for use for the scenarios in Table 2.

Published data sources include:

- *Lees' Loss Prevention in the Process Industries* (especially Chapter 12 and Appendix 14) [2];
- IEEE Standard 352-2016, *IEEE Guide for General Principles of Reliability Analysis of Nuclear Power Generating Station Systems and Other Nuclear Facilities* [3];
- *Offshore and Onshore Reliability Data Handbook* [4];
- EIGA Doc 187, *Guideline for the location of occupied buildings in industrial gas plants* [5];
- *Handleiding Risicoberekeningen Bevi version 3.3* (formerly the Purple Book) [6]; and
- *Guidelines for developing quantitative safety risk criteria* [7].

These all generally suffer by being non-specific as to the type and quality of the process industries sourced, often containing a lot of old information not applicable for modern equipment or management standards, and also may not distinguish between size of the event in the sample.

For this reason, the worked example in Appendix A examined the following published references, which not only give failure rate data for the types of event considered in the above methodology but also indicate a distribution of the data between sizes of the event (for example, small, large and rupture):

- *Classification of Hazardous Locations*, (particularly Chapters 15 - 18) [8];
- *Cryogenic System Operating Experience Review for Fusion Applications* (page 5-19) [9];
- *An initial prediction of the BLEVE frequency of a 100 Te Butane storage*, (Appendix 1) [10];
- API 581, *Risk based inspection* [11]; and

- HSE FR1, *Failure Rate and Event Data for use within Risk Assessments* [12].

Example frequencies for leak terms from these sources are given in Appendix A together with the example.

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 is 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 5.1 and Figure 2. A harm criterion 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 criterion 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.

The selection of criteria should depend upon the vulnerability of the population compared to an industrial population. EIGA Member companies shall be consistent in their approach to protect their own employees and offsite populations.

If no effect criteria 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.

If a company does not have its own criteria, the figures below may be used.

For no harm corresponding values for jet fires of 1.6 kW/m², based on API 521, *Pressure-relieving and Depressuring Systems*, and for flash fires 50% of Lower Flammable Limit (LFL) is common practice [13].

For short duration exposure examples, a value of 9.5 kW/m² is used (pain threshold reached after 8s, second degree burns after 20s, (reference API 521) [13]. Where a flash fire of a flammable gas cloud could occur, the maximum extent of the cloud to the LFL should be taken as the hazard range.

For equipment, a value of 37.5 kW/m² (sufficient to cause damage to process equipment, reference World Bank *Manual of Industrial Hazard Assessment Techniques*) is suggested [14]. Where equipment is protected, for example 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 (*Methods for the determination of possible damage to people and objects resulting from the releases of hazardous material*) discusses this issue in some detail [15].

In cases where blast is considered, the following values should be taken into account in determining safety distances to harm or no harm:

- No harm to people: less than 30 millibar (reference Buncefield Major Incident Investigation: *Initial Report to the Health and Safety Commission and the Environment Agency of the investigation into the explosions and fires at the Buncefield oil storage and transfer depot, Hemel Hempstead, 2005* [16].

- Harm to people: 70 millibar (threshold of injury causation by building damage, masonry wall collapse, cladding behaving as projectiles). Optional explosion effect harm criteria can be defined more specifically as inside and outside effect on humans differ. Examples would be 30 millibar for inside harm examples broken glass from windows and 100 millibar for outside harm, injuries due to projectiles (reference *Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure*) [17].

- Harm to equipment: 200 millibar (onset of damage to heavy machines, storage tanks and steel frame buildings etc), reference *Explosion phenomena and effects of explosions on structures. III: Methods of analysis (explosion damage to structures) and example cases* [18]. More specific values can be chosen from this reference if appropriate.

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 criterion could be a cloud temperature below –40 °C, with no harm at 0 °C (from BCGA TR1, *A method for estimating the offsite risk from bulk storage of liquefied oxygen*) [19]. 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 criterion of harm.

6.2 Oxygen enrichment or deficiency

The release of oxygen or inert products in gaseous or liquid phase can cause potential harm.

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 23.5% oxygen level in the atmosphere and reaches its maximum from approximately 40% or higher oxygen concentrations (reference BCGA Report TR1) [19]. This increased oxygen concentration is only a secondary hazard as it requires a fuel supply and source of ignition before the hazard is realised.

Allowing for a reaction time, a total oxygen concentration of 35% would lead to a fatality rate of 0.8% and should therefore be considered as harm criteria and 23.5% oxygen concentration for no harm (reference BCGA Report TR1) [19].

For more information on oxygen enrichment hazards see EIGA Doc 04, *Fire Hazards of Oxygen and Oxygen Enriched Atmospheres on enrichment* [20].

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, for example boilers, vehicles, or by asphyxiation of people.

These effects are seen as hazardous below 16% oxygen with certainty of fatality below 10%. A total oxygen concentration of 12.5% should be taken as the criteria for “harm” and 19.5% for no harm.

For more information on asphyxiation hazards see EIGA Doc 44, *Hazards of Oxygen Deficient Atmospheres* [21].

6.3 Toxic effects

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:

- Acute exposure guideline level proposed by AEGL-3 is the airborne concentration, expressed as parts per million (ppm) or milligrams per cubic metre (mg/m³), of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death [22];

- Emergency Reponses Planning Guidelines for Air Contaminants ERPG Level 3 from the American Industrial Hygiene Association, who states values for the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects [23]; and

- Immediately Dangerous to Life or Health (IDLH) Values from the US National Institute for Occupational Safety and Health [24].

For no harm levels, it is proposed to use ERPG level 2 or AEGL-2:

- The ERPG Level 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 [22].

- AEGL-2 is the airborne concentration (expressed as ppm or mg/m³) 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 [23].

- Other sources of data include:
  - HSE EH40, *Workplace exposure limits* [25];
  - OSHA *Threshold Limit Values* in the US [26]; and
  - AGW values in Germany [27].

