DSB

The Norwegian Directorate for Civil Protection

Report

Guidelines for quantitative risk assessments of facilities handling hazardous substances

Revised edition

Report information

Guidelines for quantitative risk assessments of facilities handling hazardous substances: Revised edition

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00	JAP	JD	KDA	18 Oct 2017	First publication
01	JAP	JD	KDA	1 Jul 2021	Revision after experience with use
02	AML	JD	BM	06 Feb 2026	Revision after experience with use
02a	AML	JD	BM	28 July 2026	Clarifications regarding modelling of tank ruptures
02b	AML	JD	BM	12 August 2026	Technical updates (no substantive changes)

The document has been translated to English by DSB.

Document revisions

Revision	Date	Description/changes	Changes made by
Rev. 00	18.10.2017	First edition after meetings, input, and hearing with the industry in Norway	Joar Dalheim / Jan Pappas / Jan Røed
Rev. 01	01.07.2021	Revision after experience with use	Joar Dalheim / Jan Røed
Rev. 02	06.02.2026	Revision after experience with use	Joar Dalheim / Celin Tonheim
Rev. 02a	28.07.2026	New section in Chapter 3.4.4 with clarifications regarding modelling of tank ruptures	Joar Dalheim / Celin Tonheim
Rev. 02b	12.08.2026	Technical updates (no substantive changes)	Joar Dalheim / Celin Tonheim

Overview of changes from rev. 01 to rev. 02:

The following chapters are significantly modified:

- Chapter 3.4.2.3 New section with model for leaks from road tankers during transportation
- Chapter 3.4.2.6 Brief information about the new SAFEN models
- Chapter 3.4.2.8 Leaks from pipelines (new)
- Chapter 3.4.4 Recommended leak frequency data (changes in summary)
- Chapter 3.6.4 MISOF updated to include hydrogen
- Chapter 3.6.5 Recommendation for delayed ignition indoors extended to smaller room volumes
- Chapter 3.6.6 Ignition probability outside the facility area (new description of the same model)
- Chapter 3.6.7 Recommended ignition probability models (changes in summary)

In addition, minor editorial changes have been made that do not affect the content of the guidelines.

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Abbreviations

BLEVE	Boiling Liquid Expanding Vapour Explosion
CFD	Computational Fluid Dynamics
FFI	Forsvarets forskningsinstitutt (Norwegian Defence Research Establishment)
HAZID	Hazard Identification
HAZOP	Hazard and operability study
HSE	Health and Safety Executive
HyRAM	Hydrogen Risk Assessment Models
IOGP	The International Association of Oil & Gas Producers
LEL	Lower Explosive Limit
LFL	Lower Flammable Limit
LH2	Liquid hydrogen
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MISOF	Modelling Ignition Sources on Offshore oil and gas Facilities
NCS	Norwegian Continental Shelf
P&ID	Piping and Instrumentation Diagram
PLOFAM	Process leak for offshore installations frequency assessment model
RIVM	National Institute for Public Health and the Environment (NL: Rijksinstituut voor Volksgezondheid en Milieu)
SIL	Safety Integrity Level
UFL	Upper Flammable Limit
SAFEN	Safe Energy Carriers Joint Industry Project
TNO	The Netherlands Organisation for Applied Scientific Research (NL: Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek)
QRA	Quantitative risk assessment

1 Introduction

1.1 Foreword

This report is the third edition of DSB's guidelines for quantitative risk assessments for facilities handling hazardous substances. The first and second editions of the guidelines were published in October 2017 and July 2021, respectively. The report has been prepared by Vysus Norway AS for DSB.

The most important changes in the report, compared to the 2021 edition, are listed at the beginning of the document.

The work on revising the guidelines has consisted of three phases: identification of the need for changes, consultation, and assessment of consultation input. Based on their own experience with using the guidelines, feedback from users, and new knowledge on methods and data sources, Vysus Norway AS and DSB initially compiled a list of needs for changes in the 2021 edition and implemented these in the document. The proposal for revised guidelines was then published for consultation on DSB's website from 29.04.2025 to 15.06.2025. Relevant stakeholders (consulting companies, authorities, industry associations, and selected companies that handle hazardous substances) were notified directly about the consultation, and eight of these submitted one or more comments on the proposal. The consultation responses have been assessed, and necessary changes have been implemented into the document.

The report is available at www.dsb.no.

1.2 Objective

The objective of these guidelines is to reduce random variation due to data sources and methods when preparing quantitative risk assessments for facilities handling hazardous substances. In this context, hazardous substances refer to flammable, reactive, and pressurised substances, as defined in *forskrift om håndtering av farlig stoff*[1] (the Norwegian regulations on the handling of hazardous substances) § 4. It is also an ambition that the guidelines shall help ensure that the risk assessments are prepared in a way that makes them understandable, verifiable, reproducible, and comparable, regardless of which tools are used and who performs the calculations.

The guidelines are primarily developed for major accident establishments but may also be used when preparing quantitative risk assessments for smaller facilities handling flammable, reactive, or pressurised substances.

As mentioned above, there can be significant uncertainties associated with the preparation of quantitative risk assessments. Even though there are existing standards and internationally acknowledged methodologies for this type of calculations, we have considered it necessary to publish detailed guidelines on how the risk assessments should be performed.

The guidelines provide for the calculation of location-specific individual risk, presented as risk contours. These risk contours can be used directly as a basis for the establishment of consideration zones in land-use plans. DSB has an objective that there should be established consideration zones around all of Norway's approximately 200 major accident establishments with hazardous substances.

The guidelines must be seen in connection with *temarapport om sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer* (guidance report on the safety around facilities handling flammable, reactive, pressurised and explosive substances) (2013), ref. /1/, and *veileder om sikkerheten rundt storulykkevirksomheter* (guidance report on the safety around major accident establishments*)* (2019), ref. /2/, both published by DSB.

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1 Forskrift 8. juni 2009 nr. 602 om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen

The former DSB guidance report (ref. /1/) describes the regulatory framework for land-use planning around facilities with hazardous substances and provides criteria for acceptable risk to the population in the areas surrounding these facilities. The guidelines for quantitative risk assessments have been developed in accordance with the principles presented in the guidance report. Note that the risk acceptance criteria presented in the report relate to the presence of members of the public, and that risk contours developed under these guidelines must be based on the incidents that may affect the population in the area around the facility.

The latter DSB guidance report (ref. /2/) is primarily aimed at municipal use in land-use planning and risk management in the areas around major accident establishments. It also places processes of compliance and permits according to DSB's regulations (consents and permissions) into a land-use planning perspective. The guidance report discusses the use of consideration zones in the following situations:

- when it is necessary to maintain an appropriate safe distance to the population around major accident establishments
- when new developments (changes) are established around major accident establishments
- when new major accident establishments are established, or changes are made to existing major accident establishments

The Norwegian major accident regulations (*storulykkeforskriften*[2]) require the establishments, upon request, to provide the municipality with information about their risk. As of August 2026, the current regulations do not explicitly require establishments to calculate risk contours, but both guidance reports rely on the use of risk contours as a basis for establishing consideration zones around major accident establishments. It should be noted that the revised regulations on the handling of hazardous substances (*forskrift om håndtering av farlig stoff*) will enter into force on 01.01.2027. These revised regulations introduce a requirement for major accident establishments to calculate and present their risk in the form of risk contours (§ 14).

Consideration zones are used as a management tool in planning processes according to the Norwegian planning and building act (*plan- og bygningsloven*[3]), to ensure, among other things, that the risk to the population in areas surrounding facilities with hazardous substances remains acceptable. Provisions are determined for the consideration zones, describing what restrictions apply within the zone, while the zone itself indicates which areas are covered by the provisions and what type of hazard is involved. Relevant provisions may include conditions for land use (prohibiting e.g. residential buildings), sequential provisions, requirements for detailed regulation, and requirements for further investigations before implementing measures.

Risk management in areas surrounding facilities with hazardous substances is hence mainly performed through municipal enforcement of land-use plans and restrictions. Risk management within the facilities themselves is regulated through the Norwegian fire and explosion prevention act (*brann- og eksplosjonsvernloven*[4]) and its associated regulations, including the major accident regulations (*storulykkeforskriften*) and the regulations on the handling of hazardous substances (*forskrift om håndtering av farlig stoff*). The regulatory framework for handling hazardous substances requires companies to implement necessary technical and organisational measures, possibly combined with spatial restrictions (such as consideration zones), to ensure that the handling of hazardous substances does not cause unacceptable risks.

It is important to note that it may be necessary to consider more factors than risk contours alone when making decisions on consideration zones and associated planning provisions. However, the risk contours constitute an important basis of information for the work with land-use plans where major accident establishments or other facilities with hazardous substances are located within the planning area and may, as mentioned, be used directly as a basis to establish consideration zones. In practice, the facilities’ risk assessments are often

2 Forskrift 3. juni 2016 nr. 569 om tiltak for å forebygge og begrense konsekvensene av storulykker i virksomheter der farlige kjemikalier forekommer

3 Lov 27. juni 2008 nr. 71 om planlegging og byggesaksbehandling

4 Lov 14. juni 2002 nr. 20 om vern mot brann, eksplosjon og ulykker med farlig stoff og om brannvesenets redningsoppgaver

used as expert reports as a basis for the more general risk- and vulnerability studies (in Norwegian: ROS-analyse) that follow the planning process.

DSB expects that the revised guidelines will be used in the preparation of new quantitative risk assessments with risk contours, as well as in updating (changing) existing risk assessments, e.g. as a result of significant changes at a facility.

1.3 Fundamental principles

This chapter describes the principles used in the development of the guidelines:

- Risk exposure for the surroundings shall be assessed based on the overall activity in the facility or enterprise, i.e. all relevant facility sections, activities, and incidents shall be included in the risk assessments. Moreover, sources of external impact (natural hazards, domino effects from other enterprises, etc.) shall be included in the risk assessments.
- Calculation of the risk contours shall be performed and presented as "best practice" (best approach), given the information available and the chosen method for the risk assessment. This implies that the risk contours presented as a result of the risk assessments are considered to be neither “conservative” nor “optimistic”. For example, if one includes considerable conservatism in parts of the assessment as an attempt to take uncertainties into account, one risks losing the ability to determine which events contribute most to the risk and which barriers are critical and most effective. One also loses precision in the representative risk contours. The risk assessment should therefore use the best estimates in assumptions (e.g. expected leak frequency) and the most realistic interpretations of the expected extent of consequences for the scenarios assessed.
- It is important that the risk assessments are not based on assumptions that can be easily changed or are beyond one's control. This applies particularly to assumptions on how a member of the public will behave or be protected during an incident. It should therefore be assumed that members of the public will be unprotected, stay put, and not seek shelter. In reality, this will not be the case, but it is considered more important that the risk contours are independent of uncertain assumptions than to remove all conservatism. The same applies to assumptions about how the level of activity in the surroundings affects the probability of ignition of a gas cloud that extends to areas beyond the facility boundary. For example, consideration zones should not be dependent on traffic density, housing density or recreational activities in the area. It must therefore be assumed that a flammable gas cloud that reaches areas beyond the facility boundary – where ignition source control is not required – will ignite.
- The possible effects of implementing risk-reducing measures or (other) significant changes or activities in the facility shall be reflected in the extent of the risk contours.
- Uncertainties related to the available information and use of methodology shall be assessed and described but not quantified. Uncertainties are discussed further in Chapter 3.11.

1.4 Selection of content

These guidelines are based on the Norwegian standard NS 5814:2021. The guidelines mainly relate to the analytical part of the standard and are not intended to cover the entire risk assessment process.

The guidelines mainly focus on the factors that to the largest extent affect the calculation of risk contours, see Figure 1-1.

In order for the risk analyses to provide as accurate a risk picture as possible, they must reflect the actual conditions of the facility analysed. It is therefore important to include all relevant experience with the facility to ensure the analysis model is sufficiently realistic. The methodology applied and analysis results must be justified and explained in an understandable manner.

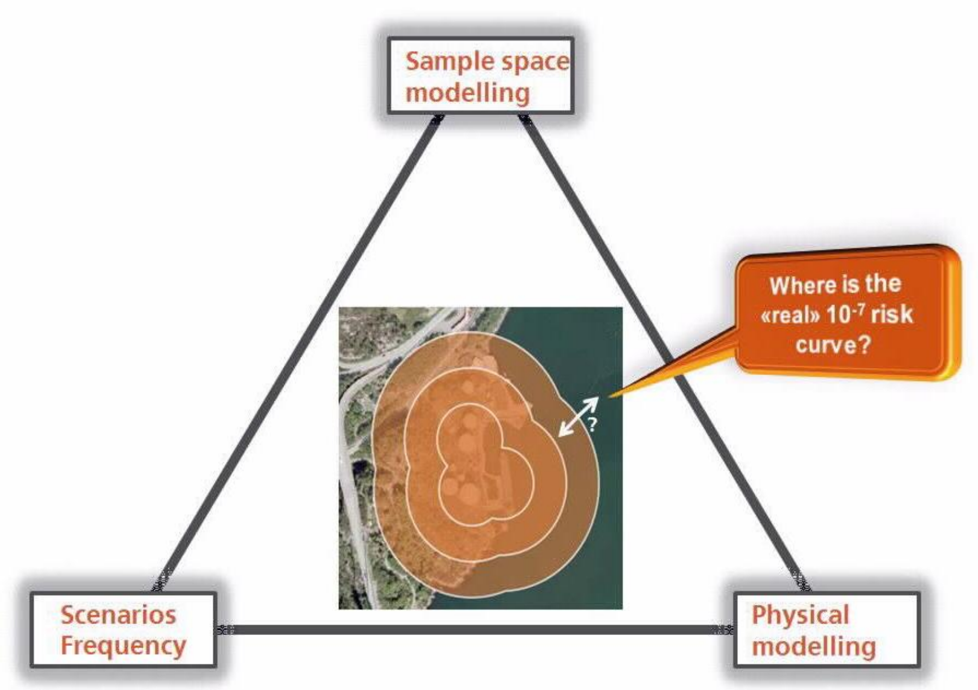

Figure 1-1 - Main drivers for establishing best estimate risk contours

1.5 Definitions

Definitions of some key terms used in the report are presented below. In general, reference is made to the definitions in NS 5814:2021.

Iso-contour

An iso-contour is a line or surface through all points in the solution space that represent the same solution value. For example, the iso-contour passing through all points with a fatal exposure frequency of 1E-7 times per year represents the risk contour that defines the outer consideration zone according to the guidance report (2013), ref. /1/.

Risk contour

The guidelines propose the use of iso-contours to express the risk to members of the public in the area around facilities that handle hazardous substances, so-called risk contours. The risk contours are created by drawing a line between points with the same individual risk. Individual risk is the statistical frequency of fatality for a hypothetical person who is continuously located at a given point outside the facility. The individual risk is calculated by combining the statistical frequency of a fatal event occurring with the probability of death at the given location outside the facility. Thus, the risk contours are not affected by how many people are actually present in the surroundings of the facility.

Consideration zone

Land-use plans must, to the extent necessary, show considerations and restrictions that are relevant to the use of the land. This shall be indicated in the land-use plan as consideration zones with associated guidelines and provisions. To the extent necessary, each consideration zone shall specify the provisions and guidelines that apply, or will apply, in compliance with the planning and building act or other acts. This is important in order to safeguard the consideration indicated by the zone. In other words, consideration zones are stipulated by the planning authority (usually the municipality) based on studies, assessments, and consultations, etc. as part of the current planning process.

Best estimate

A best estimate value is a value that is considered neither conservative nor optimistic. For example, if one includes considerable conservatism in parts of the assessment in an attempt to take uncertainties into account, one risks losing track of which events contribute most to the risk and the effect of barriers, including which barriers are critical. In other words, one loses precision in the risk contours. This may affect the ability to conduct effective land-use planning. The risk analysis should therefore use the best estimates in assumptions (e.g. expected leak frequency) and the most realistic interpretations of the expected extent of consequences for the scenarios assessed. This principle is referred to in this report as making the risk analysis best estimate.

Top event

Through a hazard identification (HAZID), one will establish an overview of all events with hazard potential that may occur at a given facility. Some of these will, for various reasons (typically low consequence severity or low frequency), not be included in the further analysis. Events to be included in the risk analysis must be defined with a clear starting point and an end point for consequence calculations. The starting point for such events is often called top events and is usually an unintended leakage of a hazardous substance. The top event is therefore not the direct or underlying cause of the leak, but the leak itself. A top event can lead to several possible end events (all with different probabilities), such as "unignited leak", "fire" or "explosion". In the guidelines, the term "scenario" is used both for end events and for a specific sequence of events.

Sample space modelling

The risk contours sum up the risk contribution from all identified (end) events, which range from relatively small/frequent to large/rare events. This makes the picture complex and difficult to get an overview of, and one should therefore show which end events are the main contributors to the risk contours.

Sample space refers to all the possible outcomes of a top event. For example, the sample space for rolling a single six-sided dice is {1, 2, 3, 4, 5, 6}. For a process plant, the sample space for a top event will be significantly greater; there are practically an infinite number of events that could occur, as a result of small variations only in, for example, leak location, leak direction, leak rate, wind conditions, temperature, atmospheric class, mechanical conditions (temporary obstructions), time of ignition, etc.

By "spanning a sample space" we mean to cover the entire sample space, or as much as practicable, with specific scenarios so that the analysis can, to the greatest extent possible, capture all relevant consequences of the top events at a facility.

It is also important to note that the number of scenarios one simulates has a significant impact on the risk contours (see Chapter 3.10).

Flammable gas

In this report, a flammable gas shall be understood as a gas classified as flammable with a concentration within the flammable range.

2 Preparation

A risk analysis should be suitable for the purpose and adapted to the degree of risk represented by the analysis object. One objective is that it is performed in such a manner that it can be verified and recreated regardless of which tools are used and who performs the analysis.

The execution of a risk analysis follows the steps defined in NS 5814:2021. The risk analysis process is not reproduced in its entirety in the guidelines, but the process is summarised in Table 2.1.

Table 2.1 - Main steps in the process for risk assessment from NS 5814:2021

	Main steps in the process for risk assessment covered by NS 5814:2021, ref. Figure 1 in the standard
Step 1 *Framework for the risk assessment*	Purpose, requirements, and scope
	Values to be protected
	Safety objectives and evaluation criteria
	Object and system description
	Method
Step 2 *Identify unwanted events*	Identify hazards and threats
	Specify unwanted events
Step 3 *Risk analysis*	Assess vulnerability
	Assess probability
	Assess consequences
	Describe uncertainty
	Describe risk
Step 4 *Risk evaluation*	Evaluate achievement of safety objectives
	Propose risk management

2.1 Competence

Anyone responsible for preparing a quantitative risk assessment must obviously have solid knowledge of, and understanding of, the properties of the hazardous substances, the functionality of the equipment/facility, the processes taking place at the facility, etc.

The necessity to possess sufficient competence is stipulated in *forskrift om håndtering av farlig stoff* (regulations on the handling of hazardous substances) § 7. This provision requires that anyone who, among other things, designs equipment and facilities used for handling hazardous substances must have the necessary competence. As part of the design process, the competence requirement also applies to anyone who prepares risk assessments for facilities/equipment used for handling hazardous substances. The competence must include, among other things, knowledge of the hazardous substances to be handled, as well as the technical design and operation of the equipment and facility.

2.2 Understanding the facility

Appendix A (Chapter 1) can be used for mapping the facility, and contains elements considered important to clarify in the initial phase of the project. The checklist items will normally indicate which documentation is required for further work, as well as provide guidance on assumptions and methodology selection.

In case there have been modifications or extensions to an existing facility, it is important to collect operational and maintenance experience from the facility. In addition, documentation from incidents, accidents, audits, internal audits, etc. may be relevant. Those responsible for performing the analysis must have good knowledge of the analysis object, and a site visit should be conducted at the start of the analysis if the local conditions are not sufficiently well known.

2.3 Choice of approach and methodology

Based on an initial mapping of the complexity and extent of the facility, surrounding conditions, and overall assumptions for the task, further activities, methodology, and tool selection are planned. All assumptions and decisions made, and which form the basis for calculating risk contours, should be justified and documented. This also applies to later project phases to ensure traceability of decisions made along the way and may influence the outcome of the analysis.

2.4 External conditions

The risk assessment must include natural and environmental conditions (landslides, floods, etc.), as well as incidents in nearby businesses and surroundings. The need for mitigative measures must be assessed for these conditions. Any residual risk that can be expected to significantly affect the frequency of release of hazardous substances shall be included in the calculation of the risk contours.

If external events lead to scenarios that differ significantly from the internal events, it must also be considered whether these can affect the risk contours.

2.5 Design and barriers

The facility’s design and barriers must be considered to the greatest possible extent in the risk assessments, both to provide the best estimated risk picture and to provide an incentive for the facilities to follow ALARP. An example is detection with automatic shutdown and possible pressure relief, which reduces the duration of the release (and the released amount). Reduced duration of the release will reduce the consequences of the incident, including the probability of ignition outside the facility boundary (see Chapter 3.6.6).

Failures or malfunctions in barriers must be included if they may affect the risk contours.

3 Risk analysis

3.1 Identification of hazards, unwanted events, and barriers

Before a QRA can be undertaken, a HAZID must be performed to identify the hazardous events that may occur in the facility. These events are then assessed in an event tree analysis, bow-tie analysis or similar. In addition to systems and equipment, organisational and operational conditions must also be assessed. Poorly executed or a lack of maintenance, operator errors, etc. can, for example, cause or contribute to unwanted events. One of the main objectives of the risk analysis is to identify effective barriers, both preventive and mitigative. In order to achieve this effectively, it is important that all types of causes and initiating events are adequately identified.

Examples of guidewords for use in HAZID are given in Appendix A. In the preparation phase, one will break down the facility into subsystems and use a selection of relevant guidewords. Fault tree analyses and HAZOP reports or similar may also be used as inputs in a HAZID process.

The risk analysis should clarify how the transport of hazardous substances into or out of the facility is assessed. Events related to transport to and from the facility will usually not be included in the calculation of risk contours for the facility, but relevant events related to the transport and transfer within the facility must be included in the risk analysis. This may include events related to overfilling or overpressure of transport tanks, events during transfer to ships, etc. For the risk analysis, it is typically transfer activities that contribute, but all hazards associated with transport of dangerous goods within the facility must be assessed regarding whether they may influence the risk contours.

3.2 Establishing top events

Those who perform the risk analysis and the HAZID must, together with the company, decide which top events to cover in the analysis. The selection made should be justified and documented in the analysis. Events that do not influence the risk contours may be excluded from the analysis.

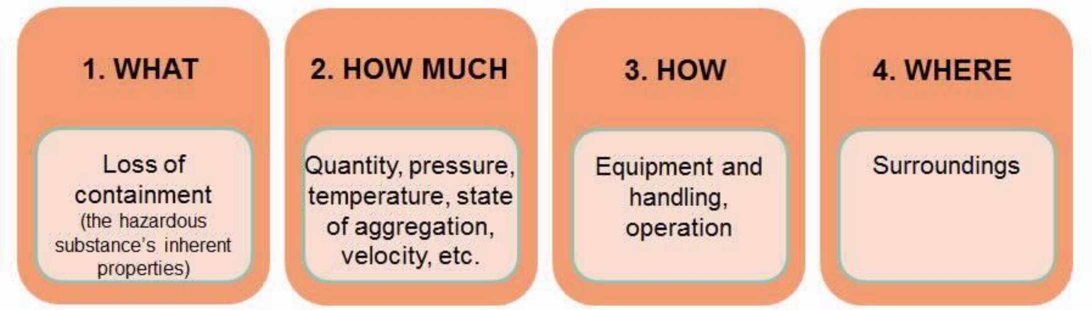

Figure 3-1 - Example of questions when establishing a top event

3.3 Event development/event tree

An event tree can be used to model different courses of events after an initial event (typically a leak in the system) has occurred.

In a risk analysis, event trees are used to calculate the relative contributions of the different scenarios (end events) that may follow from a top event.

An event tree will be able to show how events (e.g. ignitions), actions (e.g. manual activation) or barriers (e.g. automatic safety systems) can affect the course of the event.

Results from HAZOP analyses can be used as a basis for establishing event trees.

Probability of failure in (or activation of) safety systems can preferably be stated based on SIL analyses or similar. Response times should also be clarified in connection with the establishment of event trees.

Assessment of ignition probability is discussed under “Ignition analysis”, see Chapter 3.6.

3.4 Frequency analysis for top events

3.4.1 General

The selection of frequency for the top events will affect the calculated risk contours. In order for the risk contours to be accurate, the leak frequencies used must be representative for the facility analysed. If the company has specific and well-documented historical data for leak frequencies that are more relevant than the generic models, these should be used. If there are special conditions at the facility that indicate that leak frequencies will deviate from the models used, the leak frequencies can be adjusted, provided that the adjustment is justified and documented. Human, operational, and organisational conditions can affect the expected value for the frequency of the top events. The generic leak frequencies assume that the facility maintains an average industry level for these conditions.

Figure 3-2 illustrates how the risk contours are affected by the estimated frequency for the top events. The black circle illustrates the risk contour resulting from a given frequency. Here, the frequency decreases with increasing leak rates (and associated representative dispersion). If the frequency of all leak scenarios is increased by the same factor, this can be represented by the orange dashed line. The resulting risk contour will accordingly become larger (orange circle).

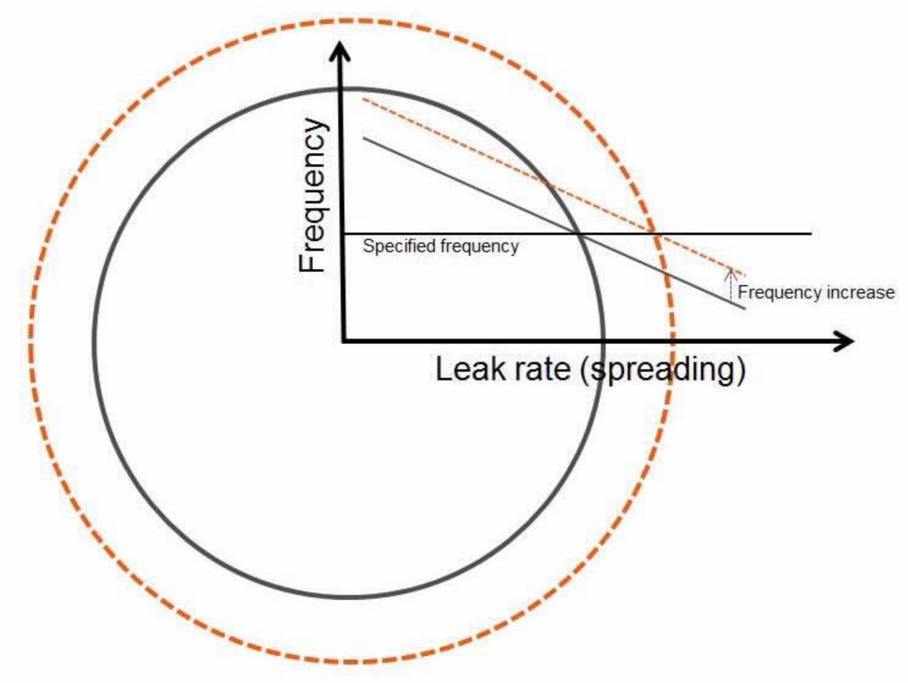

Figure 3-2 - Illustration of how the selection of frequency model affects risk contours

There are different models for establishing leak frequencies. These can be used to calculate frequencies of top events, which will normally be leaks with different classes of leak rates. The models either provide frequencies for different leak sizes (rates, quantities) directly or frequencies for different hole sizes, and then leak rates for the hole sizes are calculated based on the process conditions of the leaking fluid (liquid, gas).

The models mainly differ in:

- The level of detail of the facility information required to use the models. That is, does the information only cover the main equipment in the facility (such as pressure vessels, storage tanks, pumps, compressors, and distillation columns) or does it also include component-level information (such as flanges, valves, instruments, pipes, etc.)
- In which format the frequencies are presented. This must match the level of detail in the subsequent analysis, i.e. whether the model provides frequencies for different scenarios in terms of rates and durations or released volumes, or whether the model provides frequencies for different hole sizes.

The use of the more advanced models requires more detailed information on leak sources than simpler models. This can create challenges when preparing risk contours in the early stages of a project, before the final P&IDs are completed. In such cases, the risk analyst must estimate the number of components, which introduces uncertainty into the calculated risk contours. Such estimates may be supported by, for example, reference to similar facilities. For an operating facility, all equipment is known.

The use of a simple model will, to a limited extent, reflect the design conditions in the facility and the associated scenarios will be correspondingly simplified. By using the models that provide hole size distributions, the fluid type, pressure, and temperature are used to calculate the frequency distribution of release rates, resulting in top events defined by leak rates that reflect the design conditions to a greater extent. To exploit this, a more detailed subsequent analysis is required.

The choice of leak frequency model can be determined based on:

- How simple or comprehensive an analysis one wants to perform. The need to evaluate the effect of risk-reducing measures must be considered; more advanced models generally provide greater opportunities for assessing the effect of such measures.
- How much information is available about the facility.

- How site-specific the analysis should be. The level of detail in the leak frequency model must be balanced against the analysis model in which it will be applied.

3.4.2 Leak frequency models

The following leak frequency models are relevant for analyses of land-based facilities and are further addressed in these guidelines:

- RIVM
- HSE
- IOGP
- PLOFAM
- HyRAM
- Shell (LNG transfer hoses)
- BLEVE
- Recommended failure rates for pipelines

In addition to these, extensive work is being carried out in the ongoing industry project SAFEN, where recommended models for various types of land-based facilities, particularly facilities handling gases involved in the renewable energy industry (hydrogen, ammonia, CO_2), are under development. SAFEN primarily focuses on developing leak frequency models that cover leaks from process systems and storage tanks, as well as leaks during transfer operations, but will also propose models to cover risks related to material handling and pipelines.

Historically, RIVM and HSE are the most widely used models for land-based facilities in Europe. IOGP and PLOFAM originate from the offshore industry but are also used for downstream activities such as terminals and petrochemical industrial plants. As of today, the data basis from offshore facilities is significantly better and more comprehensive than that for land-based industry. It is desirable in the long term to obtain larger and better databases from land-based industry.

For special fluids that are likely to affect the possibility and frequency of leakage, it should be considered whether the standard leak frequencies need adjustment, for example due to known corrosion mechanisms or other degradation mechanisms. HyRAM is an established model for hydrogen leaks, based on work conducted at Sandia National Laboratories in the USA.

To ensure the best estimated risk contours, it is important to use the correct model for each type of equipment and scenario. For example, there are different models for process equipment, tanks, cylinders, and hoses.

3.4.2.1 The RIVM model

The RIVM model (Reference Manual Bevi Risk Assessment) (ref. /3/) is mainly based on the Purple Book (ref. /42/). This is the simplest of the mentioned methods, as it provides leak rates combined for equipment groups and not for single components (such as flanges and valves) that are part of equipment and pipelines. RIVM is therefore most applicable to facilities where there is a limited number of leak sources outside these equipment groups (without necessarily implying that there are few leak possibilities in the facility). Furthermore, the frequencies for three different release scenarios are given as a mixture of quantity, rate, and hole size:

- instantaneous release of the entire content
- release of the entire content at a constant rate over 10 minutes
- continuous release through a 10 mm hole

For pumps and compressors, frequencies are given for hole sizes (10 % of the diameter).

The frequency is independent of the equipment size and pipe dimensions for pipes below ground. For pipes above ground, the frequency depends on the pipe dimension. As only large equipment is included, the number of leak points is easily counted.

A comparative study between RIVM and HSE (ref. /4/) shows that an important prerequisite RIVM sets for using the leak frequencies for pressure vessels, is that the leaks are not caused by external impacts (collision, shock), corrosion, fatigue due to vibration or operator error, as it is assumed that the facility has control over this. If such conditions exist, either special assessments must be made using the RIVM frequencies for pressure vessels, as these are basically dominated by conditions such as design defects, ageing, wear, etc., or the HSE or PLOFAM models should be used.

The background for the frequencies of hose rupture in this model is very unclear (ref. /5/), and they are therefore not recommended for use.

3.4.2.2 The HSE model

The HSE model (UK Health and Safety Executive, ref. /6/) is based on data from the United Kingdom (UK). The model can be used for failure frequencies of equipment where leakage is the failure mode. It is more detailed than the RIVM model, as it also includes data for components such as flanges and valves. The HSE model provides frequencies for different hole sizes for tanks, generally 3-5 sizes depending on the equipment, while for valves, flanges, and pumps, only one generic size is given. The frequencies for a piece of equipment are independent of the size of the equipment, except for large storage tanks (two size classes) and pipes, where there are frequencies for hole sizes for pipes in different size classes. For flanges, there is no corresponding differentiation regarding pipe dimensions. Note that flanges on tanks (except for the connection to the process) and other major equipment are included in the frequencies for the equipment, so that the specific frequencies for flanges are applied to freestanding flanges.

Compared to the RIVM model, the HSE model offers a somewhat more detailed analysis by providing a higher level of detail regarding equipment components and by accounting for the effect of process conditions (pressure, temperature, and fluid density).

The HSE model has leak frequencies for loading/unloading with hoses and loading arms to transport tanks, based on fault tree analysis of the operation and associated barrier systems, see ref. /7/. However, the HSE model does not have leak frequencies for loading/unloading with hoses to ships, but it does contain frequencies for loading/unloading with loading arms to ships. A comparison of the failure frequencies for transfer to transport tanks using hoses versus loading arms shows a factor of 20 increase in the frequency for full hose rupture, while leaks from smaller holes have the same frequency. For leak frequencies for loading/unloading to ships using hoses, it is therefore recommended to adjust the leak frequency for full rupture during transfer with loading arms to ships by a factor of 20 and use the same frequency for smaller hole leaks.

Since the HSE model has a significantly greater level of detail regarding leak sources than the RIVM model, the counting of leak sources will also be significantly more extensive than when using the RIVM model. The clear advantage of using the HSE model is that the top event frequencies will more accurately reflect the facility design.

3.4.2.3 The IOGP model

IOGP has developed the IOGP Risk Assessment Data Directory for use in QRA in the onshore and offshore oil and gas industry. Each guideline is developed by reviewing available data sources and input and comments from IOGP's members. Three of the guidelines (ref. /8/, /9/, and /10/) are collectively referred to as the IOGP model in these guidelines.

The data basis for the reports is:

- For process equipment (ref. /8/), recommended frequencies are based on historical data from offshore UK in the period 2006 to 2015 (data from HSE). This is the same data basis from the UK that is used in PLOFAM.

- For tank events (ref. /9/), the guidelines were published in 2022 and include a review of available sources, including data from HSE, the Netherlands, and Belgium. It is noted that HSE's recommended values for tanks have remained unchanged since 2004.
- For leaks during transport of dangerous goods (ref. /10/), the frequencies are based on older data from the UK and Hong Kong.

The IOGP model for process equipment and tanks (ref. /8/ and ref. /9/) is thus also based on a selection of HSE data but is structured differently from the HSE model. The primary differences are:

- The IOGP model has data for significantly more process components than HSE.
- For each process component, the leak frequency is given as a function of both hole size and equipment dimension in the form of different classes.

The IOGP model for tank events includes event data for various tank types. The tank types are generally the same as those covered in the HSE data, but additional data sources are also used. For each tank type, different data sources are discussed, and the recommended values are based on a discussion of these sources. The model distinguishes, among others, between the following tanks and events:

- The IOGP model has frequencies for tank ruptures on double- and full-containment tanks with outer shells of concrete.
- The frequencies for refrigerated tanks only include tanks operating at approximately atmospheric pressure. The IOGP frequencies for pressurised tanks cover all storage tanks operating above 0.5 barg.
- IOGP has its own frequencies for leaks in small containers and cylinders, as well as for ISO containers.

The IOGP model for leaks from road tankers during transport, ref. /10/, covers events while the tanker is in transit and does not cover the actual loading and unloading activity. The frequencies are based on general transport of dangerous goods globally and have some limitations:

- IOGP provides leak frequencies for the transport of dangerous goods per kilometre but specifies that when using the data in connection with "process QRA", the data should only be used if transport risk is expected to make a smaller contribution.
- IOGP also emphasises that the data should not be used without a thorough assessment of both local transport conditions and the validity of the data.

IOGP does not provide data that covers leaks from road tankers and associated equipment located within a facility in connection with loading or unloading.

3.4.2.4 The PLOFAM model

The PLOFAM model (Process Leaks for Offshore installations Frequency Assessment Model, ref. /11/ and ref. /12/) is currently considered to be the most comprehensive, advanced, and best validated model for calculating leak frequencies in offshore and onshore process plants that process oil and gas. PLOFAM is also regarded as relevant for use in petrochemical plants, refineries, larger LNG facilities, etc. (see scope described in ref. /12/). This includes hydrogen-rich streams in such facilities, for example in the production of methanol or ammonia from methane reforming and reforming processes at refineries.

When it comes to tanks, however, the model is less nuanced in terms of types than, for example, HSE. PLOFAM is based on offshore historical data from the entire UK (data from HSE) and NCS (Norwegian offshore sector, data from the Petroleum Safety Authority Norway) from 1992 to 2020. With requirements from both HSE and the Norwegian Ocean Industry Authority (Havtil) on the format of incident reporting, it has been possible to assess and classify each event thoroughly.

The equipment components included are the same as in the HSE model, but with some additional classes. What mainly distinguishes PLOFAM from the other models is:

- The frequencies are dependent on the equipment dimension. It should be noted that the equipment dimension model is closely linked to the characteristics of the equipment used in oil and gas facilities.

The dependence on equipment dimension therefore makes the model less suitable for other types of process plants than oil and gas. PLOFAM is expected to be most accurate for equipment above 1".

- For each equipment dimension, the frequency is a continuous function of the hole size from 1 mm to full rupture. In other words, there are no classes of hole sizes and therefore all effects related to transition between classes are avoided. For the calculation of risk contours, however, only larger leaks are normally relevant.
- PLOFAM has been validated by applying the model to counts from all installations on the NCS as well as all the major land-based oil and gas facilities in Norway (including hydrogen-rich streams on these facilities) and then comparing with observed leak frequencies on the corresponding installations.

Although the PLOFAM model is based on UK and NCS data from the petroleum industry, a review (ref. /13/) shows that there is no reason to assume that the data are different for petrochemical land-based plants of equivalent size, where requirements for inspection, testing, maintenance, etc. are comparable and where the process fluid is no more challenging than for systems with pure petroleum products. PLOFAM is therefore considered relevant to use also for petrochemical plants, refineries, larger LNG facilities and similar.

PLOFAM is the leak frequency model that to the largest extent reflects the design conditions of an oil and gas plant, but it is also the one that is most comprehensive to use. The effort required to count leak sources will be at the same level as with the HSE model. However, it must be noted that simplified methods for counting components can be used and will make the work less time-consuming. Simple methods where only major components (pumps, compressors, pressure vessels, filters, heat exchangers, etc.) are counted and combined with generic models for the number of smaller components (flanges, instruments, and valves) associated with these have largely been conducted for the major land-based facilities in Norway.

PLOFAM covers roughly the same equipment components as IOGP, but it has both a significantly better database and is methodologically more correct. It is therefore recommended to use PLOFAM rather than IOGP where relevant.

For loading arms to ships, it is recommended to use PLOFAM land's model, ref. /14/. Guidance on how loading arms should be modelled is presented below.

Considerations that are important to take into account:

- It is assumed that two loading arms are in use per transfer. If four loading arms are in use during loading, it is recommended to use a safety factor of 1.3 in addition to doubling the frequencies.
- Mooring failures, falling loads, and passing ships are not included and should be assessed separately. A safety factor of 1.1 is recommended for both passing ships and mooring failures if detailed analyses are not performed.
- The model does not apply directly to media other than hydrocarbons. For other media, it is recommended to use a safety factor of 2, except if the media has been transferred in loading arms over a longer period.
- Recommended leak categories are:
    - full rupture (100% of the pipe diameter)
    - medium leak (10% of the pipe diameter)
    - small leak (1% of the pipe diameter)

3.4.2.5 The HyRAM model

HyRAM (HyRAM+) is an established model for hydrogen leaks based on the work at Sandia National Laboratories in the USA, ref. /15/. Sandia has estimated these frequencies in connection with IEA expert group work in the years around 2005-2010, with the participation of, among others, HSE, TNO, INERIS, DNVGL, TELTEK, and GEXCON. The underlying data is older and originates from the petroleum industry and from hydrogen facilities.

HyRAM has been used by the industry for many years, but it is considered uncertain due to insufficient validation against transparent and well-representative historical data. By comparing HyRAM with PLOFAM (see Figure 3-3), one can see that they are relatively similar for small equipment, but that the difference becomes larger as the equipment size increases. The figure compares valves, but the same trend can also be seen for other equipment. The difference is partly because HyRAM bases the value for leak frequencies on relative hole size, without correcting for the size of the equipment. HyRAM is considered too conservative for equipment dimensions associated with piping systems with a diameter greater than 1".

There is therefore significant uncertainty associated with the use of HyRAM. However, there are no other openly available frequency models that stand out as being clearly more validated for hydrogen leaks (apart from, in the future, results from the ongoing work in SAFEN to develop leak frequency models), and it is considered an advantage that HyRAM is easy to use and thus consistent between the various users. Until better validated models become available, it is recommended to use HyRAM for dimensions 1" and smaller, and PLOFAM for dimensions larger than this. This is because HyRAM is established on a data basis from small equipment diameters, while PLOFAM is established from larger diameters. This is not a perfect solution, but it accounts for the weaknesses of both models regarding their close link to equipment dimensions and that HyRAM probably has a relatively good data basis for small equipment in pure hydrogen facilities.

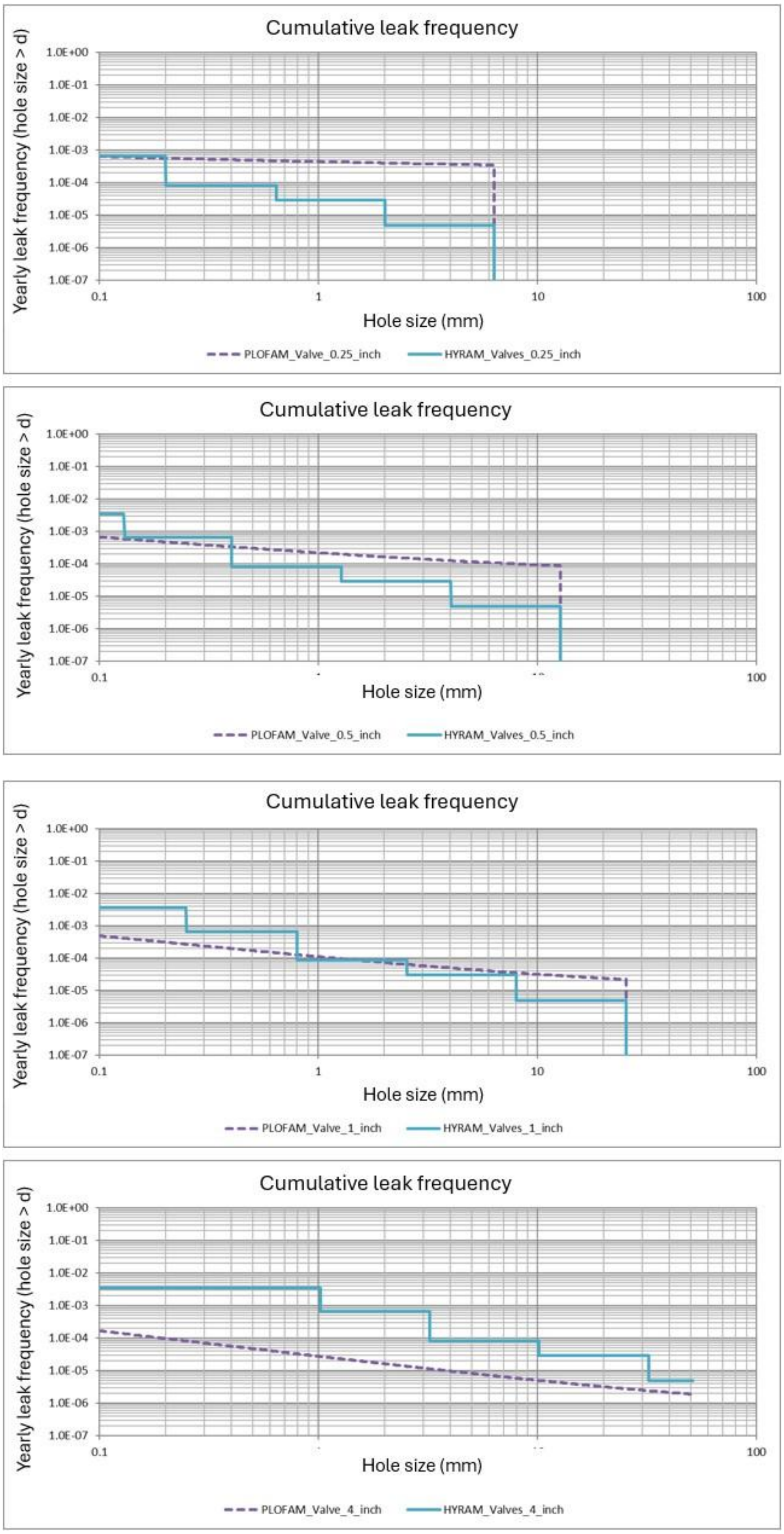

Figure 3-3 - Comparison of leak frequencies for valves from HyRAM and PLOFAM

3.4.2.6 SAFEN models under development

SAFEN is an ongoing industry project established to fill knowledge gaps in our understanding of driving hazardous situations with associated failure mechanisms and causes of failure within the renewable energy sector. The objective is to establish an industry standard for modelling leak frequency as well as fire and explosion frequency in risk analyses for facilities handling hydrogen, ammonia, CO_2, and other relevant gases and liquids related to the energy transition. The first phase of the project was completed in 2023 and delivered the first versions of the developed models. The models were presented at the FABIG technical meeting in London in October 2023 (see www.fabig.com). The ignition probability model for hydrogen was later presented at a conference in Naples (see Chapter 3.6.4 and ref. /16/). Phase 2 of the project was started at the end of 2024.

3.4.2.7 Leaks from transfer hoses for LNG and LPG

For leaks from transfer hoses in general, HSE is recommended, see Chapter 3.4.2.2.

Shell has presented data for hose ruptures for stainless steel LNG hoses based on experience from facilities in the USA and Europe, ref. /17/. These frequencies are lower than the generic frequencies of hose ruptures given in HSE, but it is considered reasonable to assume that hoses designed for LNG have somewhat higher integrity than generic hoses, since they usually operate in a somewhat stricter safety regime. The same trend can also be seen in HSE's frequencies for tanks, where LNG tanks have lower leak frequencies than generic tanks. For leaks from stainless steel LNG hoses with threaded end connections, the following failure probabilities (from Shell) are therefore recommended:

- full rupture: 9.7E-8 per operation
- 25 mm leak: 1.9E-7 per operation

Hose ruptures for LPG hoses are discussed in a database published by the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Hazardous Materials Safety (OHMS), ref. /18/. Leakage data from this database suggest that the frequency of leaks from LPG transfer hoses may be equal to that for LNG. However, because no hose ruptures have been registered when loading LNG at facilities in Norway, while hose ruptures have been registered for loading LPG, it can still be expected that the frequencies for LPG are somewhat higher than LNG, though not as high as HSE. If no special assessments are made for the analysed LPG facility, it is recommended to set the leak frequency for LPG hoses halfway between Shell (LNG) and HSE (generic). Considerations regarding LPG frequencies will be discussed under uncertainties, see also Chapter 3.11.

3.4.2.8 Leaks from pipelines

For leaks from pipelines, it is recommended to use frequencies and hole size distributions from the DNV report "Recommended failure rates for pipelines", ref. /19/. The frequencies are based on historical data from land-based pipelines in Europe and apply to both gas and liquid pipelines, based on either the diameter or the thickness of the pipe.

3.4.2.9 Frequency of BLEVE

There are generic frequencies for BLEVE (e.g. HSE), but it is considered to be inaccurate to use generic frequencies for this type of event.

Instead, assessments should be made in each case of how likely it is that prolonged fires can expose tanks with content that could cause a BLEVE (see Chapter 3.9.1). In this assessment, a simple event tree should be set up that assesses frequencies for prolonged fires and the probability that these expose tanks. IOGP also recommends basing the frequencies for BLEVE on event trees and the probability of exposure from prolonged fires.

The generic frequencies provided by HSE are considered to be significantly on the conservative side and should therefore be avoided in the process of calculating best estimate risk contours.

Cold BLEVE can be considered as rupture of pressure vessels, and the HSE models (Chapter 3.4.2.2) are recommended for this.

3.4.2.10 Use of historical data for facilities or companies

For some facilities, historical data for leak frequencies may be available. There are also companies that have historical data for leaks from all their facilities.

If historical leak frequency data is available and considered relevant for the analysed facility, these can be included in the assessment of the expected leak frequency. In that case, it must be proven that the historical data has sufficient reliability to be used for the intended purpose.

If well-documented historical data is available, the historical frequencies can be weighted equally with the generic frequencies (discussed in Chapter 3.4.2.1 to Chapter 3.4.2.9).

It is thus acceptable for the models used to deviate from the recommended models if it is demonstrated that this will make the risk contours a better estimate.

3.4.3 Other leak causes

Unintentional releases of flammable or toxic substances that may represent a societal risk may occur without being the result of a leak whose frequency is covered by the models in Chapter 3.4.2. This may, for example, be runaway reactions or other abnormal process situations that lead to overpressure with associated rupture or release from safety valves. Releases of toxic substances may also occur from atmospheric air conduits from process plants or storage tanks due to fire or accidental mixing of products or intermediates.

It is therefore a prerequisite that HAZID and HAZOP studies are carried out adequately to reveal any possibilities for such scenarios where relevant. Such scenarios must be included in the risk contour calculations if they make a significant contribution.

3.4.4 Summary

A summary with recommendations is given in Table 3.1.

Note that in order to span the entire sample space of events that may occur, all failure modes in the data source used must be modelled. In the case of tank rupture events in particular, this must be considered as a rupture in the tank itself and not in pipe penetrations. The event type is modelled as an instantaneous release of the entire tank contents unless otherwise explicitly stated in the guidance for the frequency model used.

In principle, all the leak frequency models discussed in Chapters 3.4.2.1 - 3.4.2.10 are suitable for use in risk analyses. In addition, other models or historical data can be used as a basis for the risk analyses, but then it must be argued that the chosen model is expected to give a better estimate than the proposed models. This can be done, for example, in a discussion of uncertainty in the analysis (see also Chapter 3.11).

There may be many factors that determine which leak frequency models should be used, and for each individual case an assessment must be made of what information is available and what level of detail is desired in the results. In this summary, a recommendation is given on the preferred model for different types of scenarios.

Note that the simplest models are often the most conservative, but there is still no guarantee that the simple models are always conservative for all facilities. The most complex models can also be assumed to be the best estimate for each facility, but these models require more analysis and are therefore more expensive to implement. For example, facilities with particularly small equipment diameters may lead to conservative leak rates if a simple leak frequency model is used. This is because the models do not reflect small diameters, and the assumed hole sizes may be larger than the diameter of the equipment. In such cases, one of the complex models should be used. Similarly, facilities with particularly large equipment diameters and pressures may be underestimated when using the simplified models, and one of the complex models should be used.