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 can instead conform to probability distribution functions. A statistical method of assessment is the probit method. For 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 (1% lethality), and the no harm level be set at a probit of less than 1.91 (0.1% lethality). See EIGA Doc 189, *The Calculation of Harm and No-Harm Distances for the Storage and Use of Toxic Gases in Transportable Containers* [28].

Parameters for probit equations exist for (among others) ammonia, chlorine, and carbon monoxide.

Sources for these parameters are:

- *Methods for the determination of possible damage to people and objects resulting from the releases of hazardous material* (TNO Green Book) [15];
- *Guidelines for developing quantitative safety risk criteria* [7];
- *Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment*, [29]; and
- *Handleiding Risicoberekeningen Bevi version 3.3* (formerly the Purple Book) [6].

7 Calculation of hazardous effects

In order to calculate the hazardous effects, there is a requirement to consider the series of physical effects that could occur, including:

- rate of release of the substance including flashing, aerosol and evaporation effects;
- gas dispersion;
- fires or explosions;
- exposure to cryogenic temperatures;
- exposure to oxygen enrichment;
- exposure to asphyxiants;
- exposure to heat radiation; and
- 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 corrosion holes, from open valves or from emergency vents. The discharge can be gas, liquid or two-phase flashing liquid releases.

The estimate of release rate and quantity of the discharge become important inputs into dispersion models. The actual duration of the release shall also be determined for subsequent consequence estimation. In order to calculate the inventory released there is requirement to consider the installed equipment such as interconnecting pipework, heat exchangers, vessels and vent lines.

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 or valve leak containing gas under pressure;
    - flexible hose leakage, rupture or disconnection;
    - emergency relief discharge (vapour only); and
    - boil off or evaporation from liquid pool.

- Liquid:
  - hole in atmospheric storage tank, vessel or connecting pipe under liquid head; and
  - hole in pipe or vessel containing pressurised liquid below its normal boiling point.
- Two-phase:
  - hole or emergency relief discharge from a pipe or vessel containing pressurised liquid above its normal boiling point, for example externally heated tank, (fire) containing LPG.

Gas discharge from pressure relief valves can be calculated from the initiating event placing a demand on the relief device, for example estimating a vent rate in the case of external fire. For simplification, separation distances can be calculated for the rated relief valve capacity for a short-term release.

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 can 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 can 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. The AIChemE DIERS literature is a source of information on pressure relieving systems [30]. 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

Gases can be released through several different mechanisms such as evaporation from liquid pools, high momentum releases from the opening of a relief valve or high-pressure process vent, low momentum continuous releases from conservation vents or instantaneous releases from catastrophic rupture of process equipment. Each of these types of releases have different physical characteristics such as temperature, velocity and release direction.

When a gas is released, the resulting vapour cloud will be diluted by air entrainment. The rate of dilution is controlled by several factors which include the physical properties of the gas (temperature, density, the release rate, meteorological conditions and terrain).

As a gas cloud disperses down-wind from the release point, any initial jet momentum will eventually decay until the cloud is moving passively with the wind. The cloud density may change over time as the gas cools, or warms, affecting the rate of dispersion.

Many modern dispersion modelling software tools have Unified Dispersion Models which can model all of these effects within a cloud. Some simpler models however, only work for specific scenarios such as low momentum, or dense gas release.

Below is a list of some of the more commonly used dispersion modelling software tools available and when they should be used:

- ALOHA: Low momentum, dense or neutrally buoyant gas [31];
- DEGADIS: Dense gas jets or low momentum dense gas releases [32];

- HGSYSTEM/SLAB:(Various US research sources generally available on request) [33];

- ISC: Industrial Source Complex Model generally used for routine buoyant air pollutant modelling - includes downwash and building effects (US EPA) [34];

- PHAST: Gas or liquid release cases (DNV GL) [35];

- SUPERCHEMS: ioMosaic Corporation single and two phase pressure releases [36]; and

- FLACS (CFD, Gexcon) comprehensive modelling including buildings and terrain [37].

7.3 Calculation principles for thermal effects

For the calculation of thermal effects, the following types of fires shall be considered:

- pool fire;

- flash fire; and

- jet fire.

Fireball is typically excluded as very low probability event.

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

- heat convection; or

- heat radiation.

Heat convection can 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.

Heat convection shall be taken into account if the heat source is under or close to the installation. In this case heat convection shall be a part of the calculation as well as the heat radiation.

The transmission of heat via radiation can heat up the installation even if the heat source is separated by several metres from the installation.

The effect of heat convection is influenced by:

- temperature and heat capacity of flame and combustion products;

- flow regime (turbulent / laminar); and

- atmospheric conditions.

The effect of heat radiation is influenced by:

- dimension of the fire;

- burning rate;

- mean surface emission flux;

- atmospheric conditions; and

- distance and orientation between fire and object.

Models and tools for calculation of heat radiation include:

- API RP 521 [13];
- SUPERCHEMS Mosiac [36];
- EFFECTS, TNO [38]; and
- PHAST, DNV GL [35].

More detailed calculations for a risk-based approach of the separation distances could be required, for example, thermal radiation impinging on a cryogenic vessel from a jet fire or a pool fire.

7.4 Calculation principles for explosion effects

An accurate calculation of the potential explosion effects can be calculated by using methods such as Computational Fluid Dynamics (CFD). CFD is able to take into account environment, weather conditions, obstacles and / or confinement.

Typical explosions experienced in the industrial gases industry can be the result of the following:

- Rapid chemical reactions;
- 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);
- Confined explosions, where a rapid chemical reaction takes place inside the vessel, process or congested area; and
- Physical explosions, where the stored energy of the system is released by rupture. This can include a Boiling Liquid Expanding Vapour Explosion (BLEVE).

The result is usually examined in terms of a shockwave although projectiles can be a major threat from physical or confined explosions.