Table 3.1 - Recommended data for leak frequencies

Characteristics	Has/requires information about	Recommended models
Process areas	Only larger equipment and associated quantities. Not important to detail dependence on pressure or equipment size.	RIVM/TNO (not for pressure vessels, see Chapter 3.4.2.1)
	Limited information on individual sources, but no dependency on hole size. Valves, flanges, pumps, hoses, and pipes must be counted, in addition to larger equipment. Takes pressure in the process/facility into account.	HSE
	Large facilities (refineries, petrochemical plants, large LNG facilities, etc.). This includes all types of process fluids in such facilities – i.e. including hydrogen-rich streams. Information on individual sources, must be counted. Provides frequencies dependent on equipment dimension and hole sizes (continuous distributions).	PLOFAM
Tanks	Petroleum tanks (including LNG and LPG)	IOGP
Tanks	All other types of tanks, except tanks with outer shells of concrete	HSE
Tanks	Tanks with outer shells of concrete	IOGP
Cylinders	Propane cylinders etc.	IOGP
Road tankers	Leaks from road tankers during transport	IOGP
Hoses	Hoses in process	PLOFAM
	Loading/unloading with hoses to transport tanks	HSE
	LNG hoses	Gasnor (Shell)
	LPG hoses	See Chapter 3.4.2.7
Hydrogen	All hydrogen leaks	HyRAM (frequency for filters must be adjusted, see Chapter 3.4.2.5) for dimension ≤ 1". PLOFAM for dimension > 1".
BLEVE	All types of BLEVE	Calculated with event tree (see Chapter 3.4.2.9)
Pipelines	All fluids, can also be used for CO_2	Recommended failure rates for pipelines, see Chapter 3.4.2.8

3.5 Leak and dispersion analysis

3.5.1 Leak modelling

A good description of the release is a prerequisite for the subsequent dispersion analysis and, if relevant, explosion analysis to be performed accurately.

There are two steps in the leak process before a source of dispersion analysis can be identified. The first step is to determine the actual leak rate out of the hole; the second step is to determine the phase and thermodynamic state just outside the hole as the starting point for the dispersion analysis. The source in dispersion analyses of gas leaks (regardless of whether CFD or an empirical model is used) is not the hole itself but will be where the post-expansion of the gas has reduced the pressure to ambient pressure, i.e. at the so-called Mach disk (usually ≤ 1 m from the hole).

These processes require the use of different physical models, both in relation to the two steps and in relation to the phase (state) of the fluid before release.

Note that if the choice of release location (e.g. height above ground) can affect the risk contours, the leak locations should be distributed in the most realistic way possible according to the distribution of defined release points.

Also note that in the event of a tank rupture, the leak is assumed to originate from a rupture or hole in the tank shell itself, and not from pipe penetrations or connections on the tank.

3.5.1.1 Leak rate through the hole

The fluid may be released as a pure gas, pure liquid or a combination of liquid and gas, depending on the type of fluid/phase and the location of the leak along the segment. What is crucial is the thermodynamic state of the fluid inside the container:

- If the fluid temperature is higher than the boiling point of the liquid at the container pressure, the fluid will be a gas.
- If the fluid temperature is between the boiling point of the liquid at the container pressure and the boiling point at ambient pressure, the pressure drop during the leakage will cause the liquid to boil. Depending on the degree of superheating, boiling (gas bubble formation) will start in the liquid before the leak hole or possibly in the leak hole. This affects the density of the fluid in the hole and thus the leak rate. All evaporation requires heat, which is taken from the liquid, so the amount that actually boils off depends on the liquid temperature above the boiling point, i.e. the degree of superheating. These are complex physical processes that can be approximated with different calculation models. If the liquid contains components with different boiling points, this must be particularly considered.
- If the fluid temperature is lower than the boiling point at ambient pressure, the liquid will evaporate without boiling as the pressure decreases in the leak. The amount that evaporates is determined by the vapour pressure curve of the liquid, but this evaporation takes a while.

Empirical tools have a variety of simpler models to handle the different thermodynamic scenarios. For complicated cases, more advanced models should be used.

If the leak is from a pipe rather than from a vessel, the leak rate will be reduced, depending on the hole size and the pipe length. For short pipes, certain empirical models can be used. For long pipes, suitable calculation models for piping systems can be used to improve the accuracy of the release rate.

The leak models assume free flow out of the hole. Special conditions, such as large temperature drops and high humidity, can cause ice formation, which may partially block the opening and reduce the release rate compared to the rate calculated by the leak models. If the experience with the use of a fluid is limited, literature/accident databases should be reviewed to find potential experience on how such a leak behaves. It must then be considered whether this experience can be transferred to the current scenario.

3.5.1.2 Conditions immediately outside the leak – The near field

Here, the situation depends on whether the scenario is a pure gas leak or a multiphase leak.

In the case of a gas leak with critical flow and overexpanded jet, air will be mixed into the jet before the Mach disk. In this situation, it is important to accurately calculate the mixing of air so that the initial leak in a CFD simulation will have the correct gas-air concentration, temperature, and velocity.

Because the heat capacities of methane and natural gas are higher than that of air, some leaks may behave as heavy gas at one mixing ratio with air, and as light gas at another mixing ratio. This means that the gas may initially be lighter than air but becomes heavier than air when mixed. Humidity and temperature can affect these conditions. Therefore, the safety data sheet alone will not be sufficient to assess how a leak will spread.

In the case of a two-phase or pure liquid leak, the liquid may be atomised or form a spray. Depending on the droplet size, a larger or smaller portion of the liquid will form a liquid pool. Several different mechanisms determine the state of the release immediately outside the leak:

- Mechanical atomisation of the liquid into droplets. This is the dominant mechanism for liquids with a temperature below the boiling point in the surroundings. Atomisation and droplet sizes are determined by hole diameter, the liquid's velocity and density, surface tension, and viscosity. For small holes, even relatively low pressures (the order of bar) can cause spray formation. Liquid flowing down vertical surfaces onto horizontal profiles may also lead to atomisation and formation of gas clouds, ref. /20/.
- Atomisation of the liquid due to boiling and expansion of gas bubbles. This is the dominant mechanism for superheated liquids (and BLEVE, see Chapter 3.9.1); the greater the degree of superheating, the greater the proportion of atomisation. The most important factor for the subsequent dispersion calculation is the fraction of the liquid that is released and forms a liquid pool, and the fraction that is atomised and follows the gas in the dispersion. The fraction of the liquid that appears as large droplets is determined by the droplet size distribution, which is significantly more uncertain than the average droplet size. This means that, for issues where spray versus liquid pool is important, sensitivity studies regarding the degree of liquid spray formation should be performed. Upon cooling of the gas, condensation may also contribute to droplet formation. Due to flashing, the temperature in the two-phase cloud will decrease, and the cloud (with or without fog particles) will normally behave as a heavy gas.
- For liquids with multiple components with differing boiling points, special assessments must be made. Depending on composition, pressure, and temperature, such releases can become a combination of a spray and a liquid pool where gas components boil off or an atomised spray with no or minimal rainout.
- In the case of a release from a pressurised multiphase tank, the pressure drop as a result of the release may cause significant evaporation, so that the amount of gas released can be several times greater than the original gas content in the segment.
- Local wind conditions can affect the evaporation rate from liquid pools, so for scenarios where evaporation is important, the local wind conditions should be considered.
- In the case of an LNG release, the evaporation rate will be dominated by heat transfer from the ground, which, in turn, is determined by the temperature difference between the liquid pool and the ground. Cooling of the ground will eventually reduce the boil-off, thus affecting both the dispersion of the liquid pool (unless it is limited by dikes or similar) and the evaporation rate as a source of dispersion in the far field. Reference is made to ref. /21/ and /22/ for models describing evaporation rates for LNG liquid pools.
- Selection of model parameters (for example "constant entropy" or "constant enthalpy") may also affect the results of the simulations. Detailed guidelines regarding the use of model parameters are not given here, but this must be considered for the modelling of each individual release.

3.5.2 The far field

In order for the risk contours to represent reality as accurately as possible, it is crucial that the modelling of the simulated scenarios is as physically realistic as possible. It must therefore always be considered whether there are special conditions at the facility that require a certain type of modelling tool to simulate leaks to the far field.

In principle, there are two types of simulation tools for calculating dispersion in the far field from a leak: empirical tools and CFD tools:

- Empirical tools (also called integral tools or 2D tools) apply simplified physical models that are tuned to reproduce experimental trials as accurately as possible. These models are robust and very fast, but they take limited account of the actual physical conditions of the facility being assessed.

- CFD tools aim to a greater extent to simulate the physics (Navier-Stokes equations) in the release but also use some simplified models to make the simulations run faster. For example, turbulence models and sub-grid geometry models (porosity models) are often used to estimate the effect of physics occurring on a smaller scale than can be handled by the chosen resolution of the discretisation model.

Neither of these two types of simulation tools can be considered as always being conservative. Therefore, the user must be familiar with the limitations and uncertainties associated with each simulation tool and always seek to use the type that is most appropriate for the assessed facility.

Empirical tools and CFD tools produce very similar results for flammability/toxicity in areas where the far field has no or minor obstructions that may affect gas dispersion (see ref. /23/). For facilities where this is the case, it will be possible to obtain good estimates of gas dispersion with both types of modelling tools.

If the facility to be analysed exhibits one of the following characteristics, CFD tools should be considered:

- **Terrain**: Facilities located in terrain that will significantly affect the dispersion of gas to the far field. This is especially applicable if the facility can produce emissions of heavy gas that can be trapped and guided by the terrain, see Figure 3-4. For such scenarios, empirical tools may be non-conservative in the directions in which the gas propagates. On the other hand, in directions in which the gas does not propagate, for example due to mountainsides or steep terrain, the use of empirical tools may result in excessive risk contours.
- **Large buildings**: Facilities located near buildings or other obstructions that significantly affect the dispersion pattern. In such cases, empirical tools may give incorrect results due to, for example, changes in local wind conditions, eddies, blockages, and changes in direction.
- **Complex or large diffusive releases**: Releases coming from bunds (secondary containment) with complex or large areas. In such cases, an approach with point release could give significant uncertainty in the results if empirical tools are used.
- **Releases in congested areas**: Releases where the kinetic energy is significantly absorbed by the gas flow (jet) hitting process equipment or buildings. When the kinetic energy is absorbed by process equipment, the mixing of air will be reduced (the jet speed is stopped mechanically instead of through friction with air), allowing the flammable or toxic gas to reach further before it is diluted. In such cases, empirical tools can be non-conservative. If a high-velocity release hits a small surface (building or similar), the impulse will change significantly in both direction and size. In such cases, empirical models will not represent the physics adequately, see Figure 3-5. In congested areas, it can also be expected that local wind speeds are significantly lower and different from the wind field at the nearest weather station. This must be considered in analyses, especially when using simpler empirical tools.
- **Special scenarios**: In very special scenarios, one operates outside the range where the empirical models are valid. An example of this is the release of heavy gas in calm wind (< 1 m/s), where empirical tools may have limited simulation capabilities. Note that there may be areas where CFD tools also operate outside a domain where it has been adequately tested.

Alternatively, if empirical tools are used, uncertainties related to assumptions about conditions as mentioned above must be described, and possibly, how attempts have been made to compensate for such conditions.

For calculating toxic concentrations over long distances in the far field, there may be some challenges when using CFD. Due to computational time, it can be challenging to both model the near field accurately, whilst at the same time adequately representing the far field. When modelling such scenarios, the person performing the study should be aware of the validity/limitations, relevant validation tests, and guidelines for using the tool for such situations. Turbulence effects due to buoyancy caused by local solar heating are difficult to recreate with CFD (Pasquill A, B, C stability), and CFD tools tend to provide conservative hazard distances in such situations. Empirical tools can be more robust and easier to use for such situations, although they are also unable to model the local effects of, for example, small obstructions and varying heat transfer coefficients from the substrate. When using empirical tools, however, one must ensure that important elements of modelling close to the release are not omitted and that there are no low-wind scenarios that cannot be modelled.

Empirical tools accurately reproduce the experiments they are calibrated for, but as soon as the parameters deviate from the experiments, the uncertainty also increases significantly for empirical tools.

Therefore, for the calculation of toxic concentrations in the far field, there is uncertainty associated with the results for both CFD and empirical tools, and this uncertainty must be discussed in the risk analysis (see also Chapter 3.11).

The choice of the type of modelling tool for the far field can have a major impact on the risk contours, and it must therefore be documented that this is considered in the risk analysis. Empirical tools and CFD tools may also be combined within the same risk model.

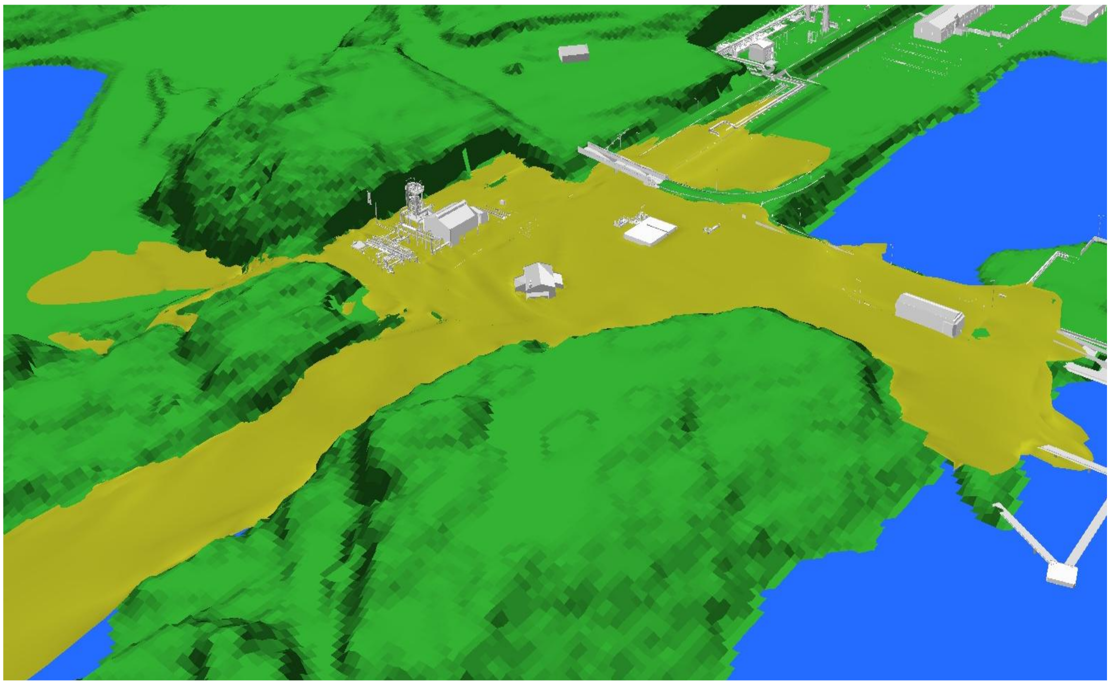

Figure 3-4 - Release of heavy gas (yellow colour) in an area with uneven terrain. The figure shows that the result field is strongly affected by the terrain for heavy gas emissions

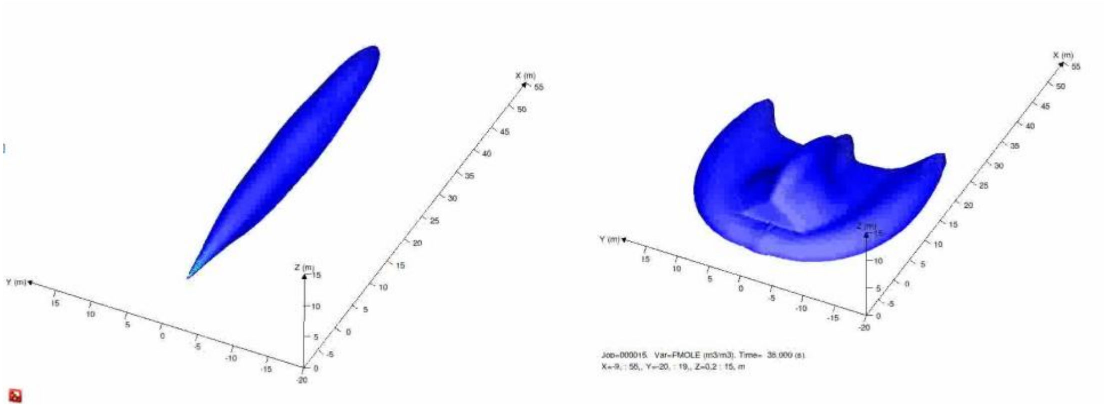

Figure 3-5 - Unobstructed leak (left) and the same leak with 3x3 metre obstruction (right). The figure illustrates that if leaks hit buildings, the solution field can change significantly

3.5.3 Largest extent of leaks

Turbulent fluctuations and small changes in the wind field will cause fluctuations in the real cloud field even if the leak is stationary. These fluctuations can be modelled with CFD, but it requires complex simulations with long simulation times. Steady-state calculations will, however, represent a good estimate of an average largest extent (sometimes the cloud will extend longer and at other times shorter), and in relation to the best estimate risk contours, it is therefore recommended to use steady state as a basis for calculating fatality (50 % fatality should be used as a threshold value, see Chapter 4.2.1).

3.6 Ignition analysis

3.6.1 General

Ignition requires that there is a flammable concentration of gas, either as a result of a gas release or as evaporation from a liquid, which is exposed to an ignition source. For liquids, this requires a temperature that provides sufficient evaporation. Normally, liquids with a high flash point (above 60 ˚C) are not considered flammable without being heated. Note, however, that spray leaks of this type of liquid can ignite at temperatures lower than 60 ˚C. See Chapter 3.5.1.2 for discussion of spray leaks.

The probability of ignition of a leak is a product of two probabilities:

1. the probability that the cloud generated by the leak exposes ignition sources
2. the probability of ignition, given exposure to ignition sources (ignition intensity)

In reality, the leak rate will decrease with time, and in combination with wind or ventilation conditions, the cloud size and thus the exposure probability will also vary with time, i.e. be transient.

Ignition can either occur immediately after the release, resulting in a fire, or it can occur after a time delay, resulting in an explosion or flash fire followed by a fire for as long as the leak lasts. The different probability models handle the relationship between immediate and delayed ignition in different ways. This affects the probability of delayed ignition to a greater extent than for immediate ignition. The choice of model is thus more important for the explosion risk than for the fire frequency.

There are also different types of ignition sources, which must be handled differently:

- **Ignition sources inside the facility**: This is the main focus of all ignition probability models. Historical databases are available, but with varying degrees of detail (which means that more is known about the total ignition probability than the distribution of contributions from different ignition mechanisms). The ignition probability of special ignition sources, such as fired units, is so dependent on the detailed design that they should be assessed on a case-by-case basis. In the case of self-ignition, the ignition probability is set to 1.0.
- **Ignition sources outside the facility**: For the assessment of ignition outside the facility, different assessments must be made for different uses of the risk contours:
    - For the calculation of risk contours for use in land-use planning, the total ignition probability shall be set to 1.0. This is done because the ignition probability would otherwise depend on the activity level, density of housing, etc., and it is not appropriate for the extent of the consideration zones to depend on such conditions. The ignition probability will in any case be high, as there is no requirement for ignition source control outside the boundaries of the facility. Note that an ignition probability of 1.0 does not directly coincide with the principle of best estimate analyses (see Chapter 1.5). Guidance on how ignition outside the facility can be made as accurately as possible is therefore given in Chapter 3.6.6.
    - For the calculation of risk contours which are not to be used in land-use planning, an ignition probability < 1 outside the facility may be used if this can be documented to be a better estimate. An example would be when calculating risk contours for a facility located within an industrial area, where there are requirements regarding ignition source control, and no gas clouds can expose areas outside the industrial area.
    - Quantification of ignition outside the facility must be given considerable uncertainty. There is great variation in the types of ignition sources outside a facility, there is insufficient historical data, and at the same time there is no ignition source protection, which results in an uncertain and potentially very high ignition intensity. Ignition outside the facility is also not covered by the ignition models discussed in Chapter 3.6.2 – Chapter 3.6.5. Separate assessments of ignition sources must

therefore be made, where it is essential to consider the probability of exposure, since the ignition intensity in any case will be high.

Leakage of liquids with a temperature above the self-ignition temperature may ignite when they come in contact with air. This is particularly relevant for refineries, where parts of the process have high temperatures.

There are mainly four ignition models that are used:

- RIVM
- IOGP
- MISOF with additions for land-based facilities and hydrogen
- HyRAM (for hydrogen)

The models handle the exposure probability and ignition intensity in different ways and have different requirements for input. When several models are applicable, select the model that best fits the level of detail in the risk analysis.

There are also other very simple models where the ignition probability is determined by the area of a region with ignition sources that are exposed to a cloud, but it is recommended to use the IOGP model instead, because it is just as easy to use, is better validated, and provides a more nuanced picture of the ignition probability.

3.6.2 The RIVM ignition model

The RIVM model (ref. /3/) describes the exposure probability and ignition intensity in a simple way:

- The exposure probability is a factor that the user must determine without any guidelines for how this should be done.
- The ignition intensity is given as a factor that increases inversely exponentially as a function of time from 0 to 1. Different ignition sources are characterised by different ignition probabilities for an exposure duration of 1 minute, which can easily be converted into a characteristic constant in the exponential function.

The ignition intensity inside a facility is only given for boilers and furnaces and is therefore not very applicable to most facilities. The model also provides ignition intensities for third-party ignition sources:

- neighbouring facilities
- houses and offices per person
- high-voltage power lines
- ships
- vehicles and trains

However, for the calculation of risk contours for land-use planning, the probability of ignition given exposure outside the facility boundaries should be set to 1, ref. Chapter 3.6.6.

3.6.3 The IOGP ignition model

The IOGP model (ref. /24/) refers to the UKOOA model (ref. /25/) developed by the Energy Institute in the UK in 2006 based on HSE data from land-based and offshore facilities, and therefore explicitly covers both land-based and offshore facilities. The ignition probability is given as curves or correlations as a function of leak rate for:

- various types of facilities and areas of land-based (and offshore) facilities
- gas, oil, and LNG
- various ventilation conditions in the areas
- different density of equipment (to some extent)

The correlations provide total ignition probabilities, i.e. the sum of immediate and delayed ignition. The immediate ignition probability is set to 0.001 for all releases so that all correlations start at 0.001 for a leak rate of 0 kg/s. The ignition probability decreases with time, mainly because the gas cloud will not expose new ignition sources once it has reached its maximum.

The IOGP/UKOOA model is simple in the sense that it does not require a model for exposure probability but provides the total ignition probability directly.

Since the IOGP/UKOOA model does not consider the transient conditions of a leak, it is well suited for use in analyses that do not include models for transient cloud progression. Therefore, the ignition probability of a given leak rate can be determined without calculating any cloud size, though in order to calculate the consequences, the cloud sizes that the given leak rate entails must still be calculated.

The IOGP/UKOOA model has been tested against MISOF by analysing selected offshore facilities with both models. For relatively open areas without special ignition sources such as gas turbines, diesel engines, and pumps/rotating equipment, the IOGP/UKOOA model generally gives slightly higher total ignition probabilities than MISOF, which seems reasonable given that it is a simpler model than MISOF. With such special ignition sources in the area, it is expected that IOGP/UKOOA may give slightly lower ignition probability than MISOF.

Note that the IOGP/UKOOA model is not suitable for refrigerated condensed gases, liquid pools with high evaporation, subsonic gas releases, and non-momentum-driven releases, such as releases resulting from full rupture of atmospheric tanks. The model proposes alternative methods for such releases that can be adapted. For liquid releases with high evaporation, it is recommended to combine the correlations with ignition probabilities for gas/LPG, and for atmospheric storage tanks it is recommended to use IOGP's "Storage incident frequencies". See Chapter 3.1 in IOGP/UKOOA for further information.

Note that IOGP also refers to several other ignition models (MISOF, OLF, TDIIM, RIVM, and CCPS) which are not all discussed in these guidelines.

3.6.4 The MISOF ignition model with additions for hydrogen

MISOF (Modelling of Ignition Sources on Offshore Oil and Gas Facilities), ref. /26/, is developed for offshore oil and gas installations. Through a subsequent industrial project (ref. /27/), the model has been qualified to also be used for land-based oil and gas installations. In the ongoing industrial project SAFEN (ref. /16/), the model is further developed for hydrogen installations. It differs from the other models because it:

- is the most comprehensive model
- is the only model that considers the transient development of a gas cloud
- is based on extensive statistical data from facilities on the Norwegian and British continental shelves as well as Norwegian land-based facilities for the petroleum industry and available data for hydrogen leaks
- is aligned with PLOFAM such that the combination of PLOFAM and MISOF reproduces the historical frequency of ignited process leaks in classified areas on offshore facilities as well as Norwegian land-based facilities within the petroleum industry
- can take into account specific ignition sources such as the number of rotating equipment, air intakes for gas turbines and diesel engines, hot work, vehicles, transformers, high-voltage lines, and different degrees of EX-protection
- discusses and represents available knowledge about the ignition mechanisms associated with hydrogen releases
- can take into account gas detection with the subsequent effect of emergency shutdown and disconnection of ignition sources
- provides the opportunity to assess uncertainty associated with modelling of fire and explosion frequency

MISOF applies to large petroleum facilities, especially with typical equipment density such as offshore, not for open, relatively empty areas between different process areas where the density of potential ignition sources is significantly lower.

The level of detail in MISOF requires a detailed analysis where, among other things, transient clouds are modelled. The advantage is that it provides a significantly more design-specific ignition probability than especially RIVM, but also IOGP/UKOOA. This provides a significantly greater opportunity to investigate the effect of various measures for reduction of ignition probability in a facility. The time-dependent cloud development can be modelled using different methods and is not necessarily comprehensive. For small, simple facilities, simple considerations can provide good estimates. Furthermore, it must be pointed out that contributions from equipment not designed for use in hazardous areas often are central to land-based facilities. It is expected that the analysis identifies and discusses these.

It must be emphasised that the uncertainty associated with the further developed MISOF model for hydrogen in the SAFEN project is more prominent than for oil and gas facilities, as historical data for validation of the level is not available.

The hydrogen model includes an assessment of increased parameter values for exposure of vehicle components. This applies to:

- The parameter value for air intake for all types of internal combustion engines, including gas turbines, is increased from 50 % for hydrocarbons to 90 % for hydrogen.
- The parameter value for exposure of electric motors with brushes is increased from 90 % for hydrocarbons to 100 % for hydrogen.
- The generic parameter value for ignition when a vehicle is completely surrounded by a flammable atmosphere, in addition to the contributions mentioned above, is increased from 10 % for hydrocarbons to 30 % for hydrogen.

3.6.5 Simplified ignition model for hydrogen

As an alternative to the MISOF model, a simplified ignition model for hydrogen can be used.

Hydrogen is highly flammable over a wide flammability range and requires special models for ignition (hydrogen is flammable in concentrations between 4 % and 74 % in air and has an order of magnitude lower ignition energy than, e.g. hydrocarbons for concentrations in air above 20 %).

Sandia National Laboratories has published a model for ignition of hydrogen in which immediate ignition accounts for 2/3 of the total ignition probability and delayed ignition the remaining 1/3 (the HyRAM model, ref. /28/). Immediate ignition leads to fire, while delayed ignition leads to explosion (possibly with a subsequent fire). HyRAM states the ignition probability in step functions and has no refinement for leaks above 6.25 kg/s (all leaks above 6.25 kg/s have the same total ignition probability of 35 %).

However, the literature shows that the ignition probability for hydrogen can be significantly higher than what the HyRAM model states if the leak has a high back pressure (over 100 barg) and associated high leak rate, see, for example, ref. /29/. In ref. /30/ a new ignition model is presented which is based on a model from DNV for small leak rates. The DNV model is improved by being made continuous as a function of leak rate, and the new model (HYEX) takes into account that large leaks may have a significantly higher ignition probability than what the HyRAM model suggests. The same model is later presented in /27/, which, unlike /30/, is also publicly available. The new HYEX model in ref. /27/ and /30/ is illustrated in Figure 3-6, and is expressed mathematically as:

$$Ignition\ probability = Minimum(1.0; 0.55\ x\ Leak\ rate^{0.87}; 0.267\ x\ Leak\ rate^{0.52})$$

Note that when using this model, all leaks over 12.5 kg/s will have a total ignition probability of 1.0. The distribution between immediate ignition and delayed ignition is the same as for the DNV model (2/3 immediate ignition). Note also that the model presented in ref. /27/ and /30/ is described as a temporary model, but in conversations with the author of the model, Olav Roald Hansen (HYEX), it is confirmed that there is currently no information from recent studies that suggests that the model should be adjusted.

HYEX (the adjusted HyRAM model from ref. /27/ and /30/) is therefore recommended as an ignition model for hydrogen leaks.

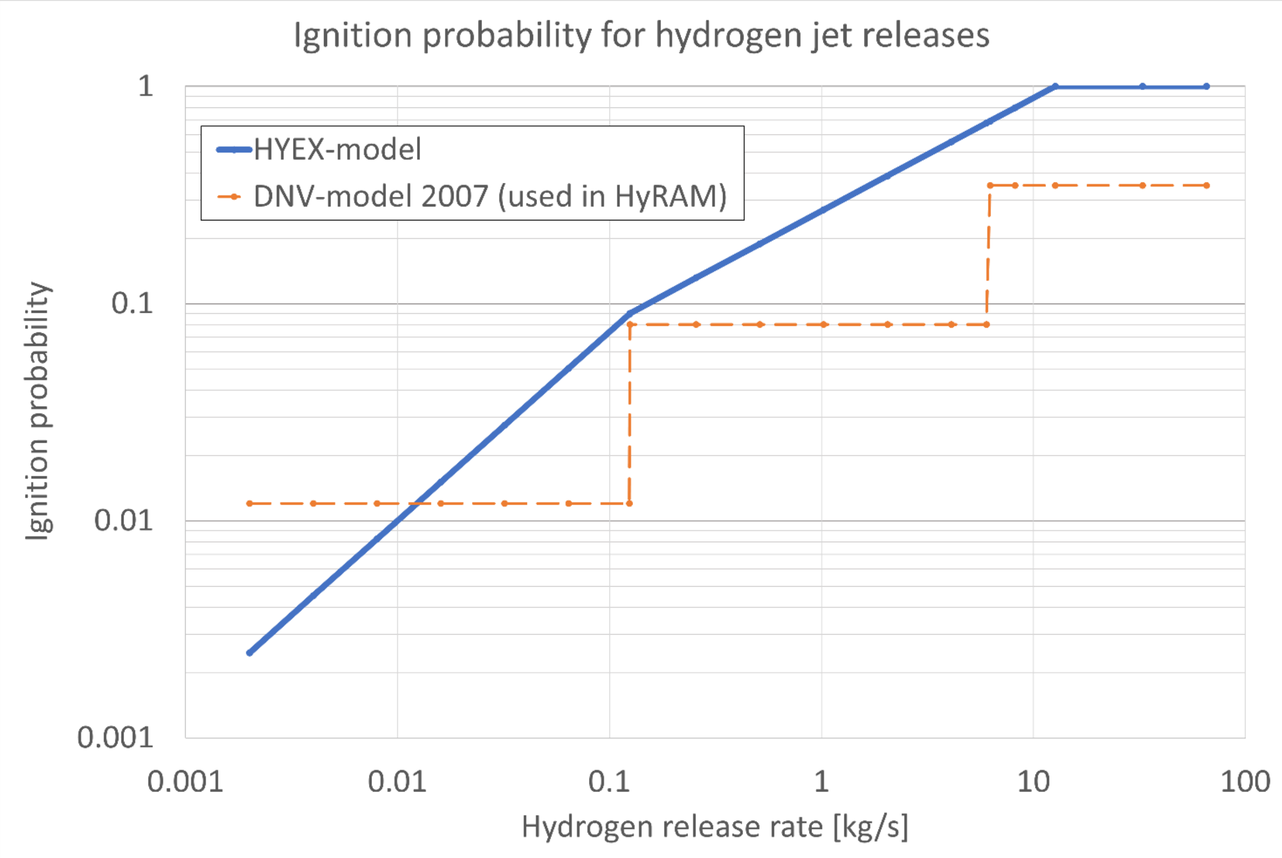

Figure 3-6 - Recommended total ignition probability for hydrogen leaks, ref. /27/ and /30/ (figure in Norwegian)

The HYEX model was originally set up for unobstructed jet leaks, but it is also recommended for use in tank ruptures and liquid hydrogen leakage.

In the event of a tank rupture, there is uncertainty as to whether delayed ignition will occur or whether close to 100 % early ignition can be expected, and thus how much of the energy should be used for explosion calculations. Here, HYEX recommends using a 1/3 delayed ignition probability and explosion corresponding to 20-50 % of the energy as a basis until experiments indicate otherwise. At the same time, this allows for better estimated assessments to be made, for example based on analysis of rupture mechanisms. This should be discussed as part of the uncertainty of the analysis, see Chapter 3.11.

In the event of a leak of liquid hydrogen (LH_2), the back pressure and thus the kinetic energy in the leak is lower than for unobstructed jet leaks. Due to lower emission momentum and lower temperature, it is not unlikely that the ignition probability will be lower. On the other hand, a release of liquid hydrogen will result in slower dilution in air, and thus longer hazard distances. In addition, the cloud will show heavy gas behaviour and stay along the ground for up to several hundred meters for large emissions. As an example, DNV GL performed experiments on behalf of the Norwegian Public Roads Administration (Statens vegvesen) with emissions of liquid hydrogen in 2019/2020, where 22-23 % hydrogen concentration was measured 30 m from releases of 0.8 kg/s LH_2 (ref. /31/). For a high-pressure emission with the same rate, the concentration would only be in the order of 5 % at this distance. With more experience with LH_2 emissions and ignition, the model can be considered for adjustment, but in the meantime, it may be appropriate to use the same model as for jet leaks. Ignition outside the facility must in any case be set equal to 1.0 for all leaks, see Chapter 3.6.6.

Considering that indoor leaks can cause accumulation of gas and thus increased (or reduced) gas cloud volume, it is proposed to adjust the delayed ignition probability as follows for leaks that can fill the entire room to concentrations above 8 %:

$$Ignition\_probability\_delayed\_enclosed = Minimum(1.0 - P(early); 0.0126xRoom\ volume^{0.58}; 0.018xRoom\ volume^{0.35})$$

In this equation, *P(early)* represents 2/3 of the total ignition probability from Figure 3-6. The contribution from delayed ignition indoors is also presented graphically in Figure 3-7. Note that the contribution from early ignition is omitted in Figure 3-7 because this contribution is a function of the leak rate, while delayed ignition is a function of the room volume. This means that Figure 3-7 is a conditional probability and must be seen in connection with the probability of early ignition. For indoor leaks that cannot fill the entire room to concentrations above 8%, the model for unobstructed jet leaks is used, see Figure 3-6.

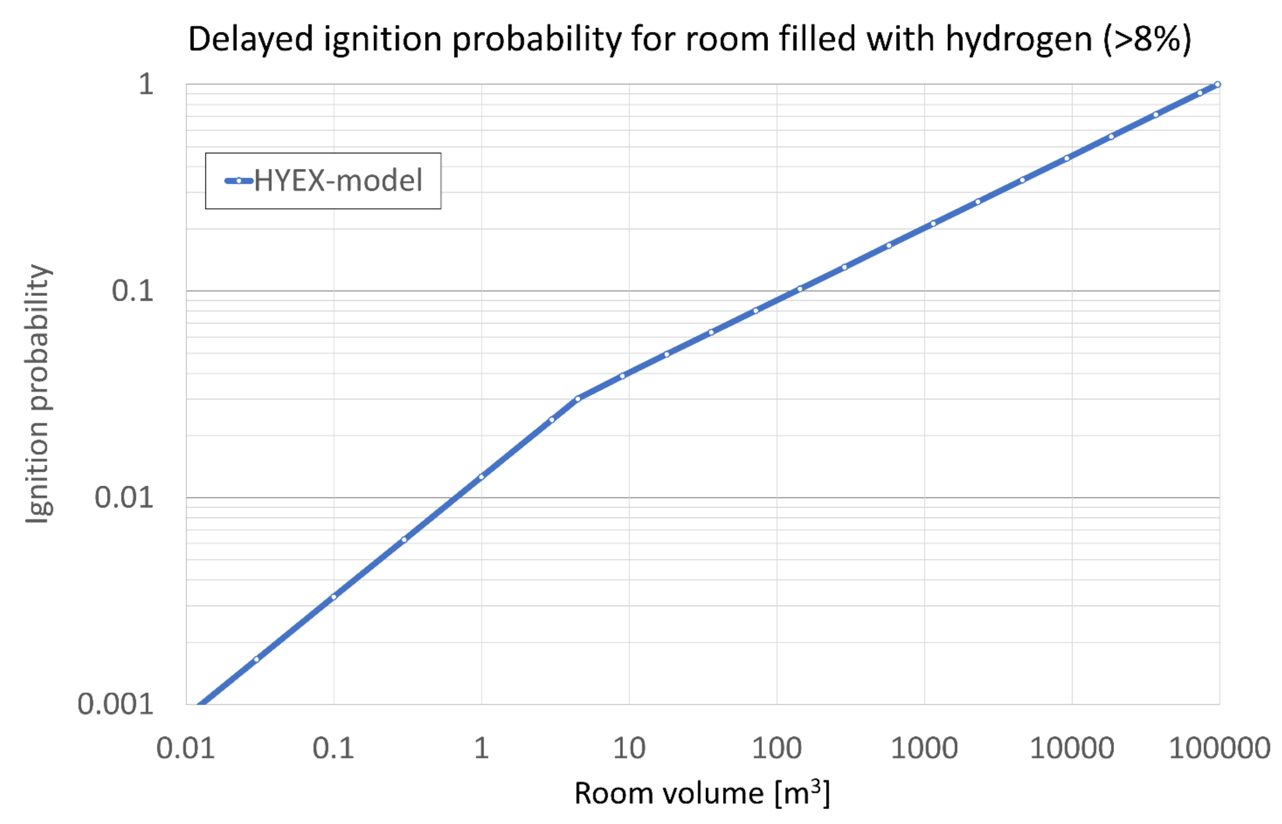

Figure 3-7 - Recommended conditional contribution from delayed ignition indoors (figure in Norwegian)

3.6.6 Ignition outside the facility boundary

Risk assessments and contours prepared in accordance with this document must reflect the design of the facility and associated safety systems, cf. the principle that the risk assessment must be the best estimate.

Risk contours intended to be used as a basis for consideration zones also cannot depend on assumptions regarding the surroundings of the facility, including the presence of ignition sources. This means that it must be assumed that a flammable cloud exposing regions outside the area controlled by the facility will ignite. It can be argued that this is not in line with the principle of best estimate risk contours, but it would not be appropriate to base the land-use planning around the facility on conditions over which the facility has no control, and which are expected to change over time.

The contribution to the risk contours from an event involving ignition of a flammable gas or vapour cloud depends on how widespread the cloud is when it ignites. If we always let the cloud ignite as soon as it reaches areas the facility does not control, the risk contours will be smaller than if we ignite the cloud after it has reached its maximum extent. In the first case, the risk contours will be too small, while in the latter case they will be too large (conservative). Thus, neither of the methods mentioned is best estimate.

The choice to always allow flammable gas or vapour that exposes areas outside the facility's control to ignite is on the conservative side. In order to make the risk contours as best estimated as possible, given the assumption of 100 % ignition, a model has been developed for the distribution of fatality in a cloud of flammable gas or vapour, as a function of distance from the point of release.

In order to say something about the distribution of fatality in a dynamic cloud that changes both size and position, information is needed on how long it takes before the supply of flammable vapour/gas to the cloud ceases. This is determined by how long it takes to isolate the segment with the leak (shutdown time), and the additional time required before all the substance becomes part of the cloud. With a short shutdown time, the duration of the gas cloud being at its maximum extent (steady state) will be short. Similarly, the cloud will remain at its maximum extent for a longer time when the shutdown time is long.

To determine the fatality in the area around the leak, it is recommended to use a mathematical model based on the following:

- The fatality at the leak point is 1.
- Calculation of the fatality at a point x outside the leak point is based on the probability that point x is inside the cloud when it ignites.
- It is assumed that the area of the cloud is proportional to the square of the distance from the leak point, and that the radial dispersion velocity is constant.
- Under otherwise equal conditions, the fatality in the area exposed by the flammable cloud outside the leak point will be lower for facilities with a short shutdown time than for facilities with a long shutdown time.
- When the shutdown time becomes very long, the fatality approaches 1 in the entire area exposed by the cloud.

Based on the above, the following expression for fatality rate as a function of distance from the release point can be established:

$$Fatality\ rate\ (x) = 1.0 - \frac{1}{(1+RV)\sum_1^N A_i}\sum_1^{n(x)} A_i$$

where

x	= distance from the leak point
$n(x)$	= number of discrete areas within point x
N	= number of discrete areas into which the cloud is divided
A_i	= area of flammable cloud no. i
RV	= relative duration of the leak: (duration of scenario at maximum extent) / (time from the leak starts until it reaches maximum extent)

The distribution of fatality rate is illustrated in Figure 3-8, where the distance from the leak point to the maximum extent is divided into *N* = 100 segments. As shown in the figure, the fatality is 1 closest to the leak point, while the areas furthest away from the release have a lower fatality. The figure also shows that the higher the relative duration, i.e. the longer the shutdown time, the higher the fatality at the maximum extent. As the relative duration becomes high, the fatality approaches 1 in the entire area exposed by the cloud.

If the duration of the leak is not known, a simplified assumption may be made that the duration is long, and that the consequence can therefore be modelled by igniting the cloud at its maximum extent and setting the fatality equal to 1 over the entire area. This is considered a conservative and acceptable approach.

If the facility's safety systems ensure that the leak is stopped immediately after the maximum extent is reached, it must be assumed that the cloud will remain at its maximum extent for approximately the same duration as the time required to reach maximum extent, i.e. that relative duration = 1. The gas will then be diluted from the point of release and outwards towards the maximum extent.

Note that the model requires that the majority of the ignition sources in the far field can be assumed to be discrete (they come suddenly and randomly). If one assumed that all ignition sources were continuous, the flammable cloud would ignite on the first exposure, and then the relative duration of the leak would not matter. Such a scenario would otherwise be equal to the curve for relative duration = 0 in Figure 3-8.

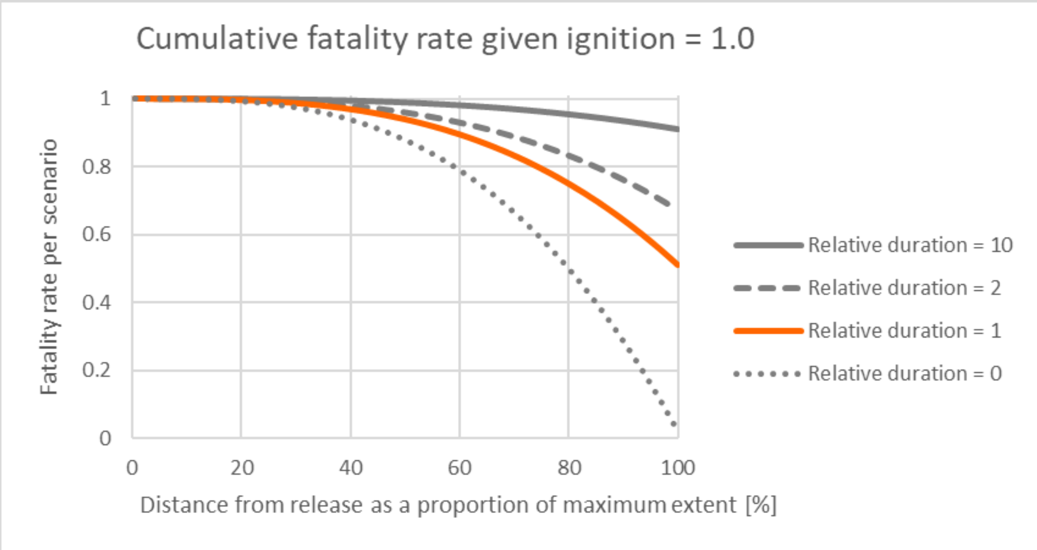

Figure 3-8 - Fatality rate distribution as a function of relative duration of the leak

Using the fatality rate distribution as shown in Figure 3-8, the outermost 1% of the flammable cloud will have a fatality of:

- 2 % at relative duration = 0
- 51 % at relative duration = 1
- 67 % at relative duration = 2
- 91 % at relative duration = 10

The innermost 1% of the cloud (at the leak point) will, for all of the above values of relative duration, have a fatality of 1.0.

The numbers behind Figure 3-8 are also given for characteristic relative lengths in the gas cloud in Table 3.2. When modelling fatality rate distribution, one can either use the equation above directly, or one can interpolate between the characteristic lengths in Table 3.2.

Table 3.2 - Fatality at characteristic relative lengths of the cloud (given ignition)

Relative duration:	Relative distance from the leak to the longest extent of the cloud											
	0 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	99 %	100 %
Relative duration = 0	1,00	1,00	0,99	0,97	0,94	0,88	0,79	0,67	0,50	0,29	0,02	0,00
Relative duration = 1	1,00	1,00	1,00	0,99	0,97	0,94	0,89	0,83	0,75	0,64	0,51	0,50
Relative duration = 2	1,00	1,00	1,00	0,99	0,98	0,96	0,93	0,89	0,83	0,76	0,67	0,67
Relative duration = 10	1,00	1,00	1,00	1,00	0,99	0,99	0,98	0,97	0,95	0,94	0,91	0,91

When implementing the model for fatality rate distribution, one can use an equivalent approach as for probits and give different fatalities for different locations within the same scenario (see also Chapter 4.1).

Additionally, the relationship between internal and external ignition must be considered. If internal ignition is significantly increased without the subsequent scenarios becoming larger, this implies that increased ignition probability inside the facility results in less exposure of fatal effects outside the facility. This is modelled by splitting the relevant leak scenarios into two events; a leak that ignites on the premises of the facility (leak frequency: base frequency*(internal ignition probability)) and a leak that ignites outside the facility boundary (leak frequency: base frequency*(1 – internal ignition probability)).

For some flammable substances with a high flash point (diesel and similar substances), a low-pressure leak will produce a very small or no flammable cloud through evaporation or spray leak. In such cases, a pool may extend beyond the facility boundary without a high enough gas concentration to create a flammable atmosphere. If a liquid leak extends beyond the facility boundary but cannot be expected to form a flammable cloud outside the facility boundary, ignition outside the facility boundary does not need to be equal to 1. The ignition probability may then be set equal to the ignition probability from an ignition model (IOGP, MISOF, RIVM, SAFEN) for the given leak rate.

For some substances that are both toxic and flammable, such as ammonia, the toxicity will extend further than the flammability, and the scenario will be most dangerous if it does not ignite. Such scenarios may also spread beyond the facility boundary where the guidelines require ignition to be set to 1.0, which will result in an underrepresentation of the hazard associated with the scenario. For such events, it is recommended to consider the substance as toxic and set ignition equal to 0 outside the facility boundary. Within the facility boundary, it is recommended to continue using a suitable ignition model (SAFEN for ammonia) and consider the substance as both flammable and toxic.

3.6.6.1 Ignition at sea

Ignition at sea shall be calculated in the same way as ignition over land.

3.6.7 Summary

A summary of recommendations is given in Table 3.3.

Table 3.3 - Recommended ignition probability models

Location	Comment	Suggested model
Within the facility boundary	No calculation of exposure probability. No time-dependent ignition probability, alternatively time-dependent for a constant cloud size.	IOGP (with adaptations for diffusive leaks, see Chapter 3.6.3).
	Calculation of exposure probability. Time-dependent exposure probability. Operating regime as for large facilities or offshore.	MISOF for process areas in the facility.
	Explicit consideration of special ignition sources (gas turbines, diesel engines, and pumps).	MISOF (requires calculation of exposure probability).
	Fired units.	Considered specifically for each unit, RIVM for simpler analyses.
Outside the facility boundary	Cumulative ignition probability = 1.0.	See Chapter 3.6.6.
Special substances	Hydrogen leaks.	MISOF for large petroleum plants, HYEX for other facilities, see Chapter 3.6.5.

3.7 Explosion analysis

3.7.1 General

All events that can lead to rapid build-up of pressure should be considered. Both gas, liquid (atomised droplets), and dust can contribute to explosions. Normally, the explosion will be a deflagration, but with high equipment density and long flame paths, it can turn into a detonation that gives a pressure in the order of 15-20 barg throughout the cloud. For detonations in environments that are not at atmospheric pressure (for example inside pipes), the detonation will cause a pressure increase approximately 15-20 times higher than the initial pressure.

The size of the explosive clouds is usually significantly smaller than the distances to the societal risk contours, such that it is the pressure propagation outside the flammable cloud that determines the risk contours. The pressure outside the cloud is in turn determined by the explosion pressure inside the cloud and the size and shape of the cloud. However, the pressure outside the cloud decreases in such a way that when the overpressure inside the cloud exceeds 0.5-1 barg (50-100 kPa), further increase in pressure has only a moderate effect on the pressure outside the cloud (except very close to the cloud). This means that for the assessment of powerful explosions, it is important to have control over the cloud size during ignition.

In facilities where rupture of equipment due to explosion can lead to a significant escalation of the incident, such as release of toxic substances or large quantities of hydrocarbons, the explosion analysis inside the facility must be sufficient to assess the extent to which equipment may rupture. The necessary scope and methodology for such an analysis depend on the relationship between the size of the loads that can be expected and the design strength of pipes and other relevant equipment.

3.7.2 Cloud size influence on explosion loads

For the best possible quantification of risk, it is necessary to use a good selection of leak rates. NORSOK Z-013, Annex F, recommends at least 9 leak rates for analyses of process plants in the petroleum industry. For each leak rate, a probability distribution of ignited cloud sizes must be calculated that includes everything from small clouds that will have negligible consequences to the largest clouds that may occur. The goal of this is to estimate frequencies for different explosion energies. Figure 3-9 shows an example of how this can be presented.

To the extent that very strong explosions (detonations) can occur inside a facility, it is not only the gas cloud inside the process plant that is of interest, but also the size and position of the flammable cloud outside the most obstructed area, as this part of the cloud for detonations also will contribute to the pressure wave energy. Some substances, such as hydrogen, detonate more easily than other substances, and in such cases, it is particularly important to consider the energy from the entire flammable cloud (and not just the one within an obstructed area).

For events inside buildings or process equipment, the cloud size will be limited by the size of the building or equipment. For such scenarios, the quantity required to achieve hazardous gas/dust clouds (clouds that can cause significant local damage) will be much smaller than for outdoor releases. On the other hand, the building/equipment will limit the energy of the pressure wave in the far field.

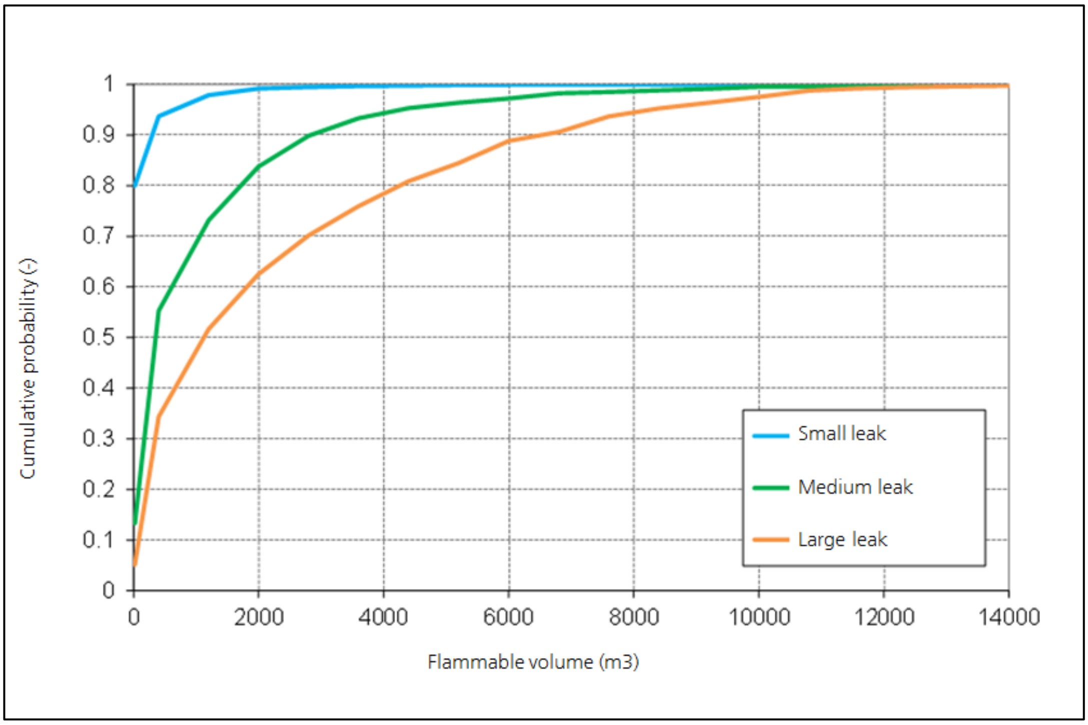

Figure 3-9 - Example of distribution of flammable cloud size, given leak size. The figure shows, as an example, that there is approximately 78 % probability that a large leak will result in a flammable cloud size of 4,000 m^3 or less (and 90 % probability of a cloud size of 6,500 m^3 or less)

By combining information on flammable cloud sizes with ignition sources (see Chapter 3.6), information on ignited cloud sizes as a function of frequency is established, see Figure 3-10.