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 overpressures can be estimated from TNT. There are some limitations of using the TNT model, see API 752, *Management of Hazards Associated With Location of Process Plant Permanent Buildings* [39].

- Baker-Strehlow-Tang (BST) Model [40]:

  The BST Model predicts the effects of reactivity and confinement for a vapor cloud explosion (VCE). The model is based on numerical modelling of constant velocity flames and accelerating flames spreading through spherical vapor clouds. With this method, the strength of the blast wave is proportional to the maximum flame speed achieved within the cloud and is presented in the form of a Mach number. For the estimation of the Mach number, the flame expansion (1 to 3 directions), obstacle density (low, medium and high) and material reactivity (low, medium and high) are taken into account.

- 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.

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, evasive action, possible provision of PPE such as escape masks are important considerations 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 shall 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 continuous emissions (approximately constant concentrations over time downwind) or puff emissions (concentrations varying with time). Alternatively, the distances to the time adjusted direct effect model criteria (examples SEI, SEL, SELS (France), BImSchG, (Germany), SLOT and SLOD, (UK) AEGL, Acute Exposure Guideline Levels, ERPG Emergency Response Planning Guidelines) can be gauged from the dispersion information.

7.6 Software for effect calculation

The blast and toxic gas effects can be modelled by commercial software, examples include, but not limited to:

- PHAST: DNV GL [35];
- SUPERCHEMS: ioMosiac [36]; and
- SafeSite, Baker Risk [41].

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 reduce risks as far as possible.

Separation distances can be calculated from a theoretical basis. These distances can be large, but from a practical point of view it may be necessary to reduce these distances without reducing the level of safety. This can be achieved by the use of additional safety measures, also known as prevention or mitigation factors.

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

Normal measures include:

- installations are designed, manufactured and installed in accordance with recognised codes and standards;
- installation is operated by personnel trained in operating and emergency procedures;
- regular inspection of flexible hoses; and

- maintenance including periodic inspection, is carried out according to national regulations and manufacturer's recommendations.

Additional measures include:

- prevention by reducing the probability of the event;
- mitigation by reducing the consequences of the event such as by secondary containment, water curtains and firefighting; and
- locating workstations for non-essential personnel at or beyond the no-harm distance.

8.1 Examples reducing the probability of an event

Examples of items reducing the probability of an event include:

- use of higher class of material;
- use of welded connections instead of flanges;
- use of high integrity valves such as bellow sealed or diaphragm valves;
- redundant components, for example the use of two safety valves or of a safety valve and a bursting disc, the use of two quick acting shut off valves;
- redundant instrumentation;
- 100% non-destructive testing of welds of pipelines;
- double-wall vessels with leakage indicator on the interspace; and
- 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.

8.2 Examples reducing the consequence of an event

Examples reducing the consequences of an event include:

- use of remote controlled, automatic or manual quick-acting emergency isolating valves;
- flow rate limiters;
- provision of a bund for storage vessels;
- fire or blast resistant protection walls;
- provision of gas warning devices, which may also trigger protective devices, for example alarm, and shut off;
- fire detection devices automatically initiating a sprinkler system;
- personal protective equipment;
- ensuring buildings are located and designed to reduce occupant vulnerability;
- provision of shelters, gas escape masks; and
- emergency response training.

9 References

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Appendix A – Determination of safety distance on a liquid oxygen storage vessel at customer premises

Description of installation

A 33 000 litre capacity liquid oxygen tank is used to supply gaseous oxygen into the customer premises. The required minimum supply pressure is 8 bar, consequently the tank pressure build-up regulator is set at 8 bar with the tank regulator set at 10 bar so that pressure in the supply line will normally vary between these values. The tank pressure safety valve is set at 16 bar with an additional bursting disc set at 24 bar. The pressure safety relief devices are located under the tank at 1 metre elevation.

Ambient vaporisation of LOX is at a capacity of 300 Nm³/hr for 8 hours per day and 5 days a 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 25 000 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 thermal expansion or vaporisation of trapped liquid

Liquid carryover by overfill

Tank rupture by overfill

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

Adopted criteria

No Effect 25 % vol. O_2

Harm Effect 35 % vol. O_2

Equipment inventory and components (see Figure 4)