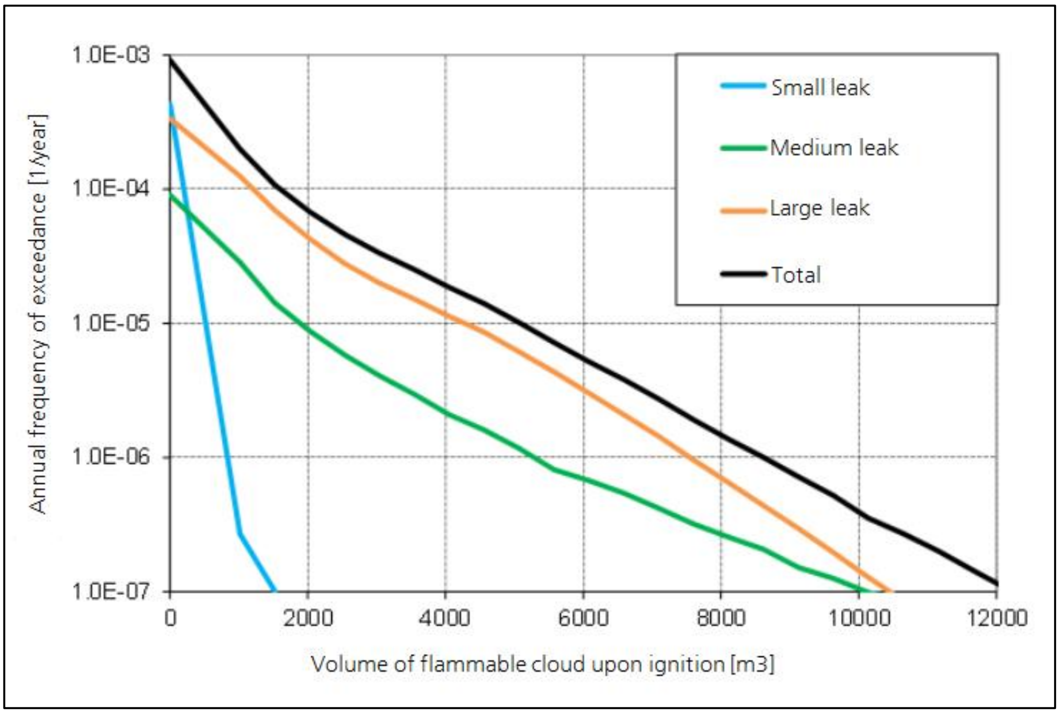

Figure 3-10 - Example of the relationship between ignited cloud sizes and cumulative frequency. The figure shows, as an example, that the total frequency for igniting a cloud greater than or equal to 5,000 m^3 is 1E-5 times per year. The total fire frequency is 1E-3 times per year

The choice of explosion model must be made in conjunction with the choice of ignition probability model, see Chapter 3.6. More advanced ignition models (MISOF) assume a transient explosion model where the leak rates and cloud sizes will vary with time. The simpler ignition probability models (RIVM and IOGP) relate to a given cloud size or leak rate, which must be determined.

3.7.3 Calculation of explosion pressure within a flammable gas cloud

Considering the risk picture outside the flammable cloud, the pressure in the cloud (source pressure) can be estimated by simpler models, for example as described as source strength in ref. /34/. This gives a pressure independent of the size and shape of the cloud and is used in the so-called multi-energy method for pressure propagation outside the cloud.

Alternatively, the source pressure within the flammable cloud can be determined more precisely by taking into account possible cloud sizes and associated frequencies. A recommended standard for establishing a pressure-frequency distribution within a cloud is NORSOK Z-013 (ref. /32/), which requires the use of CFD simulations for both gas dispersion and explosion. This methodology will provide an estimate of the relationship between cloud size and explosion pressure. When using CFD for input to the multi-energy method, it is recommended to use a representative source pressure from each simulated CFD scenario corresponding to 50 % of the highest pressure measured in a control volume for that scenario.

When using CFD to calculate explosion pressure, it is very important to have a good 3D description of geometry; if the level of detail in the geometry model is too low, the calculations will result in explosion pressures that are too low. It is also important to consider a range of scenario variations (cloud locations and ignition points) to adequately span the sample space.

3.7.4 Calculation of explosion pressure in far fields

When the frequencies of different ignited cloud sizes and associated pressures are known, the associated explosion loads in the far field can be established by calculating the pressure propagation outside the cloud. This can either be simulated by CFD or calculated with simpler models such as the multi-energy method (see, for example, ref. /41/, ref. /34/, and ref. /33/). When using simpler methods, the multi-energy method is recommended for both hydrocarbons and hydrogen.

The multi-energy method requires that the cloud is hemispherical. If the conditions indicate that the cloud will have significantly different shapes (such as oblong cigars or flat "pancake clouds"), the actual far field pressures may differ significantly from those computed by the multi-energy method. In such situations, it is recommended to use CFD simulations also for the far field pressures.

A crucial parameter in the multi-energy method is the efficiency factor (ref. /34/). This indicates how large a proportion of the combustion energy in the cloud actually contributes to the generation of an ideal pressure wave and is used to reduce the cloud size accordingly. This factor is therefore essential for how quickly the pressure decreases outside the cloud. Guidance on the choice of efficiency factor can be found in ref. /34/ based on ref. /35/. The efficiency factor will in principle increase with pressure, and for detonations it is 1.

Since the pressure in the far field becomes less dependent on the source pressure in the flammable cloud if it is above approx. 1 barg, the far field pressure in such situations is determined only by the cloud size and the efficiency factor. This means that one can make conservative estimates of explosion loads in the far field without running explosion simulations by assuming that the source pressure in the cloud is > 1 barg and using a high efficiency factor.

For general substances, the efficiency factor should be set equal to 0.5 or higher; for hydrogen it should be set equal to 1.0.

However, there will be an area close to the cloud where the pressure can still remain high or increase at source pressures above 1 barg. If the societal risk contours fall into this area, it is therefore important that the source pressure is calculated with sufficient accuracy.

See Chapter 4.2.4 for vulnerability criteria for explosion loads.

3.8 Fire analysis

When it comes to simulation of jet and pool fires, the choice of scenarios will have a big impact on the extent of the risk contours. Once the scenarios are defined (type, rate, location, direction, etc.), the energy of the combustion will also be defined, and the results are less dependent on the choice of simulation tool than is the case with flammable gas exposure, see Chapter 3.5.2. As a result, only a summary description of fire analyses is given in this chapter.

Fires can be sorted into three different types, and all types must be considered in the risk analysis where relevant:

- **Flash fires**. If a flammable gas, flammable liquid droplets or combustible dust is mixed with air and then ignited, large amounts of combustible material can be burned in a short time. The combustion in a flash fire will mainly take place where the substance is present in a flammable concentration, but due to the temperature increase during combustion, the air in the flame will expand and can push the unburned flammable cloud outwards to approximately double its size if ignition occurs in the centre of the flammable cloud. For edge ignition, this effect is significantly lower since the expansion only partially enters the flammable cloud. In addition, the fatal thermal radiation intensity will extend somewhat beyond the flammable cloud when it burns. The consequences of a flash fire can therefore in some cases be experienced well outside the original flammable cloud. If the flammable cloud is in an area with a high equipment density, this will accelerate the combustion and thus also the pressure build-up. A flash fire can then be considered as an explosion (deflagration). If there is a very high equipment density, the combustion can in extreme cases turn into detonation (such as the Buncefield incident, ref. /36/), and this should be considered as part of the explosion analysis, see Chapter 3.7. Flash fires have a short duration and therefore have less ability to transfer large amounts of heat energy to structures but can cause personnel injury. Best estimate models of flash fires require best estimate models of the flammable cloud. When assessing the fatality of flash fires outside the facility, it can be assumed that those inside the flammable cloud will die, see Chapter 4.2.3.

- **Diffusive fires (pool fires)**. If a liquid leak collects in a bund where the liquid can evaporate (either by boiling or by vapour pressure-driven evaporation), the evaporated gas can reach flammable concentrations that can ignite. In such cases, the fire will be controlled by the availability of flammable gas and the area inside the bund. Geometrical conditions regarding the bund, other than the area (which determines the flame height), are usually of lesser importance, but it should still be considered whether there are conditions at the facility that can act as shielding of thermal load towards the surrounding environment. Diffusive fires will burn as long as new flammable gas is supplied, and they can therefore last for a long time and radiate large amounts of heat to the surroundings. Normally, pool fires will generate a lot of smoke that will obscure the flame and thus greatly reduce radiation to the surroundings. However, strong winds will reduce the obscuration upwind and increase the radiation in that direction.
- **Jet fires**. If gas or liquid leaks out at high back pressure, this will form a jet with high velocity and high impulse. This jet will effectively mix gas or liquid droplets with air and can therefore burn with very high intensity and emit large amounts of heat to the surroundings. Jet fires can continue to burn as long as new flammable material is supplied and can therefore last for a long time. There is usually no distinction between the thermal load from gas fires and spray fires.

Typical thermal loads for different fire types are given in NORSOK (ref. /37/) and FABIG (ref. /38/). Hydrocarbons have higher combustion energy than most other flammable substances and therefore normally represent a greater fire risk. For fire properties of substances other than hydrocarbons, reference is made to ref. /39/.

In addition to thermal load, the smoke from the fire must be taken into account where this can have an impact on the extent of the risk contours. This is particularly important where the substances burning emit toxic gases. For example, a fire in chlorinated hydrocarbons will emit hydrochloric acid. Another example is a fire in fertilisers, which results in the generation of nitrous gases. FABIG (ref. /40/) has given typical values for the production of CO in hydrocarbon fires (< 0.5 volume percent for liquid fires) and based on these values it can be concluded that CO will normally not affect the risk contours. Fatal concentrations of CO outside the hot areas will normally only occur in fires in enclosed spaces where there is limited access to oxygen and limited ventilation (smouldering fires).

Note that fire calculations are less dependent on the choice of simulation tool than explosion calculations and dispersion calculations (see Chapter 3.5.2), but if the analysed fires significantly change their character and consequences by hitting obstacles, CFD should be considered (see guidelines in Chapter 3.5.2). This applies in particular to the assessment of escalation barriers and exposure to the public immediately outside the facility.

3.9 BLEVE and other events

3.9.1 BLEVE

BLEVE (Boiling Liquid Expanding Vapour Explosion) normally occurs when a pressure vessel with liquid stored significantly above its boiling point temperature at atmospheric pressure ruptures. This can result in different scenarios and can generate significant thermal loads, flying fragments, and pressure waves to the surroundings.

Rupture can occur either as a result of weakening of the tank due to fire exposure or due to failure from other causes without external fire impact, such as train derailment and collision. A BLEVE is often characterised as physical if the explosion does not involve chemical reactions (only expansion of gas due to phase transition due to pressure drop) or as chemical if a chemical reaction (fire or explosion) further contributes to the consequences. The different conditions of a tank rupture scenario must therefore be considered separately to obtain a complete consequence picture, see, for example, ref. /41/ Chapter 6.5.7, ref. /42/, and /43/. The formulas in ref. /41/ apply to LPG; for fluids with other molecular weights, the corresponding formulas in ref. /44/ can be used.

Pressure waves will be generated for several different reasons, which must be considered separately:

- In a tank with pressurised gas, expansion of the gas upon rupture will generate a pressure wave in the environment. This primary pressure wave is normally not considered part of the BLEVE phenomenon. However, it can be the dominant contributor to pressure waves if the gas phase has a significant volume and high pressure, and if the distance to the public is short or there is a significant degree of enclosure around the tank.
- If the liquid temperature at rupture exceeds the boiling point at ambient pressure, but is not considered superheated, i.e.:

  $T_{boiling}$ at ambient pressure < T_{liquid} at rupture < $T_{superheated}$ where $T_{superheated} \sim 0.89\ T_{critical}$,

  the boiling of liquid at rupture will not be powerful enough to generate a strong pressure wave (a so-called "cold" BLEVE). If the liquid is flammable, a fireball may form, but it will not burn as intensely or rise as high as for a "hot" BLEVE or generate a pressure wave.
- If the liquid is superheated at the time of rupture, i.e., T_{liquid} at rupture > $T_{superheated}$, spontaneous homogeneous boiling will occur, which, due to instantaneous expansion, will generate a strong shockwave ("hot" BLEVE), in addition to a full fireball if the liquid is flammable and ignites. This secondary pressure wave can often occur simultaneously with or shortly after the primary pressure wave from the gas cap. This is the scenario most often associated with BLEVE and to which standard formulas for height, diameter, and duration of a fireball apply, such as in ref. /41/. When calculating pressure from a BLEVE, one must take into account both the pressure, temperature, and volume of the liquid in the tank and the size of any gas cap.

Note that it is the liquid temperature at the time of rupture that determines whether a cold or hot BLEVE will occur. For example, rupture of a tank with propane at ambient temperature will result in a cold BLEVE, but if a fire around the tank heats the propane to more than approx. 50 °C, it becomes superheated and results in a hot BLEVE.

In addition to pressure and thermal radiation from the BLEVE, large and small fragments of the tank shell will also fly as projectiles and could pose a significant societal risk, for data, see, for example, ref. /43/.

Normally, BLEVE assumes a spontaneous rupture of the entire pressure vessel, but cracks or larger leaks in pressure vessels have also been shown to lead to full rupture with consequences similar to BLEVE (BLCBE - Boiling Liquid Compressed Bubble Explosion), even if the liquid is not completely superheated (ref. /45/). Note that this does not require an external fire that weakens the tank shell.

For tanks with liquid mixtures without a well-defined boiling point, an estimate must be made of the fraction of liquid that will atomise into droplets and not rainout at tank rupture. This can be estimated by calculating the volume fraction of the liquid that can boil at rupture. Multiplied by the tank pressure, this gives an expansion factor E. Analysis of the RELEASE experiments with various liquids, ref. /46/, shows that the fraction of liquid that is atomised into droplets is roughly proportional to E, where all liquid can be assumed to be converted into liquid droplets at E ~ 100. The potential pressure wave can be calculated based on rupture in a tank with total gas volume = initial gas volume + volume of released gas, all at the tank pressure.

3.9.2 Roll-over and boil-over

In tanks with low-temperature liquids like LNG, LH_2, and ammonia, stratification may occur due to evaporation or refilling of liquid with a different density. Heat leaks into the tank will heat the bottom layer, the density will decrease, and the layers will eventually mix. The evaporation rate will then increase far beyond normal, and if this has not been adequately considered in dimensioning the tank's safety valves, the tank may be over-pressurised.

The risk associated with roll-over is difficult to determine but should be controlled by having operational control of factors that cause stratification in tanks, primarily: composition, temperature, and density of the liquid being filled, as well as ageing (density change through evaporation). For operational support, there are several models for monitoring the state of the liquid and predicting roll-over with the associated evaporation rate, see, for example, ref. /47/.

The frequency of roll-over is difficult to define, but the literature refers to 20-30 known events of varying extent. All events refer to pressure relief over a long period of time, with the associated dispersion of a flammable gas cloud as a consequence. Furthermore, the problem is mainly related to atmospheric pressure or near-atmospheric pressure vessels.

Boil-over is a phenomenon that can occur in the event of a fire in storage tanks with oil products, where there is a layer of water at the bottom of the tank. The oil will be heated by the fire, and in the event of a prolonged fire, the water will eventually reach boiling temperature, spontaneously boil, expand, and atomise the oil into droplets. The result is a dramatic increase in fire intensity, often in the form of a fireball and an increase in associated hazard distances. The risk of boil-over is best managed by always minimising or removing water at the bottom of storage tanks. A comprehensive overview of the phenomenon and related calculation models for time to boil-over and residual liquid volume is given in ref. /48/. Similar issues may occur in pressurised separator tanks (water, oil, and gas) if the content is heated above the atmospheric boiling point of water before a possible tank rupture.

The probability of roll-over and boil-over is usually reduced through the establishment of dedicated operating procedures. The events must therefore be considered in the HAZID review.

3.9.3 Internal escalation of events

Normally, minor events, such as small fires or explosions, will not directly affect societal risk contours. However, it is important to consider whether a minor event can escalate into a larger one that could affect the surroundings. Typically, this could be a limited fire or explosion that causes rupture of equipment that releases toxic substances or larger amounts of flammable material. Important considerations include the extent to which there are sufficient barriers, either through protection systems or design strength, that can prevent such escalation.

Internal escalation must be included in the basis for scenarios that contribute to risk contours. An example of this is BLEVE, which occurs as an escalation of a minor event, see Chapter 3.4.2.9.

3.10 Establishing risk contours

In order for the risk contours to be representative of a given facility, a sufficient number of scenarios must be considered.

By using symmetry considerations and simplified physical modifications, one can reduce the number of scenarios that actually need to be simulated. It is thus possible to assess a large number of scenarios based on a significantly reduced number of simulated scenarios.

If symmetry considerations are made to reduce the number of simulated scenarios, it is important to simultaneously assess the veracity of the physics in the scenarios, according to the principles discussed in Chapter 3.5.2. It is thus possible to simulate some of the scenarios with empirical tools and others with CFD tools, depending on how much of the physics in the scenarios it is necessary to capture (and thus be able to calculate representative risk contours).

Even if the leak frequency distribution can be considered representative for the facility (see Chapter 3.4.2) and the simulated scenarios have been performed with the correct simulation tool in accordance with the guidelines in Chapter 3.5.2, it is still crucial that a sufficient number of events are considered.

A risk contour will be uncertain if it is based on too few scenarios because it then does not span a sufficient sample space. Note that even if one simulates enough scenarios that in practice "all possible" events are simulated, the uncertainty associated with other factors, such as the frequency picture, does not disappear.

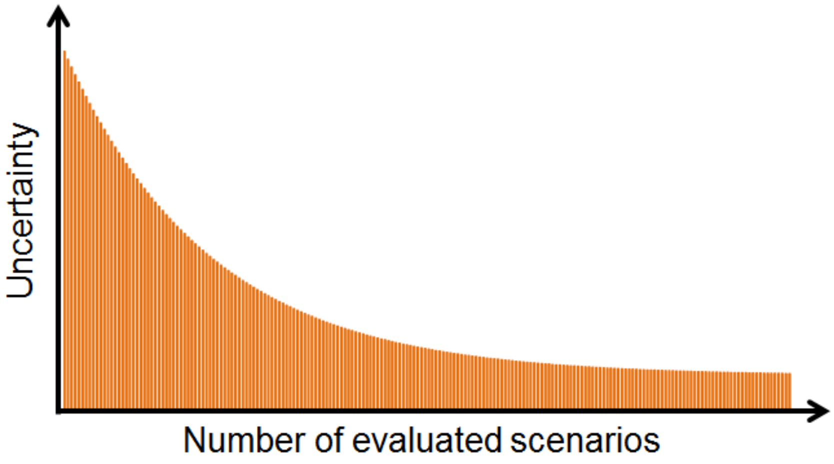

Figure 3-11 - Uncertainty associated with sample space as a function of the number of evaluated scenarios – illustration

The number of scenarios that must be considered to establish sufficiently accurate risk contours will vary for different facilities depending on size and complexity. Correspondingly, the number of calculations needed for the different consequence assessments (fire, dispersion, and explosion) will also vary.

If the risk contours are to be best estimate, the analysis must span a sufficient part of the sample space for the top events. The following three steps are recommended as a robust way to achieve best estimate risk contours:

- First, a sufficient number of simulations/calculations are run to capture the main physics in all relevant scenarios.
- If the risk contours clearly show that too few scenarios have been simulated (typically by the contours having jags/arms linked to the simulated individual scenarios), the simulated scenarios can be used to estimate scenarios that are considered sufficiently similar to those that have been simulated.
- If the risk contours still have small irregularities after interpolation/extrapolation has been performed, the result field can be smoothed (e.g. with a Gaussian smoothing as shown in Figure 7-1 in Appendix B). Such smoothing will not directly address the physics but merely represents a smoothing of the result field.

Appendix B highlights the following factors that affect the risk contours:

- effect of the number of simulations
- interpolation of simulated scenarios
- number of leak points
- number of simulated rates
- smoothing of the risk contours
- refining of the risk contours in critical areas

3.11 Description of uncertainties

All assessments that significantly affect the location of the risk contours must be described and discussed in the risk analysis. As a minimum, the following factors must be described and assessed in relation to whether they contribute to best estimate risk contours:

- Assessments of frequency. The frequency of the top event must represent the analysed facility with all relevant physical attributes and barriers to reduce leaks, see Chapter 3.4. An assessment must be made of whether the selected frequency model is representative for the facility to be analysed and how any deviations are compensated for.

- Physical modelling. The physical models must adequately assess the physics involved such that the results can be considered as the best estimate for the analysed facility, see Chapter 1.2. The choice of physical models and calculation tools must be discussed in relation to whether they adequately address the physics of the events. Uncertainties related to the use of probits and threshold values must be discussed when relevant.
- Modelling the sample space. It must be discussed whether a sufficient number of scenarios have been assessed and simulated for the risk contours to be considered best estimate, see Chapter 3.10. If an insufficient number of scenarios have been assessed such that convergence cannot be documented, it must be discussed how this will affect the risk contours.

Sensitivity analyses should be used to identify the parameters or assumptions where the uncertainty has the greatest impact on the risk contours, ref. Chapter 3 of the guidance report (ref. /1/). Selection of sensitivities should be seen in light of the need for accuracy in the analysis. In probabilistic analyses, variations in a range of parameters and conditions will be taken into account, and sensitivities are therefore selected among the parameters and assumptions that have not been subject to variations in the analysis.

In addition to frequency, physical modelling, and sample space, special assessments that are expected to introduce uncertainty in the risk contours must be discussed. An example of this is the uncertainty in the chosen ignition model, see Chapter 3.6. If this contributes significantly to the risk contours, the uncertainty related to this should also be discussed in the risk analysis. The same applies to uncertainties related to vulnerability criteria for fatality, see particularly Chapter 4.2.2 for toxicity. However, it is not necessary to quantify uncertainties related to the presented risk contours. Sensitivity analyses and uncertainty assessments should initially be described qualitatively. However, sensitivity analyses around alternative facility designs or risk mitigating measures at the facility, such as safety systems or physical barriers, would be useful to describe quantitatively if these result in changed risk contours.

4 Vulnerability criteria

4.1 The importance of vulnerability criteria for risk contours

When a sufficient number of scenarios are evaluated with selected leak frequencies and physical modelling, one will in principle have a model of "all" events that can occur and what consequences these have (concentration of toxic substances, flammability, thermal load, and explosion load). Before a realistic risk curve for fatality can be established, however, one must have a model that indicates which exposure is to be considered fatal. The choice of vulnerability criteria for fatality will affect the extent of the risk contour. Recommendations for choice of vulnerability criteria (threshold values) are given below.

Figure 4-1 illustrates how the choice of vulnerability criterion (for toxicity) affects the risk contours for the same event. The concentration of toxic substance will decrease with the distance from the leak point, and if one sets the vulnerability criterion at a low concentration (orange curve) or at a slightly higher concentration (green curve), one gets different risk contours for the same simulated scenarios.

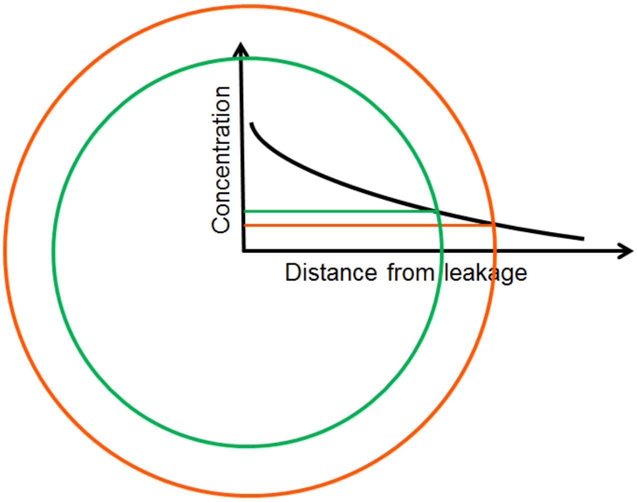

Figure 4-1 - Illustration of how the choice of vulnerability criterion for toxicity affects the risk contours

There are two types of vulnerability criteria: threshold values and probits. Threshold values are binary in the sense that they state that for values below the threshold value there is no fatality, while for values above the threshold value 100% fatality is assumed. For probits, a gradual transition is assumed where fatality for doses below a low threshold is set to zero, and then there is an increasing probability of fatality at increasing doses. For doses above a high threshold, 100% fatality is assumed. An advantage of using probits is therefore that a single scenario will have a gradual transition between 0 % fatality and 100 % fatality, and this will give smoother risk contours when the frequencies for all simulated and assessed scenarios are added together. The use of probits therefore makes the risk contours less sensitive to the choice of which scenarios are simulated (because fatality is not binary but is distributed over a larger area). It is therefore recommended to use probit functions to the greatest extent possible when calculating risk contours.

To calculate fatality associated with intensities that vary over time, the dose must be integrated over the duration of the scenario. In practice, this is done by dividing the intensity into intervals with constant intensity and multiplying by the time. The average intensity is then calculated, which, over the total duration, gives the same dose as the integrated dose with different intensities. The probit function for the average intensity is then used to calculate fatality.

Note that when calculating doses, it is the duration of the exposure at a given point that should be used (since the risk contours should apply to fixed points in the terrain). The possibility of escape and evacuation must not be taken into account, cf. Chapter 1.5 (see also Chapter 4.2.1).

If threshold values are used to calculate the fatality for each simulated scenario, the probit for 50 % fatality must be used as the basis for determining the threshold value. This is in keeping with the goal of generating best estimate risk contours, and the expected value of a probit that is normally distributed is equal to the 50th percentile (which is also equal to the mean value). If a threshold value based on a probit function with a fatality above 50 % is used, the results will be non-conservative and, conversely, threshold values based on a probit function with a fatality below 50 % will lead to conservative risk contours.

If the probit function for 50 % fatality is used as the threshold value to estimate fatality for a single scenario, it is also achieved that a Gaussian smoothing of this scenario will result in a fatality distribution similar to that obtained if the probit function was used to calculate fatality. This is because both the probit function and the Gaussian smoothing are normally distributed. This is illustrated in Figure 4-2.

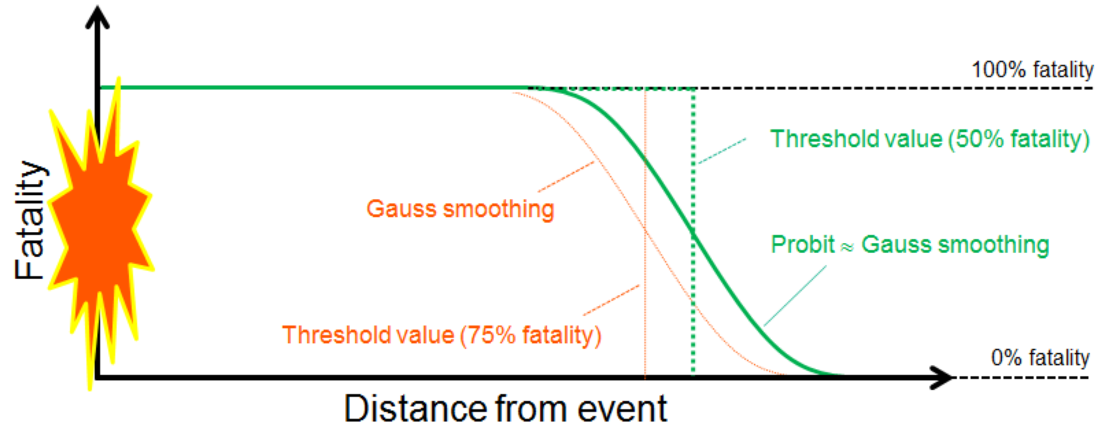

Figure 4-2 - Illustration showing that when smoothing a fatality rate curve that has been obtained using a threshold value corresponding to probit for 50 % fatality, the smoothed curve will have a similar shape as if probit was used to calculate fatality for the simulated scenario (see also Appendix B). If a threshold value with a fatality other than 50 % is used, the smoothed curve will shift relative to the probit function (orange curve)

4.2 Recommended vulnerability criteria

4.2.1 General

It is recommended to use probit functions to the greatest extent possible when calculating risk contours, see Chapter 4.1. When using probit functions, the probability of death can be calculated as a function of exposure time and concentration of toxic substance/heat flux. As it is not taken into account how long any people may be in the area, i.e. that they can escape, ref. definition of risk contour in Chapter 1.5, the exposure time in the probit function will be identical to the duration of the scenario.

For scenarios with a very long duration, it is not the best estimate to assume that people can be exposed to thermal and/or toxicity loads for many hours or days without emergency services carrying out evacuation. It is therefore appropriate to see exposure time in connection with the time it takes for emergency services to evacuate the population after an event. This depends on factors such as the organisation of and distance to the fire department, population density, and the population's ability to self-evacuate. In cases where it is not possible to provide a good estimate of the evacuation time, the evacuation time is set to the response time plus 60 minutes.

If the probit function is not available, threshold values can be used to calculate the consequences of each simulated scenario. In order to achieve the best estimated risk contours as possible, a threshold value representing 50 % fatality must be used as a basis for the analysis, see Chapter 4.1.

If there are special uncertainties when using probits or threshold values, this must be described, see also Chapter 3.11.

4.2.2 Toxicity

DSB has published an overview of recommended probits for the most commonly used substances in Norway (www.dsb.no). The probits recommended on DSB's websites must be used when calculating risk contours.

The overview is based on a review of new and old probit functions from RIVM that the Norwegian Defence Research Establishment (FFI) has carried out on behalf of DSB. The report from FFI is available at www.dsb.no.

If the substance is not in DSB's list of probits, it is recommended to use probits defined by RIVM. Current probit functions can be found in the *Guidelines for Quantitative Risk Assessments* "*Purple book*", ref. /42/, published by RIVM. RIVM has developed a general method, ref. /49/. This method has been developed by the Dutch expert panel on probit functions, on behalf of RIVM, and replaces the previous version of the method from 2001. RIVM has also published *Probit functions status overview* (ref. /50/). For most substances given in the overview, new probit functions are specified, with the status "Determined in terms of content".

4.2.3 Fires

Clothing will generally provide some protection against thermal radiation, depending on the type of clothing and the degree of coverage. The population must therefore be assumed to be protected against thermal radiation to a certain extent, but there will be great uncertainty associated with the degree of protection. It would therefore complicate the risk calculations considerably if protection from clothing were to be taken into account when calculating risk contours. Additionally, the risk contours would then depend on an assumption about the degree of protection, which is not in line with the overall principles for calculating risk contours. It must therefore be assumed that members of the public are always unprotected against thermal radiation from fires (bare skin).

For fires resulting from an ignited gas cloud, the threshold value for death is set to be the lower explosion limit (LEL). This threshold value applies to the calculation of risk contours. For emergency preparedness purposes, it may in some cases be desirable to use the distance to ½ LEL.

For thermal radiation, TNO, ref. /42/, Chapter 5, Eq. 5.4, provides the following probit function[5] for death by exposure of bare skin:

$$Pr = -12.8 + 2.56\ln(D)$$

where the received dose is

$$D = tq^{4/3}\text{, with units } q\left(\frac{kW}{m^2}\right) \text{ and } t(s)$$

The correlation between heat flux and duration corresponding to 50 % fatality (i.e. Pr = 5) is shown in Figure 4-3. A lower limit of 1.5 kW/m^2 (exposure time 610 s) has been set, which corresponds to the threshold for unbearable pain, cf. ref. /51/.

For heat fluxes lower than 1.5 kW/m^2, it is recommended to set the fatality equal to zero. This applies regardless of exposure time and regardless of whether a probit function or threshold value is used to calculate fatality from thermal radiation.

When using a probit function to calculate fatality, it is not recommended to use an exposure time shorter than 30 s. This applies even if a shorter exposure time can be argued for. This is because the relative uncertainty in the estimate of exposure time will normally be high for such short durations.

If threshold values are used to assess the consequences for the simulated scenarios, the fire duration (t) associated with the simulated fires must be assessed, and then the thermal load corresponding to a 50 % probability of death from the probit must be determined and used as the threshold value. The threshold values for different durations will then be as given in Table 4.1 (the numbers can also be read from Figure 4-3).

If the analysis tool allows modelling probits with long exposure times, this is recommended before using a threshold value (see also Chapter 4.2.1).

Note that the highest heat flux given in Table 4.1 is 15 kW/m^2, corresponding to an exposure time of 28 seconds. It is not recommended to use a threshold value higher than 15kW/m^2 when assessing thermal radiation. The reason for this is the same as for the recommendation not to use an exposure time shorter than 30 s when using the probit function to determine fatality.

5 When the unit W/m^2 is used for q, the probit function takes the following form: Pr = -36,38+2,56ln(t*q$^{4/3}$)

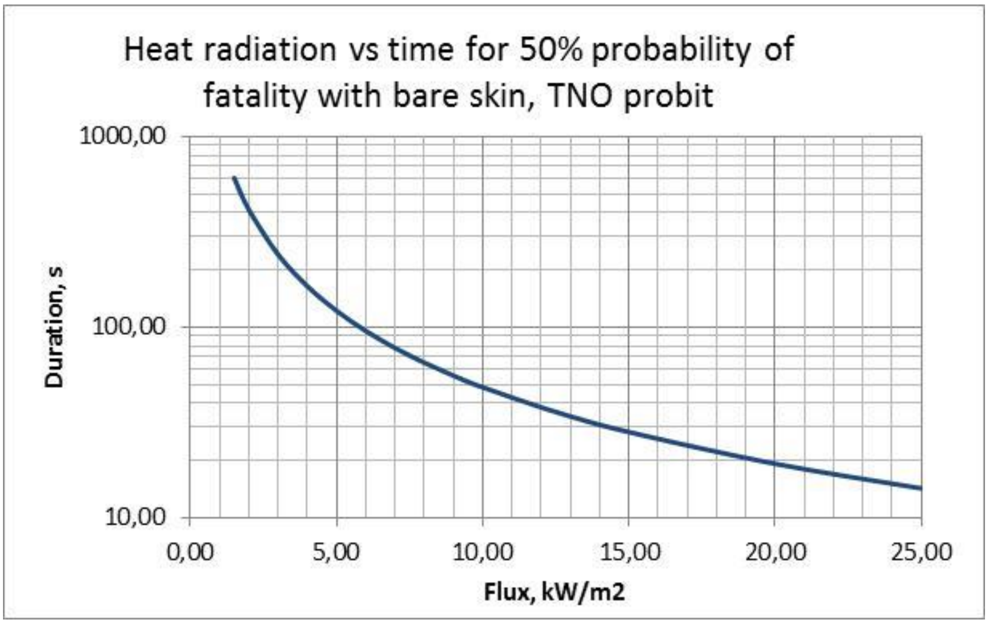

Figure 4-3 - Correlation between heat flux and associated durations that give a 50 % probability of death for unprotected exposure (bare skin)

Table 4.1 - Threshold values for death as a function of fire duration (TNO probit for 50 % fatality)

Duration of fire exposure	Threshold value for fatality due to heat flux
≥ 610 seconds	1,5 kW/m^2
415 seconds	2 kW/m^2
242 seconds	3 kW/m^2
165 seconds	4 kW/m^2
122 seconds	5 kW/m^2
65 seconds	8 kW/m^2
49 seconds	10 kW/m^2
28 seconds	15 kW/m^2

In addition to the thermal load, the smoke gases from the fire must be taken into account where these may have an impact on the extent of the risk contours, see also Chapter 3.8. In practice, the load with the greatest consequence (of heat and smoke) is used as the basis for the risk contours. Carbon monoxide (CO) produced by hydrocarbon combustion will not normally contribute to the risk contours, but in special cases, the burning substances can emit toxic combustion products (for example, chlorinated hydrocarbons can emit hydrochloric acid, and fertilisers can emit nitrous gases). When toxic gases are generated during fires, this must be assessed in the same way as direct emissions of toxic substances. This means that one must calculate the emission rate in the near field and the dispersion in the far field. For fatality, probit is used if available; otherwise, a threshold value for 50 % fatality is used.

For flash fires, it can be assumed that those who are inside the flammable cloud will die, while those who are outside survive. This is a simplification that both contributes to simpler analyses but also represents a form of weighting of factors that are both conservative and non-conservative, so that the resulting risk contours can be claimed to be close to the best estimate. In the non-conservative direction, the most important factor is that one does not take into account that the flammable cloud can expand when it burns (see Chapter 3.8). This is compensated for by using a conservative approach to ignition outside the facility boundary (see Chapter 3.6.6).

There are no as well-recognised probits for exposure from hydrogen fires as there are for hydrocarbon fires. Hydrogen fires burn with lower IR radiation and are therefore considered to cause somewhat less harm to people than hydrocarbon fires with the same heat flux. For very small and pure hydrogen fires, it is known that the radiation can be so low that people can walk straight into the invisible flame without a warning from increasing radiation. For larger fires, impurities will often be drawn into the hydrogen flame, and it will both become visible and emit radiation more similar to a hydrocarbon fire. For fires with synthesis gas (mixture of hydrogen and hydrocarbons), the flames and radiation will be very similar to those of pure hydrocarbon fires.

In addition, the simulation tools, both empirical and CFD tools, have optimised their radiation algorithms for hydrocarbon fires and may be considered more uncertain when determining the intensity for hydrogen fires. In particular, the transition between an invisible flame with low radiation and a visible flame with higher radiation is uncertain.

It is therefore recommended that traditional hydrocarbon probits are also used for hydrogen fires. It is acceptable to use dedicated probits for hydrogen if these become widely available and used, but then the uncertainty in the radiation calculations from the simulation tools must also be included and discussed.

4.2.4 Explosions

4.2.4.1 General

The vulnerability criterion for explosions depend on many factors that cannot easily be summarised; effect of projectiles, collapse of buildings, broken windows, people thrown against hard surfaces, etc. These indirect effects of explosion can cause death at far lower pressures than those that cause direct death by lung collapse. Because local conditions regarding projectiles, collapse of buildings, hard surfaces, etc. vary greatly, it is extremely difficult to establish unambiguous probit functions and threshold values for death as a result of explosion pressure.

In a note published together with the guidelines on DSB's website (www.dsb.no), ref. /52/, the various consequences of explosions are discussed. This note concludes that, for the purpose of calculating risk contours for consideration zones, the most appropriate approach is to link fatality rate to the collapse of buildings. Threshold values associated with 50 % fatality as a result of the collapse of a building are therefore used as a basis for fatality rate from explosions.

4.2.4.2 Threshold values for explosions

When determining threshold values, in accordance with Chapter 4.2.1, the starting point shall be 50 % fatality in order to make the consideration zones as best estimate as possible. According to this, the threshold value is set equal to 50 % fatality as a result of the collapse of a building from ref. /52/.

The recommended threshold value for calculating risk contours is presented in Table 4.2.

Table 4.2 - Threshold values for fatality due to explosion (50 % fatality)

Duration of pressure waves	Threshold value for fatality due to explosion load
Used for all durations	40 kPa (0.4 barg)

4.2.5 Special substances

Special substances and mixtures can be challenging to model with standard consequence tools (both CFD and empirical tools).

In such cases, it is necessary to document how the special substance is modelled and how the associated uncertainty can be assessed (see also Chapter 3.11).

These substances must be evaluated specifically each time, but the following guidelines may be useful for estimating the risk associated with handling these substances:

- Assess the actual release and the mechanisms that occur during leakage, including droplet formation, phase transition, and sublimation. Assess which of the components of the release should be pursued further to assess fatality in the consideration zones. Vapour pressure can be used to assess the amount that evaporates.
- Components that are expected to cause fatality in the consideration zones can, if the tool that calculates consequences does not have these as standard, be approximated with known components with corresponding properties (vapour pressure, density, temperature, etc.). A good starting point may be to use a substance with similar properties, and adjust certain parameters as needed (LFL, UFL, flash point, etc.)
- If probits or threshold values cannot be obtained for the substances in question, fatality can be assumed to be approximately the same as a known substance that has an expected corresponding fatality.

5 Simplified methodology

For certain types of facilities, it may be appropriate to calculate safety distances based on a simplified methodology instead of relying on risk contours, see also Chapter 1.2 of the guidelines. More detailed guidelines must be developed before such a methodology can be used.

Table 5.1 shows facility units that are currently considered relevant for the use of a simplified model:

Table 5.1 - Facility units that are currently considered relevant for a simplified methodology

Type of facility	Design standard
LPG consumption facilities	NS-EN 12542 and NS-EN 14570
LNG/LBG consumption facilities	NS-EN 13645
LPG gas cylinder filling facilities	NS-EN 12542 and NS-EN 14570
LNG/LBG refuelling facilities for heavy-duty vehicles	NS-ISO-EN 16924
CNG/CBG refuelling facilities for heavy- and light-duty vehicles	NS-ISO-EN 16923
Fuel facilities with above-ground tanks for petrol and diesel	NS-EN 12285-2
Storage tank facilities for diesel and fuel oils as well as flammable liquid category 3	NS-EN 14015 or NS-EN 12285-2

Different types of facility units are defined in DSB's guidance on the registration, modification, and cessation of hazardous substances /53/. The guidance states that a facility unit can be an assembly of tanks, pipes, and equipment that constitute an entire facility or part of a facility. The list above is somewhat more detailed than in the guidance. In addition, reference is made to relevant standards for the facility types.

6 Presentation of results

6.1 Communication of small frequencies

It is recommended that all risk analyses try to give the reader a perspective on how the risk numbers should be understood and how the facility's calculated risk exposure compares to other risk exposures in society. One way of doing this is to relate the fatality rate in the areas surrounding a risk facility to the general fatality rate in society, see Figure 6-1. This figure shows that for the age group with the lowest fatality rate in Norway (5- to 10-year-olds), the average fatality rate is 1.0E-4 per year, which means that, on average, approximately one in 10 000 individuals in this group will die each year. Comparing this to the frequency requirement for the outer consideration zone (where the exposure probability for fatal effects is less than 1.0E-6 per year), this means that the facility represents an additional fatality of less than one percent for members of the public. For areas beyond consideration zones (fatality rate below 1.0E-7 per year), the facility will represent an additional fatality of less than one per thousand.

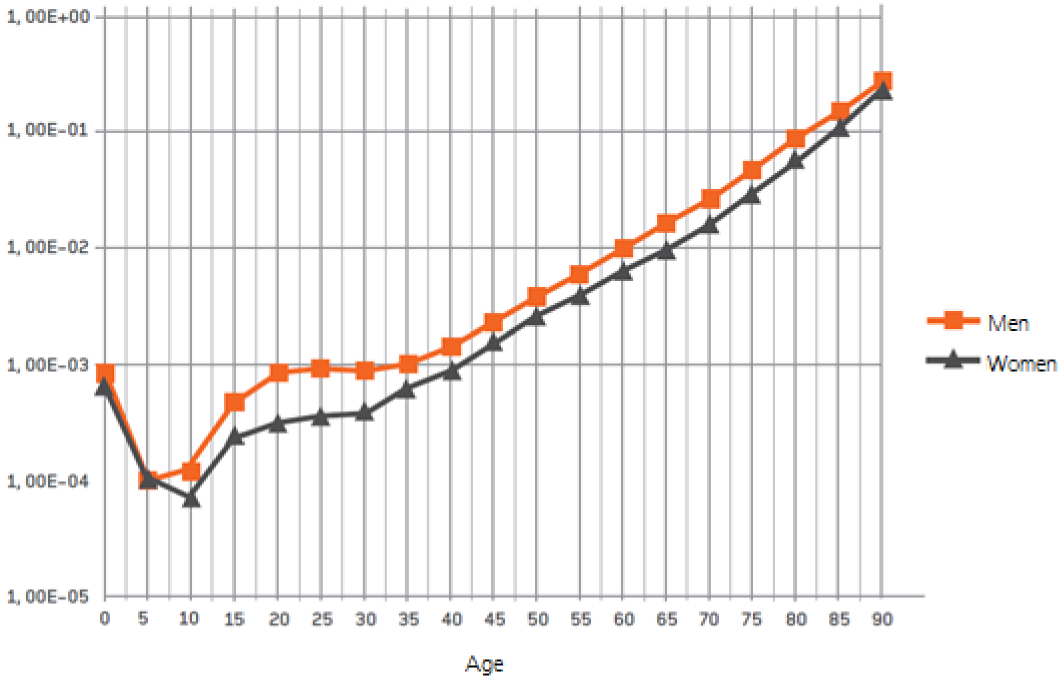

Figure 6-1 - Age-dependent probability of death in Norway, 5-year groups (2006-2010). The figure is taken from the guidance report (ref. /1/), while the values are from Statistics Norway

6.2 Results and intermediate results

All results and intermediate results that may contribute to the land-use planning must be presented. In addition, results and intermediate results that increase traceability and the ability to verify and quality assure the results must also be presented.

As a minimum, the following results and intermediate results must be presented:

- Frequency distribution of top events: presented both as frequency as a function of leak size and as frequency as a function of area (iso-contours are not required, but as a minimum, a table showing in which areas the leak points are located).
- Ignition probabilities: presented both as a function of leak size and area.
- Risk contours for total fatality.
- Examples of major events considered relevant in relation to external emergency preparedness considerations, see Chapter 7.

In addition, the following intermediate results are considered useful for communicating risk contributors and for emergency preparedness considerations (for example, in emergency preparedness planning, it may be of interest to know large areas are exposed to fatality from toxicity, thermal load, and explosion load separately and not just how large the total exposure to fatality is):

- risk contours for exposure to flammable or toxic substances
- risk contours for fire loads
- risk contours for explosion loads

For improved readability, the risk contours should be plotted on a map or photo with a specified scale. Figure 6-2 shows an example of risk contours plotted on a map, while Figure 6-3 shows the same risk contours plotted on an aerial photo. Figure 6-4 shows the same risk contours on a 3D map. All of these risk contours are plotted in the same coordinate systems as the maps, thereby eliminating uncertainty associated with manual drawing of calculated contours onto maps.

For plans to establish new facilities, the risk contours should be shown as plots in a copy of the current zoning plan (or the municipal plan map if the area is not regulated). This also applies to affected zoning plans in case of extensions or other significant changes to existing facilities.

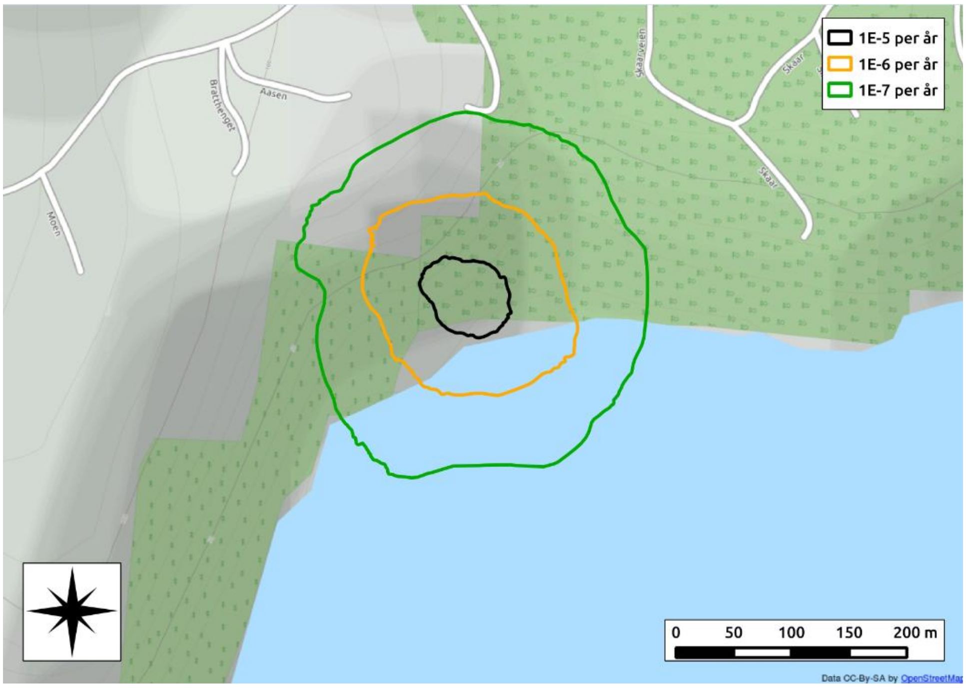

Figure 6-2 - Illustration of risk contours projected on a map (location randomly selected)

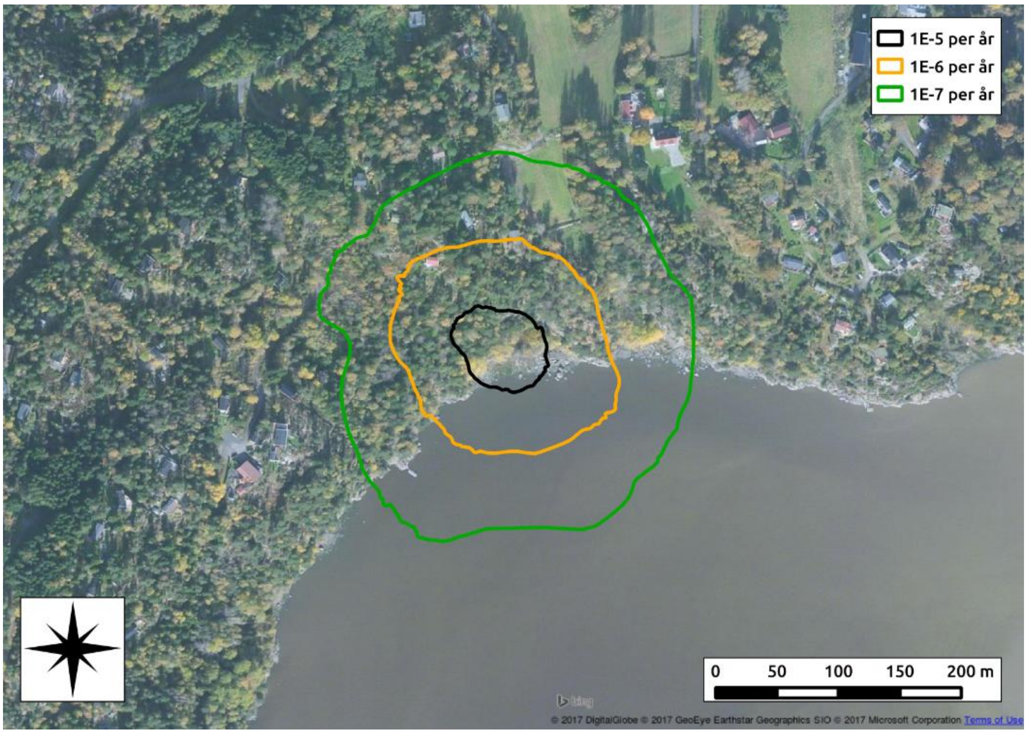

Figure 6-3 - Illustration of risk contours projected on an aerial image (location randomly selected)

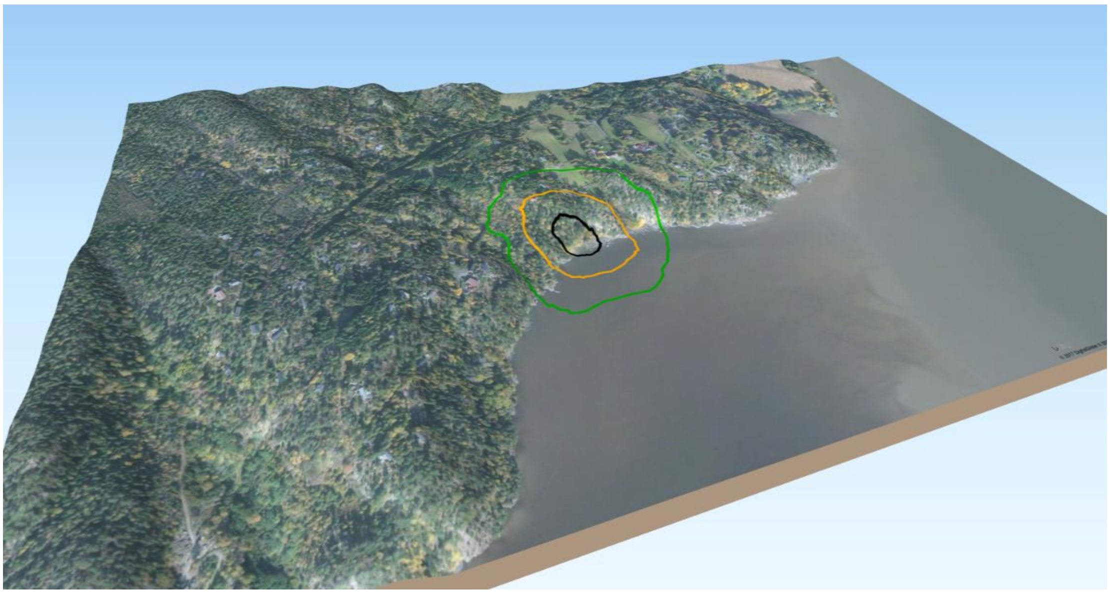

Figure 6-4 - Illustration of risk contours projected on a 3D map (location randomly selected)

6.3 How high above ground do the consideration zones apply?

Risk contours can be presented as a projected maximum contour or as contours that vary with height above ground. The projected contour is obtained by taking the highest (most severe) value at all heights (z values) for each position in the xy plane. In a projected representation, the information that the risk exposure is different for different heights above ground will not be included, but the advantage of this is that all heights can be conservatively presented in a single plot. The alternative to a projected representation is to plot risk contours for different heights. From Figure 6-5, it can be seen as an example that the exposure to flammable gas varies with height. If one wishes to highlight this effect, one can create risk contours for exposure for different heights above ground. If this is not important, one can project the highest value in the z direction down to ground level.