(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 stainless steel) 25mm

15. Liquid withdrawal valve (bronze, silver soldered) 25mm

16. Three-way valve manifold (brass, compression fitting) 25mm

19. Liquid fill line (stainless steel, soldered to valve #23 / welded to tank) 25mm

26. Line to vaporiser (copper, silver soldered to unions) 25mm

27. Vaporiser-aluminium finned tubes (aluminium bends, welded to tubes) 20mm

28. Liquid withdrawal connection (stainless steel, welded to tank / soldered to fitting) 25mm

33. Hose (stainless steel, welded to coupling) 50mm

34. Trailer fill connection (bronze, union connection) 50mm

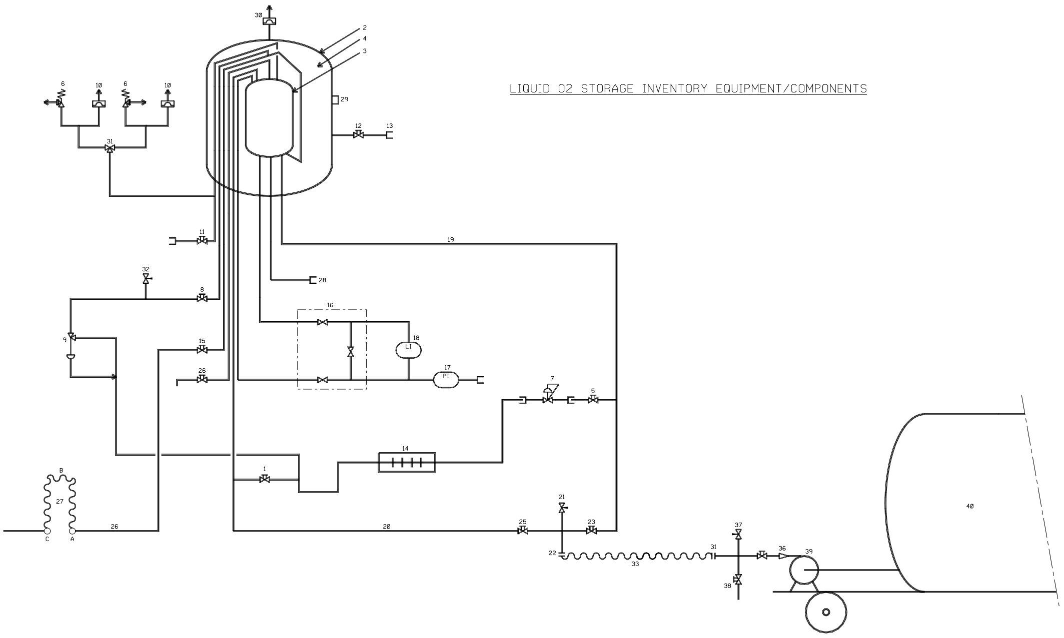


Figure 4 – Typical storage vessel on customer premises

Frequency data

Table 3 – Frequency data

Type of leak	Magnitude	Frequency of event Ft
25mm Pipe	Small leak	7.50E-06 1)
	Large leak	2.00E-06 1)
	Break	4.60E-07 1)
Valve	Gland leak	1.00E-02
Joints and unions	Small fitting leak	3.30E-02
	Large fitting leak	4.00E-03
	Break	5.00E-04
Hose	Small leak	1.00E-01
	Large leak	1.00E-02
	Break	1.00E-03
Flange	Flange leak	1.70E-04
	Flange blowout	1.70E-05
NOTE Frequency data in failures per item per year 1) Frequency data per metre		

Table 4 – Calculation example

Event	1	1.1	1.2	1.3	1.4
Harm / Effect	Oxygen enrichment				
Harm generating device	1 Safety valve				
Description of deviation	Short duration vent:30 sec	Long duration vent after instantaneous vacuum loss	Long duration vent after malfunction of pressure building regulator	Long duration vent after overfilling	Tank rupture due to overfilling
Prevention		Change to visual inspection of signs of vacuum loss by driver / technician / customer ref EIGA Doc 224 [41]		Opening of overflow valve (full trycock valve) Drwg item 24 during filling	Opening of overflow valve (full trycock valve) Drwg item 24 during filling
Estimation of frequency of event (per year)	Fd>1	Fd =1 x 5.2 x 10^{-4} = 5.2 x 10^{-4}/y: vacuum loss by leak into annular space (For vacuum loss in fire = 3.3 x 10^{-5}/yr therefore not considered)	Fd = 7 x 10^{-3} Pressure build-up fails open	Fd = N x 3 x 10^{-3} Human error by omission of procedure 3 x 10^{-3} /demand N deliveries /tank/year Large customer: N = 50, fill duration 60 min	Fd = N x 3 x 10^{-3} Human error by omission of procedure 3 x 10^{-3} /demand N deliveries /tank/year Large customer: N = 50, fill duration 60 min
Frequency, Fd	1.00E+00	5.20E-04	7.00E-03	1.50E-01	1.50E-01
Calculated geometrical effect	Cloud max width < 1m	Cloud max width < 1m	Cloud max width < 1m	Cloud max width < 20m	None
Geometrical effect, Pg	0.10	0.10	0.10	0.10	1.00
Mitigation description	Probability of ignition = 0.2	Probability of ignition = 0.2	Probability of ignition = 0.2	Operator will respond to relief device activation in 99% of cases Probability of ignition = 0.2 = 0.01 x 0.2 = 0.002	Bursting Disc Works in 99% of cases Probability of rupture at pump deadhead pressure = 0.01 See EIGA doc 151 Probability of ignition = 0.2 = 0.01 x0.01 x0.2 = 0.00002
Mitigation, Pm	0.2	0.2	0.2	0.002	0.00002
Calculated frequency (years) = Fd x Pg x Pm	2.00E-02	1.04E-05	1.40E-04	3.00E-05	3.00E-06
Consequence calc (See Fig 2)	No harm effect distance	No distance required	Harm effect distance	No distance required	No distance required
Release scenario	DN20 relief valve 18 bar	15mm ID, 100% section, 16 bar	15mm ID, 100% section, 16 bar	15mm ID, 100% section, 16 bar	Catastrophic rupture
Calculated release rate, kg/s	0.45	0.45	0.45	7.1	Instantaneous
Distance to harm effect, m 35% O2	1	N/A (1m)	1	N/A (9m)	N/A (29m)
Distance to no harm effect, m 23.5%	5	N/A (5m)	5	N/A (85m)	N/A (155m)

Event	2.1	2.2	2.3
Harm / effect	Oxygen enrichment		
Harm generating device	2 Bursting disc		
Description of deviation	Premature rupture	Justified rupture	Justified rupture
Prevention	Periodic replacement / inspection		
Estimation of frequency of event (per year)	One disk in service premature rupture = 1 x 10^{-3}/y	Pressure increase that should be released by a short duration venting safety valve fails to open: λ = 5.0 x 10^{-4}/y	Pressure increase by overfilling due to human error (omission of procedure) Fd = N x 3 x 10^{-3} N = 50 (large customer)
Frequency, Fd	1.00E-03	5.00E-04	1.65E-01
Geometrical effect description	Cloud max width < 1m	Cloud max width < 1m	Cloud max width < 20m
Geometrical Effect, Pg	0.10	0.10	0.10
Mitigation description	Probability of ignition = 0.2	Pressure increase is observed and action taken in 50% of cases Pm = 0.5 Probability of ignition = 0.2 = 0.5 x 0.2 = 0.1	Operator stops filling after tank hydrostatically full in 99 cases out of 100 Pm = 0.01 Probability of ignition = 0.2 = 0.01 x 0.2 = 0.002
Mitigation, Pm	0.2	0.1	0.002
Calculated frequency (years) = Fd x Pg x Pm	2.00E-05	5.00E-06	3.30E-05
Release scenario	DN15 bursting disc at 10 bar	DN15 bursting disc at 24 bar	DN15 bursting disc at 24 bar, at pump capacity
Consequence calc (see Fig 2)	No distance required	No distance required	No distance required
Calculated release rate, kg/s	0.7	2.16	7.1
Distance to harm Effect, m 35% O2	N/A (1m)	N/A (2 m)	N/A (9 m)
Distance to No harm effect, m 23.5%	N/A (5m)	N/A (12 m)	N/A (85m)