It is initially recommended to use projected risk contours for the use of consideration zones. This means that the same consideration zones are obtained for high-rise buildings as for detached houses. In some cases, there may be a higher risk slightly higher up than down at ground level (if the fatality is due to light gas), while in other cases, there may be a higher risk down at ground level (in the case of deadly heavy gas). The use of projected risk contours may make it easier to establish and use the consideration zones. If there is a large difference between the risk contours at ground level and high up, this should be discussed in the risk analysis, for example in the description of uncertainty (see Chapter 3.11).

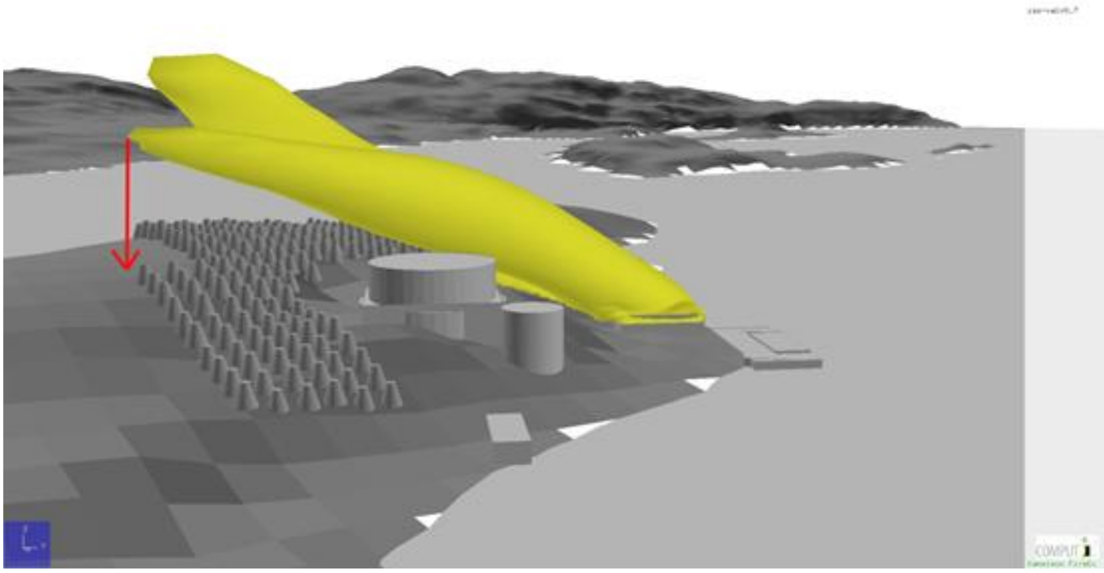

Figure 6-5 - Example showing that flammable gas exposure varies with height

6.4 Consideration zones and individual risk

The guidance report (ref. /1/) defines consideration zones for use in land-use planning, and it is therefore emphasised that the risk exposure within the consideration zones must be linked to the exposure to fatality associated with the specific coordinates, and not the individual people who may be in the consideration zones. This means that one cannot reduce the fatality in the consideration zones based on an assessment of how much time the people in the area actually spend there.

However, exposure time can be assessed if individual risk is calculated for a given group of people. This is not discussed further in this report.

7 Scenarios for emergency preparedness purposes

The risk contours do not show individual scenarios, only total societal risk exposure summed from all possible scenarios. There is also no requirement that scenarios for external emergency preparedness considerations should be linked to the criteria for acceptable risk, cf. the guidance report from DSB, ref. /1/. However, the risk analysis makes it possible to select emergency preparedness scenarios that correspond to calculated risk contours. The risk analyses must therefore, in addition to the consideration zones, present some representative scenarios that can be used for emergency preparedness considerations.

It is recommended to provide examples of scenarios for use in an emergency preparedness context that correspond to the risk contours below (all relevant types of accidents should be presented):

- Risk contour 1E-5 per year
- Risk contour 1E-6 per year
- Risk contour 1E-7 per year

Worst-case scenarios can be shown as plots for exposed areas in the worst possible event/consequence.

If there is a possibility of escalation after the emergency response organisation has been called, for example BLEVE and fire in ammonium nitrate, then these events should also be described.

8 References

/1/ "Sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer", DSB 2013, ISBN: 978-82-7768-310-2.

/2/ "Veileder om sikkerheten rundt storulykkevirksomheter", DSB 2019, ISBN 978-82-7768-420-8. HR-number 2357.

/3/ "Reference Manual Bevi Risk Assessment", National Institute of Public Health and the Environment (RIVM) in the Netherlands.

/4/ "Failure frequencies for major failures of high-pressure storage vessels at COMAH sites: A comparison of data used by HSE and the Netherlands", Clive Nussey, December 2006.

/5/ "Searching for the source of a house leak frequency", DNV-GL O&G Safety Blog, John Spouge, 11.08.2015.

/6/ "Failure rate and Event data for use within Land Use Planning Risk Assessments (HSE LUP Data Dossier HID C15)", 28/06/2012.

/7/ "Hose and Coupling Failure Rates and the Role of Human Error", M. Trainor, J. Gould and M. Anderson, Health and Safety Laboratory Report HSL/2000/09.

/8/ "Process release frequencies", IOGP report 434-1, 2019.

/9/ "Storage leak frequencies", IOGP report 434-03, 2022.

/10/ "Land transport accident statistics", IOGP report 434-9, 2010.

/11/ "Process leak for offshore installations frequency assessment model – PLOFAM(2)", Lloyds Register Consulting, Report No 107566/R1, December 6th, 2018.

/ 12/ Safetec: "Leak frequencies for land-based oil and gas facilities", Report No. ST-16529-1, Rev. 5.0, 14.02 2022.

/13/ Scandpower: "Risk Based Calculations of (Design) Explosion loads on Manned Buildings – Rafnes", Report No 80102017/R1, 23 September 2009.

/14/ LEAK FREQUENCIES FOR LAND-BASED OIL AND GAS FACILITIES, Safetec report no. ST-16529-1, Rev. 5.0, 14.02.2022.

/15/ HyRAM+, www.energy.sandia.gov, 2025 National Technology and Engineering Solutions of Sandia, LLC.

/16/ Fossan, I., van Wingerden, K., Knudsen, Ø., Wiklund, J. & Gaathaug, A.V. (2024): "The SAFEN ignition probability model for hydrogen", 15th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, Naples, Italy – June 10-14, 2024

/17/ LNG Hose Failure Probability, Shell Global Solutions (US) Inc., Houston, SR.14.11417 (2014).

/18/ Oracle Analytics Interactive Dashboards - Hazmat Incident Report Search.

/19/ DNV: "Recommended failure rates for pipelines", Report No.: 2025-0947, Rev. 1, 2025-12-04 .

/20/ "Vapour Cloud Development in Over-filling Incidents ", FABIG Technical Note TN 12.

/21/ "LNG Source Term Models for Hazard Analyses", Health and Safety Laboratories, 2010.

/22/ J. L. Woodward and R. M. Pitblado: "LNG Risk Based Safety Modeling and Analysis", AIChE and John Wiley, 2010.

/23/ Scandpower: "Comparative study on gas dispersion", Report No. 101368/R1, 24 January 2012.

/24/ IOGP Risk Assessment Data Directory: "Ignition Probabilities", Report No. 434-06, September 2019.

/25/ UKOOA/HSE: "IP Research Report. Ignition Probability Review, Model Development and Look-Up Correlations", January 2006.

/26/ Lloyds Register Consulting: "Modelling of ignition sources on offshore oil and gas facilities", Report No. 106364, 2016.

/27/ Safetec: "Modelling of ignition sources on land-based oil and gas facilities", Report No. ST-16542-1, Rev. 7.0, 22.12 2022.

/28/ HyRAM: A methodology and toolkit for quantitative risk assessment of hydrogen systems, Elsevier International journal of hydrogen energy, vol 42, pages 7485-7493 (2017).

/29/ Concept risk assessment of a hydrogen driven high speed passenger ferry, Elsevier International journal of hydrogen energy, vol 45, pages 1359-1372 (2020).

/30/ GKP7H2 high speed passenger ferry concept risk assessment, Lloyd's Register Consulting report for MoZEES project, LR report 106575/R1, April 2018.

/31/ LIQUID HYDROGEN SAFETY: Data Report: Closed room and ventilation mast studies, Forsvarets forskningsinstitutt (FFI) Norwegian Defence Research Establishment, DNV-GL Draft report, May 2020.

/32/ "NORSOK Z-013, vedlegg F".

/33/ Gary A. Fitzgerald, “A Comparison of Simple Vapour Cloud Explosion Prediction Methodologies”, Second Annual Symposium, Mary Kay O’Connor Process Safety Centre, Texas, October 30-31, 2001.

/34/ "Obstructed Region Explosion Model", PHAST Theory, Rev. 2, 2015.

/35/ "GAMES final report", W.P.M. Mercx, A.C. van den Berg, D. van Leeuwen, TNO Report PML, 1998-C53.

/36/ “Buncefield: Why did it happen?”, COMAH Control of Major Accident Hazards, 2011.

/37/ "NORSOK S-001":2018.

/38/ "Design Guidance for Hydrocarbon Fires, Fire and Blast Information Group (FABIG) Technical Note 13".

/39/ "Handbook of Fire Protection Engineering", SFPA/NFPA, 2016.

/40/ FABIG: “Fire Loading and Structural Response”, Technical note 11, 2010.

/41/ TNO: "Methods for Calculation of Physical Effects (TNO "Yellow Book")", CPR 14E.

/42/ TNO: "Guidelines for Quantitative Risk Assessments (TNO "Purple Book")", CPR 18E.

/43/ Frank P. Lees: "Loss Prevention in the Process Industries", 4th Edition, Elsevier 2016.

/44/ D.A. Lihou and J.K Maud:”Thermal Radiation form Fireballs”, I. Chem. Eng Symposium Series No. 71, The Institute of Chemical Engineers, 1982.

/45/ Xie Mengmeng: "Thermodynamic and gas dynamic aspects of a BLEVE", Delft University of Technology, Report 04-200708, 2007.

/46/ Johnson, D.W., and Woodward, J.L., “A model with data to predict aerosol rainout in accidental releases”, Centre for Chemical Process Safety (CCPS), New York (1999).

/47/ "Rollover in LNG storage tanks", Summary Report by The International Group of LNG Importers (GIIGNL), 2012-2015.

/48/ A. Buang: "Boilover in liquid hydrocardon fires", Ph.D Thesis Loughborough University, 2014.

/49/ Method for derivation of probitfunctions for acute inhalation toxicity, RIVM Report 2015-0102.

/50/ Probit function status overview | RIVM (https://www.rivm.nl/en).

/51/ TNO: “Methods for the determination of possible damage (TNO “Green Book”), CPR 16E.

/52/ Vysus Group: «Bakgrunn for terskelverdi for eksplosjon – rev.1», Notat no. PRJ11100262033, 30 June 2021.

/53/ https://www.dsb.no/farlige-stoffer/farlige-stoffer/veiledning/veiledning-til-innmelding-endring-og-opphor-av-farlig-stoff/

Appendix A - Early-phase mapping of the facility and guidewords for use in HAZID reviews

1 Tables for use in initial mapping of the facility

1.0	Purpose of the analysis	References
	Registration of new building, new establishment	
	Registration of changes to existing facility	
	Review of accident in facility or in neighbouring facility	
	Update of existing analysis and/or safety report, ref. Major Accident Regulations (Storulykkeforskriften) § 9	
	Changes in land use planning, the facility itself or neighbouring facility, the municipality	
	Special requirements from authorities	
	Other	

2.0	What kind of hazardous substances does the facility handle	References
	Pressurised substances	
	Flammable gas	
	Oxidising gas	
	Toxic gas	
	Flammable aerosol container	
	Water vapour or hot water under pressure	
	Flammable substance	
	Flammable liquid	
	Diesel and fuel oil	
	Heated liquid, heated to a temperature equal to or higher than the flash point	
	Flammable solid	
	Substance that develops flammable gas in contact with water	
	Self-igniting liquid	
	Self-igniting solid	
	Self-heating substance	
	Oxidising solid	
	Oxidising liquid	
	Self-reactive substance	
	Organic peroxide type	
	Reactive substance	
	Substance that develops toxic gas	
	Refrigerated toxic gas	
	Other	

3.0	Available documentation, degree of accuracy	References
	Plot plans or situation maps	
	Process description (block diagram)	
	Detailed piping and instrumentation diagram (P&ID), mass balance	
	Risk analysis	
	Nonconformities, report from supervision, best practice, experience transfer from the industry etc.	
	Other	

4.0	**Stored quantities of hazardous substance**	**References**
	Notifiable in accordance with Hazardous Substance Regulations (Forskrift om håndtering av farlig stoff)	
	Major Accident Regulations (Storulykkeforskriften) § 6, § 9	
	Other	

5.0	**Handling of hazardous substances**	**References**
	Loading/unloading via fixed pipes/hoses/loading arm	
	Loading/unloading from/to tanker/train/boat/car	
	Storage in atmospheric tanks/pressure vessels	
	Manufacturing/processing	
	Treatment/storage/temporary storage	
	Internal transport	
	Mixing/decanting/transfer	
	Emissions to ground, water, air	
	Other	

6.0	**Surroundings - Where is the facility located**	**References**
	Densely built-up area, city/village, area with/without harbour	
	Open landscape, scattered settlements with/without harbour	
	Hilly landscape, scattered settlements with/without harbour	
	Neighbours?	
	Particularly vulnerable objects: school, kindergarten, hospital, nursing home, community centre, sports facility	
	Hotel, accommodation, business, restaurants	
	External emergency preparedness, emergency services	
	Will unintentional/uncontrolled events that may occur in nearby facilities (industrial enterprises, etc.) pose a risk to the facility (domino effect)? - Are there potential sabotage/terror targets nearby?	
	Other	

7.0	**Infrastructure near the facility**	**References**
	Busy roads; private roads, county roads, highway etc.	
	Bus, train, tram, rail, ferry, airplane	
	Hiking trails, pedestrian and cycle paths	
	Power supply	
	Other	

8.0	**Natural conditions close to the facility**	**References**
	Vegetation; forest, avenue, dense forest, shrub	
	Are there terrain formations like steep cliffs, high mountain walls etc.	
	Exposed to floods, high tide, forest fires	
	Weather data available?	
	Other	

9.0	Emergency preparedness	References
	Does the loss of access to the following services cause inconvenience to the facility? - electricity, telecommunications services, water supply	
	Water supply? Does the area have an insufficient fire water supply (quantity and pressure)?	
	Access to external firefighters, response time, etc. Arrival route for fire truck?	
	Automatic fire extinguishing outside/inside, deluge system, water cannon, foam system, water curtain etc.	
	Fire alarm, gas alarm	
	Illegal sabotage and terrorist acts: is the facility itself a sabotage/terror target?	
	Industrial safety – basic requirements/enhanced	
	Other	

2 Guidewords for use in HAZID review

Table 2.1 Example of guidewords for use in HAZID

Category	Guideword
Loss of containment - leaks/spill or cross-contamination. Failure of process vessels (atmospheric and pressurised). Leak or rupture in heat exchanger pipes. Failure of process pipes.	• Hazardous chemicals (including hydrocarbons) • Other chemical hazards • Explosives • Unexpected reactions • Incompatible materials • Thermal uncontrolled reaction (runaway) • Air inlet • Corrosion • Erosion • Embrittlement (chemicals, low temperature) • External impact • Fatigue • Abnormal vibration • Mechanical impact • Overloading
High/low pressure High/low temperature	• Hot process/superheat • Steam • Condensate • Cold processes/cryogens • Thermal combustion • Safety valves • Flares
Buildings	The effect of external hazards
Escalation	• BLEVE • Roll-over • Boil-over • Consequence of other events

Category	Guideword
	• Fire and gas detection, fire extinguishing equipment, water curtains etc. • Evacuation routes
Transportation	• Events with rail/railroad carriage • Dock/marine events • Vehicle traffic events • Tanker trucks
Mobile equipment	• Heavy machinery • Light-weight vehicles
Lifting equipment	• Falling/swinging load • Collapse of lifting equipment, cranes etc. • Rig failure
Security	• Terrorism • Arson • Sabotage • Civil unrest • Hacking • Burglary
Operation	• Simultaneous operations • Change of personnel • Hired personnel/temporary staff • Start/stop, maintenance and inspection • Emergency stop
Marine vessels	• Ship collision with dock • Loading/unloading • Emissions
Fabrication and installation	• Complexity • Modularisation • Transportation • Overseas production
Special mechanical or electrical items	• Excessive vibration • Rotating equipment (e.g. compressor failure) • Strong magnetic fields • Noise • Stored energy • Electric shock • High voltage/low voltage, electrical hazards • Static electrical hazards • Ionizing radiation • EX zones/equipment
Structural errors	• Earthquake • Foundation (subsidence, scour) • Corrosion

Category	Guideword
	• Fatigue • Weight control • Primary structure • Secondary constructions • Temporary constructions
Failure of auxiliary systems	• Cooling water • Fire in cooling tower • Cooling • Power • Steam • Air • Inert gases • Heating, ventilation and air conditioning system • Communication system • Fire extinguishing system • Internet • Wastewater removal/treatment • Vacuum • Clogged bunding

Nature and environment	• Seismic activity
	• Weather:
	  ○ Strong wind
	  ○ Flooding
	  ○ Extreme cold or heat
	  ○ High or low humidity, fog
	  ○ Earthquake/tsunami
	  ○ Hurricane/tornado
	  ○ Lightning
	• Impact on equipment from marine environment
	• Subsidence/unstable terrain/soil and avalanches
	• Geological conditions for structural support

Organisation	• Procedures • Responsibility and authority • Culture and behavioural understanding • Training, competence • Planning • Communication • Emergency preparedness • Industrial safety • Officer on duty

Appendix B – Establishing risk curves

Table of contents

1 Introduction

This appendix is part of "Guidelines for quantitative risk analysis of facilities handling hazardous substances" and describes good principles for establishing best estimate risk contours.

2 Effect of number of scenarios

A risk analysis should be set up so that the risk contours represent a good estimate of "all" things that can happen – along with their probability (frequency). This means that regardless of what actually happens at a facility, the risk analysis should have considered a corresponding scenario.

In reality, there is an infinite number of different scenarios (end events) that can occur at a facility, and in practice the sample space for the top events must be discretised (ref. Chapter 3.2) such that an adequate number of variations of these top events are considered. This must be done by selecting a finite number of leak points, leak rates, leak directions, wind directions, and wind speeds. In addition, a limited number of ignition times and ignition points must be selected since all variations of this will have different consequences. This may lead to a very large number of different scenarios. As an example, assuming 100 leak points, 10 leak rates, 6 leak directions, 12 wind directions, 10 wind speeds, 10 ignition times, and 5 ignition points for each time, one will end up with 36 million scenarios, and it will therefore be necessary to distinguish between simulated and assessed scenarios.

By using symmetry considerations and simplified physical modifications to scenarios already simulated, one can significantly reduce the number of scenarios that actually need to be simulated. It is thus possible to assess a large number of scenarios based on a significantly reduced number of simulated scenarios.

If symmetry considerations are made to reduce the number of simulated scenarios, it is important to simultaneously assess the veracity of the physics in the scenarios, according to the principles discussed in Chapter 3.5.2 in the main report. It is thus possible to simulate some of the scenarios with empirical tools and others with CFD tools, depending on how much of the physics in the scenarios it is necessary to capture (and thus be able to calculate representative risk contours).

Even if the leak frequency distribution can be considered representative for the facility (see Chapter 3.4.2 in the main report) and the simulated scenarios have been performed with the correct simulation tool in accordance with the guidelines in Chapter 3.5.2 in the main report, it is still crucial that a sufficient number of events are considered such that the sample space is spanned with sufficient accuracy. This is necessary in order for the risk contours to be representative for the given facility and its surroundings. A risk analysis must therefore discuss whether the number of scenarios assessed is sufficient and to what extent the number affects the calculated risk contours.

A risk contour (e.g. a 10^{-7} contour) will have a high level of uncertainty if it is based on too few scenarios. One does not know whether this risk contour is conservative or non-conservative unless one knows whether the simulated scenarios are more or less severe than those surrounding the "actual" risk contour. The deviation between the calculated risk contour and the "actual" risk contour decreases with an increasing number of scenarios evaluated, see Figure 2-1. Note that even if one simulates many scenarios such that in practice "all possible" events are simulated, the uncertainty related to the frequency picture (how likely the different events are) does not disappear.

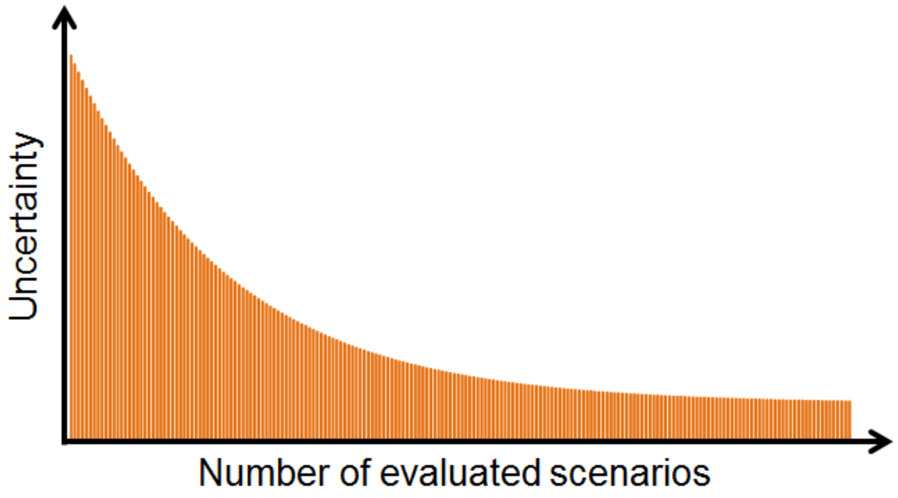

Figure 2-1 - Uncertainty as a function of the number of evaluated scenarios – illustration

The number of scenarios that must be considered in order to establish sufficiently accurate risk contours will vary for different facilities, depending on size and complexity. Similarly, the number of calculations required for the different consequence assessments (fire, dispersion, explosion) will also vary.

For example, in the top event of a fire in a bund, there will be no need to vary the number of release locations or use many large leak rates, and when using an empirical tool, it may be sufficient to use a few different wind speeds to span the sample space for the top event. When using CFD, however, there may be a greater need for, for example, assessing different wind directions.

For assessments of the top event of a gas explosion, there will normally be a need for a larger number of calculations, with different release rates, release directions, wind speeds and directions, and ignition locations and times. Because it is unrealistic to consider so many scenarios in detail, it may be necessary to minimise the effort on scenarios and scenario variations with little impact on risk. Examples of simplifications:

- For leak rates that do not produce cloud sizes that can generate significant explosion overpressure, there is no need to evaluate a range of wind directions and wind strengths. All of these scenarios can be represented by the calculation for calm wind.
- It may be necessary to simplify the analyses by decoupling the dispersion and explosion studies so that the dispersion study with subsequent transient ignition assessment provides the frequency of ignited cloud sizes (equivalent stoichiometric cloud methodology) and the explosion study provides explosion loads as a function of ignited cloud size.
- Let certain wind directions represent scenarios for wind directions that can be expected to provide similar flow fields within the area.

In this way, a case with a large number of scenarios can be reduced to a manageable amount, while at the same time it will be possible to simulate additional scenarios with the leak rates that contribute most to risk contours.

A risk analysis must analyse a sufficient number of possible scenarios for the results to be adequate. This means that the risk analysis must span a sufficient portion of the sample space for the risk contours to be representative for the analysed facility. Important factors that affect risk contours are highlighted below. Methods for processing the risk contours are also described.

3 Effect of number of directions

The number of directions considered, both leak directions and wind directions for a given leak point, has an impact on the location of the risk contours. This can be illustrated by the following idealised example of variation in leak direction (where wind conditions are idealised to always be calm):

If all possible leaks are sorted by leak size, one will be able to identify the leak rate for a given frequency, for example 10^{-7} per year (or less). If one simulates such a critical leak size (m_{kr}), one will get a result field with a given critical length and width of flammable (or toxic) concentration, see Figure 3-1.

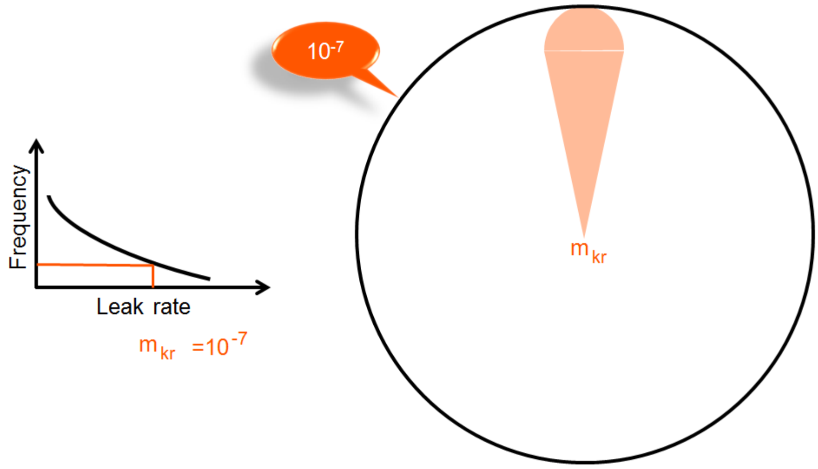

Figure 3-1 - Risk contour from drawing a circle around a single scenario with critical leak rate (m_{kr}). The figure indicates that all points within the circle have the same exposure frequency (> 10^{-7} per year)

The critical leak rate can occur in several leak directions, and the frequency can therefore be distributed between each of these directions. If the critical rate, for example, is divided into 10 directions and the frequency is assumed distributed between these in equal direction intervals, each of these will represent 1/10 of the original frequency, i.e. 10^{-8} per year. If one now draws a risk contour by drawing a circle around the tips of these scenarios, one will get a different result. The scenarios have the same length and width as before, but they have a frequency that is 1/10 of the scenario that represented all 10 directions in one direction. The same risk contour that in Figure 3-1 represented an estimate of 10^{-7} will now represent an estimate of 10^{-8}, see Figure 3-2.

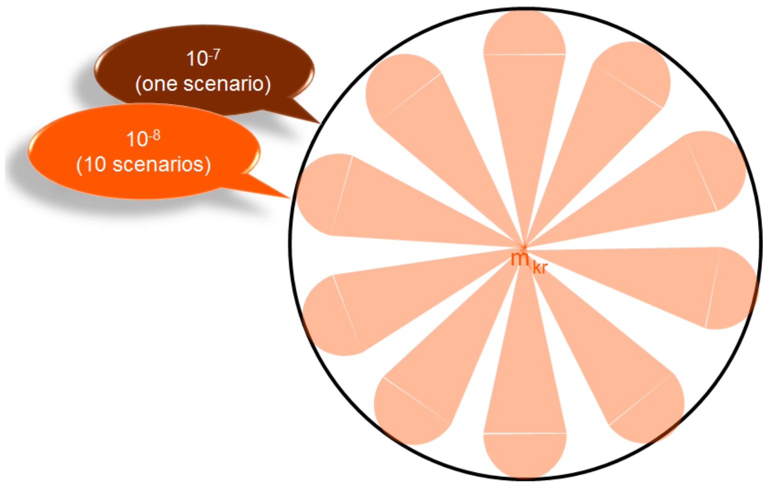

Figure 3-2 - Risk contours from distributing critical rate in 10 equal directions. The figure indicates that all points within the circle have the same exposure frequency (>10^{-8} per year)

If one continues to distribute the critical scenario in even more directions, one will get an even lower frequency per scenario, but eventually the number of directions will become so large that the scenarios begin to overlap. Then one begins to see a convergence in the risk contour. This can be illustrated by an example where 15 directions just overlap, and one assumes that each of these has a frequency of 10^{-7} per year. This means that within the tangent curve, one will have an exposure of 10^{-7} at each point, and the tangent curve represents a 10^{-7} curve.

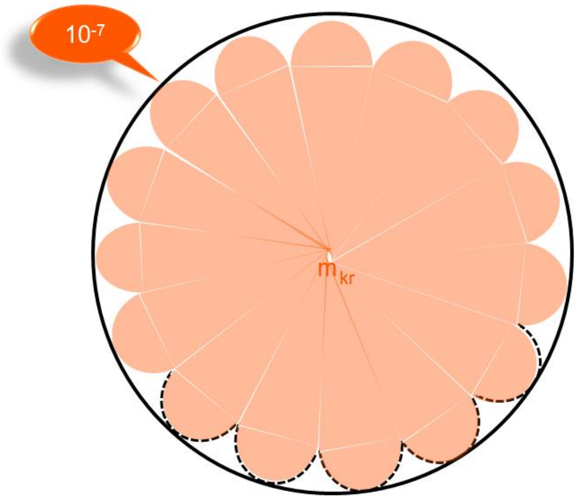

Figure 3-3 - Risk contour with frequency 10^{-7} estimated with a total of 15 different leak directions. Note that the isocontour is often defined as the edge along the scenarios (dashed line), but in this example illustrating the effect of considering multiple directions, the isocontour is defined as the circle that touches the extreme points of the scenarios

If one now doubles the number of assessed directions (to 30), the frequency for each of the scenarios will be halved, but they will start to overlap so that most of the field will still get an accumulated frequency of 10^{-7} per year in "all points". At the very edge of the field, it can be seen that the overlapping tips will have a slightly shorter extent than the non-overlapping tips, see Figure 3-4, but the difference is significantly smaller than what we saw earlier (Figure 3-2) where there were no overlapping scenarios. We now see that we have distributed the critical rate over enough directions for the isocurve to begin to converge.

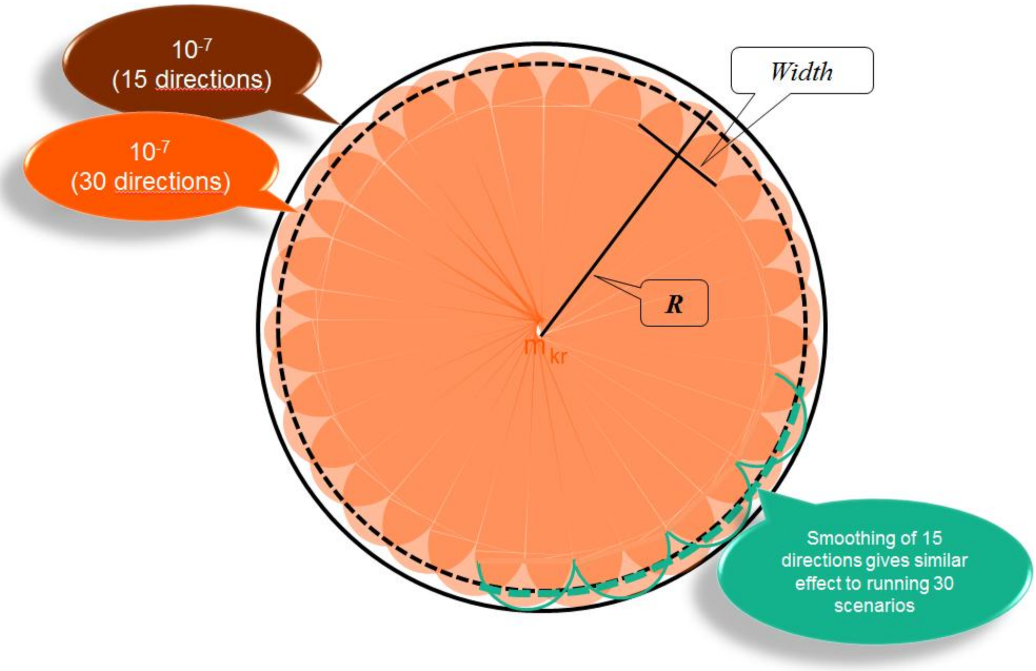

Figure 3-4 - Risk contour with frequency 10^{-7} estimated with a total of 30 different leak directions

Figure 3-4 shows that sufficient scenarios have been simulated when the number of necessary directions is proportional to Width/2πR.

A risk contour that is averaged or smoothed will be more representative than if the outermost "bumps" in a jagged contour are used.

In a real risk analysis, it will be possible to vary several factors (leak direction, wind direction) so that they smooth the field. In such cases, it will be the smoothness of the field, as well as interaction with dominant buildings or terrain, which indicates whether enough scenarios have been run.

From the figures above, it can also be concluded that using few scenarios may result in larger risk contours than using more scenarios.

4 Interpolation of simulated scenarios

If a number of scenarios have been simulated to capture the physics that is considered to be significant for the sample space of a top event, the consequences of scenarios that are relatively similar to those simulated can be estimated by using symmetry, rotation, and interpolation. The frequency must then be distributed across the total number of evaluated scenarios. Rotation can be used, for example, when it is expected that a small change in wind direction will give the same hazard distance, but in a slightly different direction. In such cases, the simulated result field can be rotated around the release point to evaluate an almost identical scenario, see Figure 4-1. The uncertainty of rotation increases the more you rotate, but some types of scenarios can be rotated considerably and still be considered to be the best estimate. An example of a scenario that can be rotated a lot and still be considered as the best estimate is evaporation from a bund located in a flat area without significant obstructions. Conversely, one could say that a scenario with a high-velocity release in an area where both wind and the jet's momentum are influenced by objects (buildings, terrain, etc.) cannot be rotated much before the physics becomes very different.

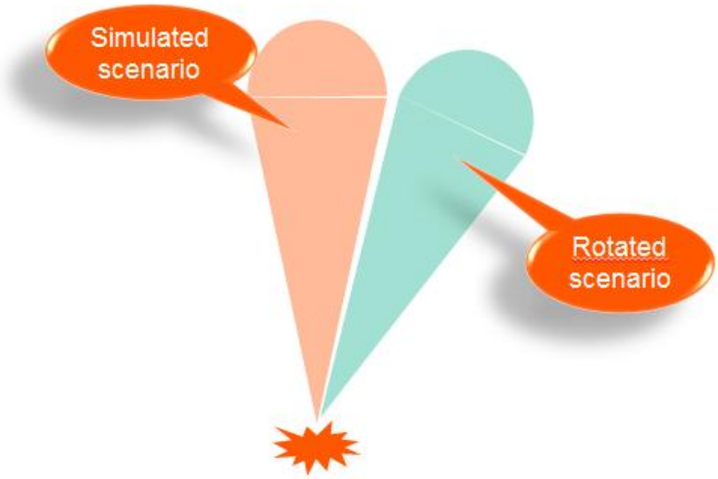

Figure 4-1 - Rotation of a simulated scenario to evaluate a similar scenario

Interpolation is another method that can be used to evaluate scenarios with slightly different leak rates or wind speeds than those simulated. In a “frozen cloud” type interpolation, the concentration in each control volume can be adjusted to evaluate what a scenario with a slightly different release rate might look like. For example, if the gas concentration in all control volumes in the result field is doubled, this may represent a release that is twice as large (double the mass rate) as the simulated one. The methodology is inaccurate and must be used with caution; it is not recommended to use this interpolation methodology for rates more than double or less than half of the simulated one.

Common to all types of interpolations and rotations is that one should not use this to evaluate scenarios that are very different from those simulated.

5 Number of leak locations

A leak can in principle occur at many locations in a process plant. In the risk analysis, a finite number of scenarios must be selected, and thus also a finite number of leak points, to model "everything" that can happen in an area. The number of leak points selected may affect where the calculated risk contours lie. However, the error made by selecting too few leak points can be estimated to be at most in the order of magnitude equal to the dimension of the process area, see Figure 5-1 (where the process area is marked with a black square).

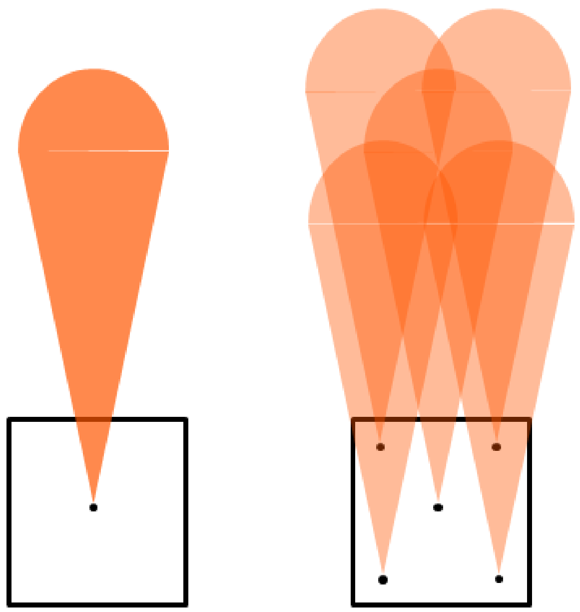

Figure 5-1 - The effect of selecting a leak point relative to 5 leak points in an area

6 Number of simulated leak rates

If the division of simulated rates is too coarse, the rates representing critical modelled leak (e.g. 10^{-7} frequency) could be either slightly too small or slightly too large in relation to the rates representing the actual critical rate. The risk contours will thus have a corresponding error in the frequency of the calculated risk contours. The error of these frequencies will, however, be limited to the difference in frequency of the rate representing the actual critical rate and the rate representing the calculated risk rate. This error is limited by the frequency difference between the simulated rate that is above and below the real critical rate, see Figure 6-1.

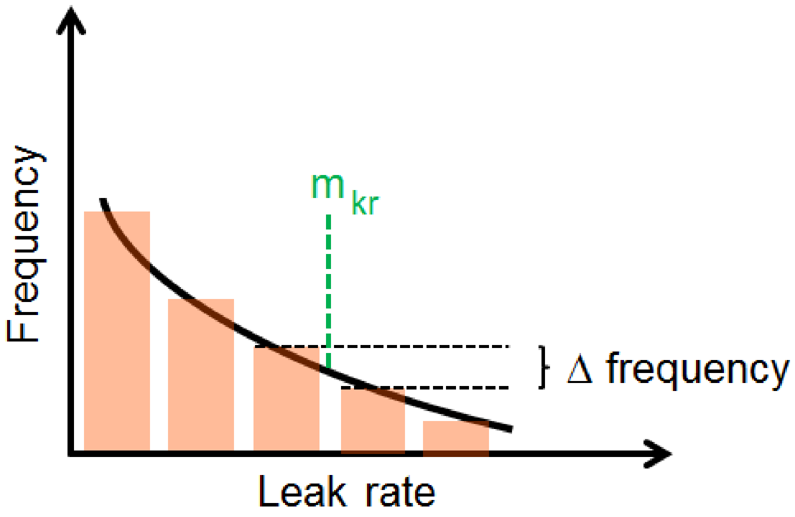

Figure 6-1 - Estimated error in isocontours is proportional to the difference in frequency between rates that are above and below the critical rate (requires that the critical rate is known before the error can be assessed). Simulated rates are marked in orange

7 Smoothing of the risk contours

If a calculated risk contour is jagged, without this being explained by specific conditions related to the facility, this is probably because the contours are based on too few scenarios. From Figure 3-4 it can be seen that smoothing of the contours must be assumed to make these a better estimate, and it is therefore recommended to smooth curves that are jagged without this being related to the facility.

Smoothing of a jagged contour has a similar effect on the result field as running multiple scenarios with slightly different input parameters. Figure 7-1 illustrates this by distributing the frequency of a scenario over 3 different scenarios with slightly different leak rates. This is compared with the effect of smoothing the single scenario using a normally distributed smoothing function. Note that the shape of the smoothed curve (green curve) is determined by the chosen standard deviation in the normally distributed smoothing function (Gaussian). The shape of the orange smoothing is determined by how much the parameters that determine the scenarios are varied.

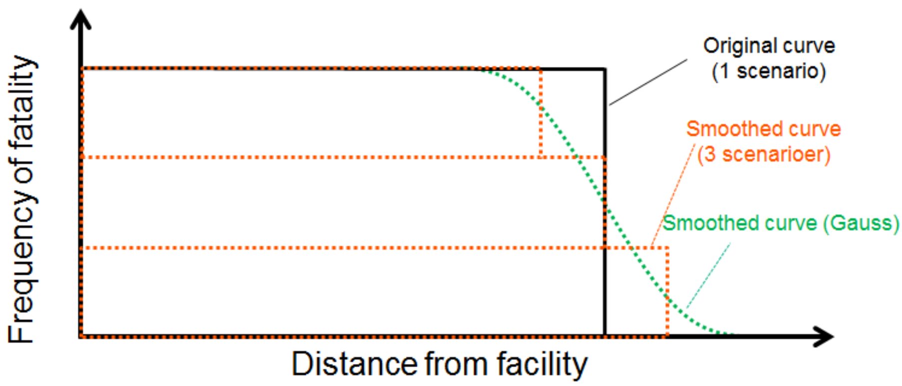

Figure 7-1 - Illustration showing that if one runs only a single scenario that represents all frequency of fatality (where fatality is determined by the threshold value, see Chapter 4.2.1 in the main report), then the frequency field can be smoothed either by running more scenarios (the orange curve shows the same frequency distributed over 3 slightly different scenarios) or by using a normally distributed smoothing function (Gaussian smoothing, see green curve)

Figure 7-2 shows a risk contour that is smoothed using a normally distributed smoothing function (Gaussian distribution with standard deviation 1.0). Such a smoothing function smooths the frequency field by adjusting each point based on the value of the surrounding points in all directions with a weighting according to the normal distribution based on the distance to the evaluated point. The standard deviation determines the weighting for each point in the adjustment as a function of the distance from the point being smoothed. The smoothed curve (green curve) follows the main trends of the risk contour but smooths out the small irregularities. Note that, even if such a smoothing will make the risk contours a better estimate in cases where the small irregularities (jags) cannot be linked to conditions at the analysed facility, such smoothing will also result in it moving frequency from the high frequency values towards the lower values (in practice, frequency is moved from the facility itself outwards in all directions), see Figure 7-3. A Gaussian smoothing with standard deviation between 1.0 and 4.0 is considered acceptable for removing small irregularities (tags).

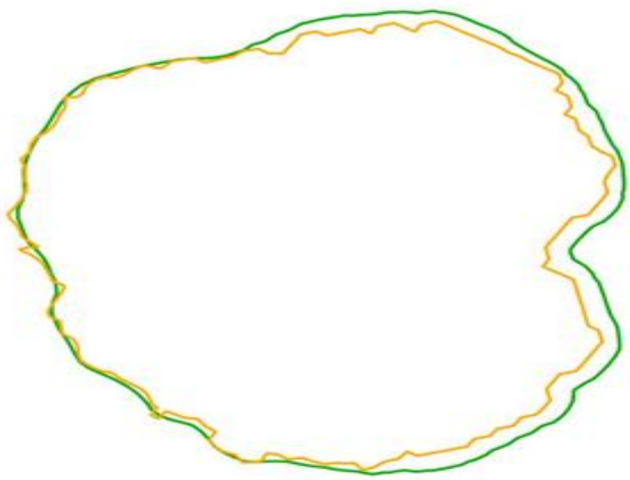

Figure 7-2 - Example of a risk contour (orange) that has been smoothed by a normally distributed (Gaussian) smoothing with standard deviation = 1.0 (green curve)

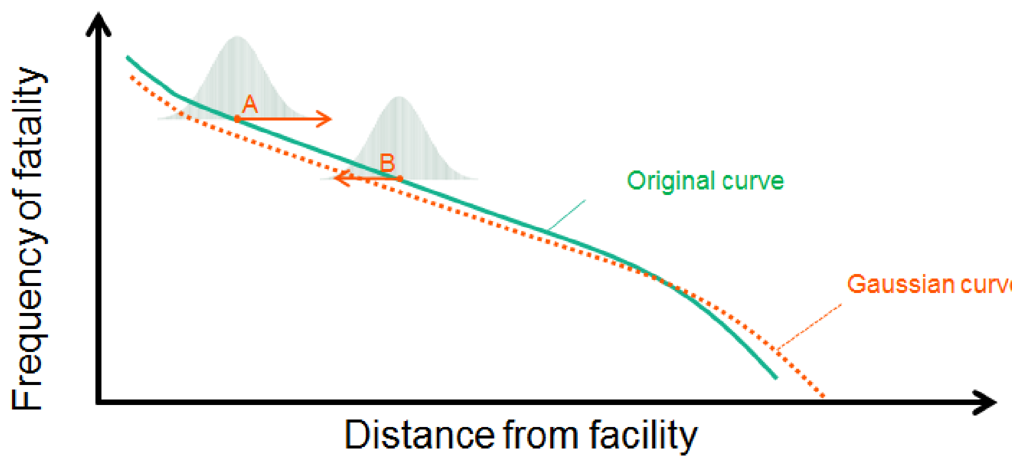

Figure 7-3 - Illustration showing that a smoothing function will move frequency from higher frequency values to lower frequency values. When frequency is moved through the normal distribution, more scenarios will move towards lower values (A) than to higher values (B) - simply because point A has a higher frequency

Also note that in real releases the wind conditions will usually be dynamic (constantly changing). This will affect how the release spreads and where flammable and toxic concentrations will occur. Dynamic wind conditions ("meandering") will normally not be used in the dispersion calculations performed in a risk analysis, even though this is partly included in the calibration of the simulation tools, and especially in the calibration of empirical tools. A smoothing of the result field could also be said to represent the same effects that would be achieved by using dynamic wind fields in the simulations.

8 Refining risk contours in critical areas

Risk contours can be more detailed in certain areas of particular interest. Through a refinement, the purpose is for the contours to become a better estimate in a given area, for example, an area where conflicts of interest are expected.

A risk contour can be refined in an area without affecting other areas by running additional simulations only where the scenarios expose the area one wishes to refine (target area).

To assess whether a sufficient number of additional simulations have been run in the target area, reference is made to the principles discussed in Chapter 3.10 of the main report.

9 Summary – risk contours

In order for the risk contours to be best estimate, the analysis must span a sufficient part of the sample space for the top events. The following three steps are recommended as a robust way to achieve best estimate risk contours:

- First, a sufficient number of simulations/calculations are run to capture the main physics in all relevant scenarios. This must be done with a number of individual scenarios, and it must be done with modelling tools that are capable of capturing relevant physics in the scenarios, see Chapter 3.5.2 in the main report.
- If the risk contours clearly indicate that too few scenarios have been simulated (typically because the contours are jagged, with "lumps" associated with individual scenario simulations), the simulated scenarios can be used to estimate scenarios that are considered to be sufficiently similar to those already simulated. Here, the concentration field will typically be rotated or manipulated to estimate similar scenarios to those simulated. Such interpolation/extrapolation will lose some of the physics in the simulated scenarios (for example, flow around large objects will not be captured correctly), but it will have the effect of smoothing the frequency of multiple events.
- If the risk contours still have small irregularities after the interpolation/extrapolation has been performed, the result field can be smoothed (e.g. with a Gaussian smoothing as shown in Figure 7-2). Such smoothing will not directly preserve the physics, but only represents a smoothing of the result field. Smoothing out small irregularities in the result field (which are not associated with conditions related to the facility) will make the risk contours a better estimate, see Figure 3-4.

An example of the process above is shown in Figure 9-1. The orange risk contour represents a given frequency based only on the CFD simulations of flammable gas. From the tags on the contour, it can be seen that too few wind directions have been simulated (12 directions are simulated – and you can count 12 tags on the curve). In the green curve, each CFD simulation is used to evaluate 3 additional scenarios with wind direction close to the simulated ones by rotating the simulated scenario around the leak point. The leak frequency of the simulated scenario is distributed over the 4 representative scenarios considered. Thus, a new risk contour can be created based on 48 directions instead of 12. The green risk curve represents the interpolated results. The green curve is smoother, and hence must be considered a better estimate than the orange curve. The black curve is obtained by smoothing the green curve (the smoothing is performed using a Gaussian smoothing with standard deviation 2.0). Note that it is not the green curve that is smoothed directly, but the entire 3D frequency field. However, when the entire 3D frequency field is smoothed, the isocontours for a given frequency move accordingly. The smoothed curve is expected to be a better estimate than both the orange curve (12 directions without smoothing) and the green curve (48 directions without smoothing).

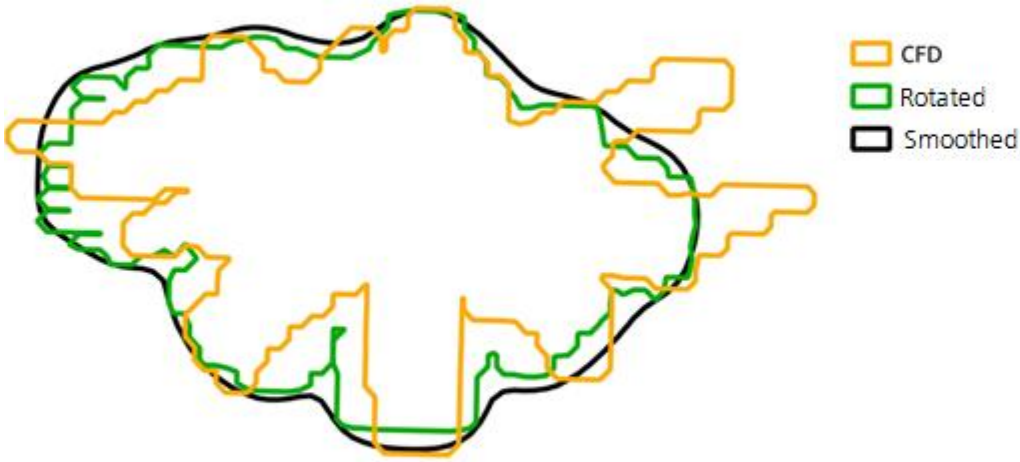

Figure 9-1 - Example of simulated (CFD), evaluated (rotated) and smoothed risk contours