Event	3.1	3.2	3.3	3.4
Harm/Effect	Oxygen Enrichment			
Harm Generating Device	3 Hose failure			
Description of Deviation	Towaway Liquid hose rupture	Large leak	Small leak	Small leak in fill couplings
Prevention	Anti-towaway device on trailer as per EIGA Doc 63			
Estimation of Frequency of Event (per year)	probability = 1 x 10^{-6} per delivery 50 deliveries/y	Hose failure: Large leak λ = 5.0 x 10^{-2}/y Time in use: 50 deliveries x 50 minutes Fd = 50 x 60 x 5 x 10^{-2}/(60 x 24 x365) = 2.9 x 10^{-4}	Order of magnitude more likely than large leak	2 couplings * = 3.3 x 10^{-2} Fd = 2 x 3.3 x 10^{-2} x time in use = 50 x 60 x 6.6 x 10^{-2}/(60 x 24 x365) = 3.8 x 10^{-4}
Frequency, Fd	1.00E-05	2.90E-04	2.90E-03	3.80E-04
Geometrical Effect description	Cloud is approx 140m wide max.	Cloud width is < 20m	Cloud width is < 20m	Cloud width is < 20m
Geometrical Effect, Pg	0.25	0.10	0.10	0.10
Mitigation description	Check valve on fill line works 99 times out of 100. Probability of ignition = 0.2 = 0.01 x 0.2 = 0.002	Operator stops filling. Fails to stop in 10% of cases Probability of ignition = 0.2 = 0.1 x 0.2 = 0.02	Operator stops filling. Fails to stop in 10% of cases Probability of ignition = 0.2 = 0.1 x 0.2 = 0.02	Operator stops filling. Fails to stop in 5% of cases Probability of ignition = 0.2 = 0.05x 0.2 = 0.01
Mitigation, Pm	0.002	0.02	0.02	0.01
Calculated frequency (years) = Fd x Pg x Pm	5.00E-09	5.80E-07	5.80E-06	3.80E-07
Consequence calc required	No distance required	No distance required	No distance required	No distance required
Release scenario	Delivery line leak, 50mm ID, 100% section	Delivery line leak, DN40, 20% section = 18mm equivalent dia leak on hose	Delivery line leak, DN40, 2% section = 6mm equivalent dia leak on hose	Delivery line leak, 50mm ID, 2% section = 7mm equivalent dia
Calculated release rate, kg/sec	7.1	7.1	1.18	1.18
Distance to harm Effect, m 35% O2	N/A (9 m)	N/A (9 m)	N/A (5 m)	N/A (5 m)
Distance to No harm effect, m 23.5%	N/A (85 m)	N/A (85 m)	N/A (31 m)	N/A (31 m)

Event	4.1	5.1
Harm/Effect	Oxygen Enrichment	
Harm Generating Device	4 Liquid Valve leak	5 Gaseous Valve leak
Description of Deviation	Gland leak	Gland leak
Prevention		
Estimation of Frequency of Event (per year)	ƛ = 1.0×10^{-2}/y 4 liquid valves Fd = 4.0×10^{-2}	ƛ = 1.0×10^{-2}/y 10 vapour Fd = 1×10^{-1}
Frequency, Fd	4.00E-02	1.00E-01
Geometrical Effect description	Cloud width is small	Cloud width is small
Geometrical Effect, Pg	0.10	0.10
Mitigation description	Probability of ignition = 0.2	Probability of ignition = 0.2
Mitigation, Pm	0.2	0.2
Calculated frequency (years) = Fd x Pg x Pm	8.00E-04	2.00E-03
Consequence calc required	Harm Effect Distance	Harm Effect Distance
Release scenario	Valve gland leak. Equivalent diameter 3mm	Valve gland leak. Equivalent diameter 3mm
Calculated release rate, kg/s	0.14	0.02
Distance to harm Effect, m 35% O2	1	1
Distance to No harm effect, m 23.5%	5	1

Event	6.1	6.2	7.1	8.1	8.2
Harm/Effect	Oxygen Enrichment			Oxygen Enrichment	
Harm Generating Device	6 Joints and unions		7 Welded and brazed fittings	8 Stainless steel pipe	
Description of Deviation	Small leak	Large leak	Small leak	Small leak	Large leak
Prevention					
Estimation of Frequency of Event (per year)	$\lambda = 1 \times 10^{-3}$/y 5 joints Fd = 5×10^{-3}	$\lambda = 1 \times 10^{-4}$/y 5joints Fd = 5×10^{-4}	$\lambda = 9 \times 10^{-5}$/y 30 fittings Fd =$2.7 \times 10^{-3}$	$\lambda = 1 \times 10^{-5}$/y/m, diameter DN40 10 metres Fd = 1×10^{-4}	$\lambda = 1 \times 10^{-6}$/year DN40 10 metres Fd = 1×10^{-5}
Frequency, Fd	5.00E-03	5.00E-04	2.70E-03	1.00E-04	1.00E-05
Geometrical Effect description	Cloud is <20m wide	Cloud is <20m wide	Cloud is <20m wide	Cloud width is small	Cloud width is small
Geometrical Effect, Pg	0.10	0.10	0.10	0.10	0.10
Mitigation description	Probability of ignition = 0.2	Probability of ignition = 0.2	Probability of ignition = 0.2	Probability of ignition = 0.2	Probability of ignition = 0.2
Mitigation, Pm	0.2	0.2	0.2	0.2	0.2
Calculated frequency (years) = Fd x Pg x Pm	1.00E-04	1.00E-05	5.40E-05	2.00E-06	2.00E-07
Consequence calc required	Harm Effect Distance	No distance required	Harm Effect Distance	No distance required	No distance required
Release scenario	Line leak, DN40, 2% section = 6mm equivalent dia	Line leak, DN40, 20% section = 19mm equivalent dia	Line leak, DN40, 2% section = 6mm equivalent dia	Line leak, DN40, 2% section = 6mm equivalent dia	Line leak, DN40, 20% section = 19mm equivalent dia
Calculated release rate, kg/s	0.14	4.77	0.14	0.44	4.77
Distance to harm effect, m	1	N/A (7 m)	1	N/A (3 m)	N/A (7 m)
Distance to no harm effect, m	5	N/A (49 m)	5	N/A (10 m)	N/A (49 m)

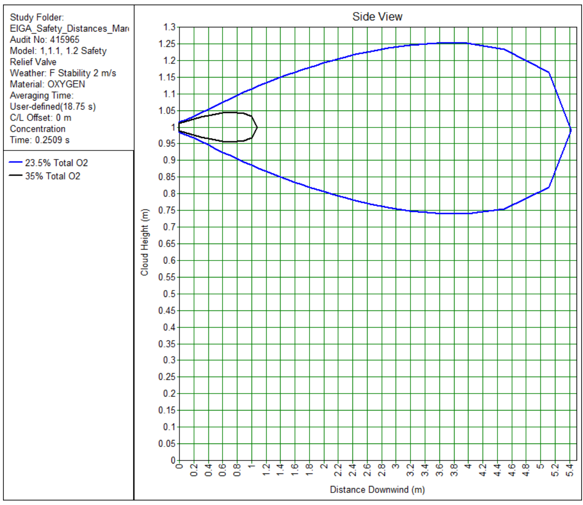
From the tables above it can be seen that the maximum no effect distance is 5m.

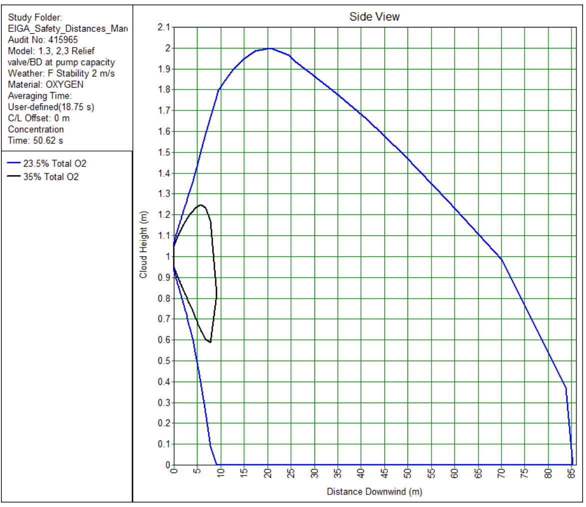
The maximum distance to harm effect is 1m.

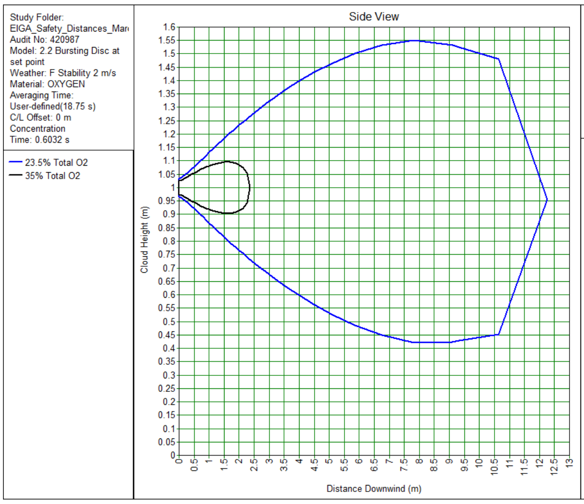
Since the no harm effect distance is the larger, the safety distance for this example is 5m.

Event	Harm / Effect	Harm Generating Device	Description of Deviation	Consequence calc required	Release scenario	Calculated release rate, kg/sec	Distance to harm Effect, m 35% O2	Distance to No harm effect, m 23.5%
1	Oxygen enrichment	1 Safety Valve	Short duration vent:30 sec	No harm effect distance	DN20 relief valve 18 barg	0.45	1	5
1.2			Long duration vent after malfunction of pressure building regulator	Harm effect distance	15mm id, 100% section, 16 barg	0.45	1	5
4.1	Oxygen enrichment	4 Liquid Valve leak	Gland leak	Harm effect distance	Valve gland leak. Equivalent diameter 3mm	0.14	1	5
5.1		5 Gaseous Valve leak	Gland leak	Harm effect distance	Valve gland leak. Equivalent diameter 3mm	0.02	1	1
6.1	Oxygen enrichment	6 Joints and unions	Small leak	Harm effect distance	Line leak, DN40, 2% section = 6mm equivalent dia	0.14	1	5
7.1		7 Welded and brazed fittings	Small leak	Harm effect distance	Line leak, DN40, 2% section = 6mm equivalent dia	0.14	1	5

PHAST Models (version 6.73) to calculate distance and geometric effect (Pg):

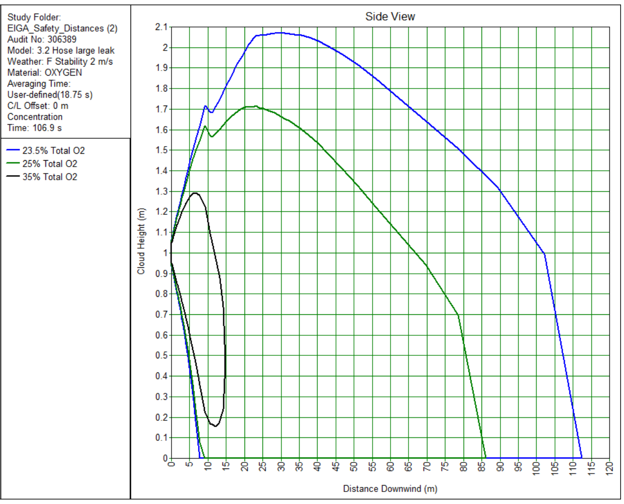






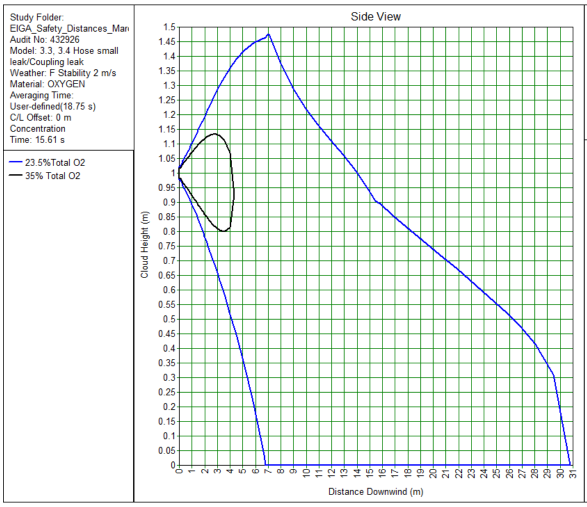
Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 420987
Model: 2.2 Bursting Disc at set point
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 0.6032 s

— 23.5% Total O2
— 35% Total O2



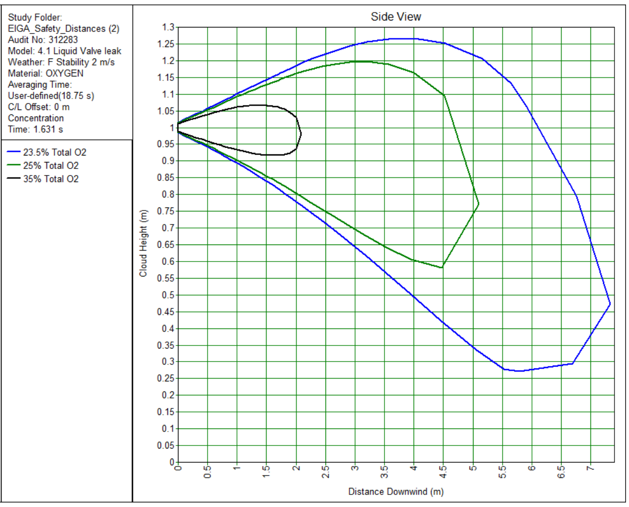
Study Folder:
EIGA_Safety_Distances (2)
Audit No: 306389
Model: 3.2 Hose large leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 106.9 s

— 23.5% Total O2
— 25% Total O2
— 35% Total O2



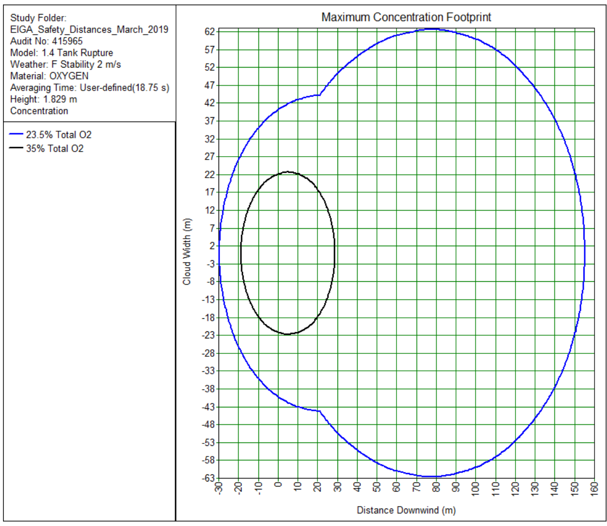
Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 432926
Model: 3.3, 3.4 Hose small leak/Coupling leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 15.61 s

— 23.5%Total O2
— 35% Total O2



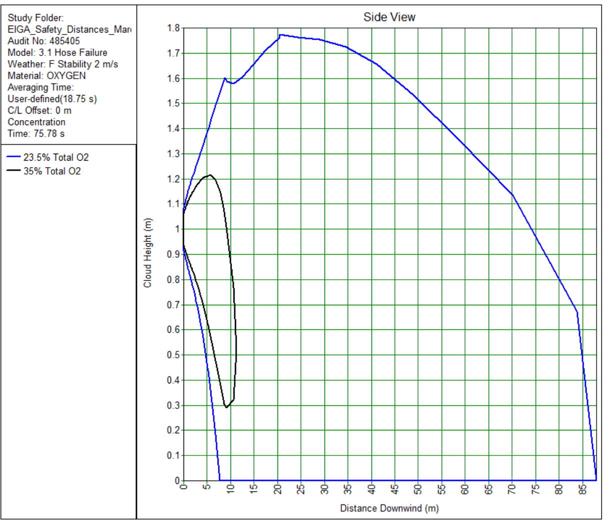
Study Folder:
EIGA_Safety_Distances (2)
Audit No: 312283
Model: 4.1 Liquid Valve leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 1.631 s

— 23.5% Total O2
— 25% Total O2
— 35% Total O2



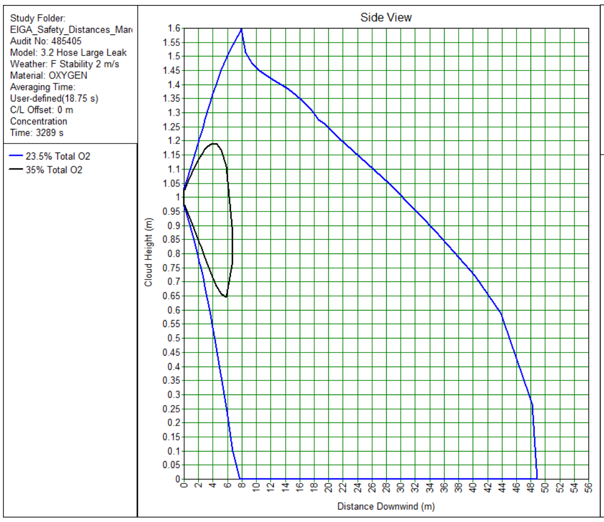
Study Folder:
EIGA_Safety_Distances_March_2019
Audit No: 415965
Model: 1.4 Tank Rupture
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time: User-defined(18.75 s)
Height: 1.829 m
Concentration

— 23.5% Total O2
— 35% Total O2

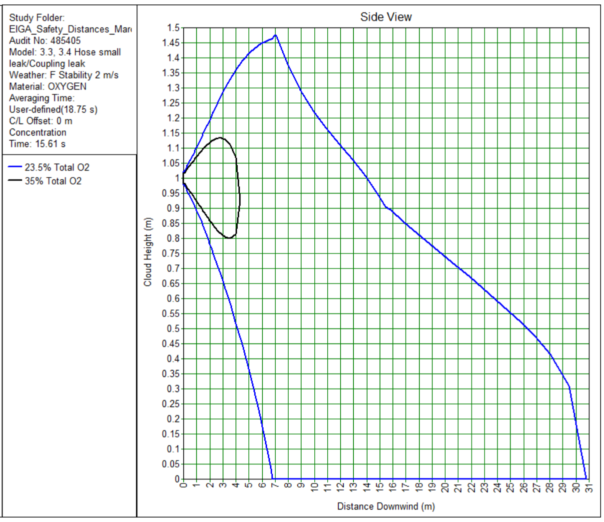


Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 485405
Model: 3.1 Hose Failure
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 75.78 s

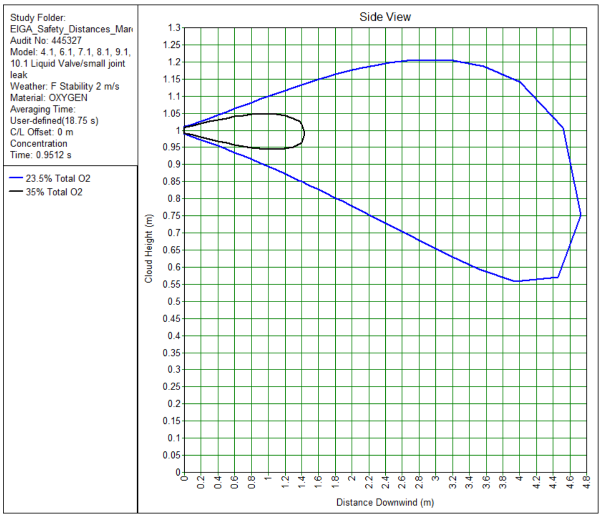
— 23.5% Total O2
— 35% Total O2



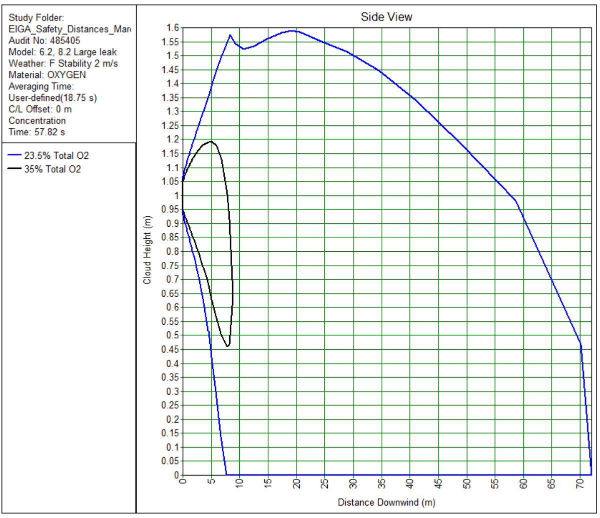
Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 485405
Model: 3.2 Hose Large Leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 3289 s



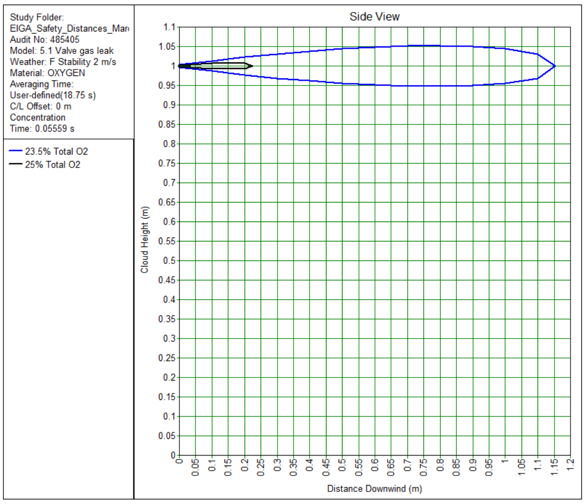
Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 485405
Model: 3.3, 3.4 Hose small leak/Coupling leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 15.61 s



Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 445327
Model: 4.1, 6.1, 7.1, 8.1, 9.1, 10.1 Liquid Valve/small joint leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 0.9512 s



Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 485405
Model: 6.2, 8.2 Large leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 57.82 s



Study Folder:
EIGA_Safety_Distances_Mar
Audit No: 485405
Model: 5.1 Valve gas leak
Weather: F Stability 2 m/s
Material: OXYGEN
Averaging Time:
User-defined(18.75 s)
C/L Offset: 0 m
Concentration
Time: 0.05559 s