Guidelines for quantitative risk analysis of facilities handling hazardous substances

Revised edition

Report for:
The Norwegian Directorate for Civil Protection (DSB)

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Summary

Guidelines for quantitative risk analysis of facilities handling hazardous substances

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Document history

Revision	Date	Description/changes	Changes made by
Consultation draft	09.07.2020	Draft version of revised guidelines based on experience feedback workshop in Tønsberg 14th November 2019	Joar Dalheim/ Andrea Risan/ Jan Pappas
External consultation draft	12.11.2020	Comments from DSB implemented	Joar Dalheim/ Jorunn Johannessen
Final report	01.07.2021	Comments from the industry evaluated and implemented	Joar Dalheim/ Jan Røed
Final report (English)	19.11.2021	Report translated to English. No change in technical content	Andrea Risan/ Joar Dalheim

Overview of changes from the previous version

The following Chapters are significantly modified:

- Chapter 2.3 External conditions (new - short specification)
- Chapter 2.4 Design and barriers (new - short specification)
- Chapter 3.1 Identification of hazards, unwanted events and barriers (new paragraph about delimitation of risk assessments for transport and transfer of hazardous material)
- Chapter 3.4.2.5 HyRAM model (new – recommended frequency model for hydrogen leaks)
- Chapter 3.4.2.6 Leaks from transfer hoses (new – clarification of frequency data for transfer of LNG and LPG using hoses)
- Chapter 3.4.2.7 Frequency of BLEVE (new)
  Table 3.1 Recommended leak frequency models (changes in summary)
- Chapter 3.6.5 Ignition model for hydrogen added
- Chapter 3.6.6 Ignition outside the plant boundary (new)
- Chapter 3.6.6.1 Ignition at sea (new – short specification)
- Chapter 3.7 first bullet point (amendment – short specification about cloud expansion for flash fires)
- Table 3.3 Recommended ignition probability models (changes in summary)
- Chapter 3.9.3 Internal escalation of events (new – short specification)
- Chapter 3.10 Establishing risk contours (edit – text moved to appendix B)
- Chapter 4.2 Recommended vulnerability criteria (text updated)
- Chapter 4.2.2 Toxicity (modifications to probit functions)
- Chapter 4.2.3 Fires (amendment – short specification about flue gases)
- Chapter 4.2.4 Explosions (changes in threshold value)
- Chapter 4.2.5 Special substances (new)
- Table 4.1 Threshold value for fatality due to explosions (recommended threshold value changed, overpressure at 50 % fatality)
- Chapter 5 Simplified methodology (revised, new heading)
- Chapter 6.3 Specification of the height above ground level to be used in results
- Chapter 7 Scenarios regarding emergency preparedness (change – short specification)

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

Abbreviations

AEGL	Acute Exposure Guideline Levels
CFD	Computational Fluid Dynamics
EPA	United States Environmental Protection Agency
FAR	Fatal Accident Rate (number of fatalities per 100 million exposed working hours)
FFI	Forsvarets forskningsinstitutt
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
HSE	Health and Safety Executive
ISO 17776:2000	Petroleum and natural gas industries, Offshore production installations, Guidelines on tools and techniques for hazard identification and risk assessment
LEL	Lower Explosive Limit
LFL	Lower Flammable Limit
LH2	Liquid Hydrogen
LNG	Liquified Natural Gas
LOC	Loss Of Containment
LPG	Liquified Petroleum Gas
MISOF	Modeling of Ignition Sources on Offshore oil and gas Facilities
NCS	Norwegian Continental Shelf
OGP	The International Association of Oil & Gas Producers
PLL	Potential Loss of Life (expected number of fatalities per year)
PLOFAM	Process leak for offshore installations frequency assessment model
SIL	Safety Integrity Level
UEL	Upper Explosive Limit
UFL	Upper Flammable Limit
QRA	Quantitative Risk Analysis

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1 Introduction

1.1 Foreword

This report is now available in a revised edition prepared by Lloyd's Register (now Vysus Group) for DSB. DSB recommends that the report is used as guidelines in the companies' work with risk assessments for calculation risk contours.

DSB would like to thank everyone who has contributed to the revision of the report. The work of revising the report is based on an experience sharing workshop at DSBs premises in November 2019, with broad participation from the industry, consultants, and developers as well as the authorities. Following this workshop, meeting minutes and a scope of work proposal for revision of the guidelines was prepared and distributed to all participants. Several comments and suggestions for changes to the scope of work memo was received.

A proposal for revised guidelines was published for consultation on dsb.no, with a deadline 1st of February 2021. The participants in the mentioned experience sharing workshop were also notified directly with an invitation to submit comments on the proposal. The assessment of the input from the consultation is summarized in a memo that is distributed to anyone who has commented on the consultation draft.

Revised guidelines are available at www.dsb.no.

1.2 Objective

These guidelines are applied in the preparation of quantitative risk assessments where the objective is to establish risk contours around plants handling hazardous substances. The risk contours will be a basis for the establishment of consideration zones for land-use planning. Even though there are existing standards and international acknowledged methodologies for quantitative risk analyses, it is recognised that there are significant uncertainties linked to the calculation of this type of risk contours. DSB has therefore initiated preparation of this guideline to ensure consistent and unbiased calculations of such contours.

The objective of the guidelines is to reduce random variation of results as a consequence of variance in use of historical data, tools and methodology. It is an ambition that the guidelines shall contribute to easier understanding of the risk analysis and its uncertainties, to improve verification, reproduction and comparison, and all this independent of choice of tool and risk analyst.

Application of the guidelines is limited to risk assessment of incidents that may endanger the population in areas around facilities that handle hazardous substances.

This guideline shall be seen in connection with the framework defined by the two Norwegian DSB reports "Temarapport 13" (2013), ref. /1/, and «Veileder om sikkerheten rundt storulykkevirksomheter» (2019), ref. /2/.

The DSB theme report (ref. /1/) defines the regulatory framework for tolerable risk for 3rd party in the vicinity of a plant handling hazardous substances, including the principle that risk from the plant shall be reduced to a level as low as reasonably practicable (ALARP). The guidelines for quantitative risk assessments are formulated in line with the principles for formulating the criteria as described in the theme report.

The DSB guidance report (ref. /2/) is primarily aimed at municipal use in land use planning and risk management around hazardous plants. It also places processes of compliance and permits according to DSB regulation into a land use planning perspective. The DSB guidance report discusses consideration zones in the following perspective:

1. Maintain appropriate safe distance to population around the hazardous plant
2. Capture changes of conditions in and around hazardous plants
3. Establishment of new hazardous plants and changes in hazardous plants

According to the European Seveso III directive (ref. /3/) the plants are committed to provide relevant information to the municipalities about the risk they expose to the public. It does not explicitly require calculation of risk contours, but both the DSB theme report (2013) and the DSB guidance report (2019) is based on risk contours as basis for municipal consideration zones.

The consideration zones should be used as a management tool to reduce risk around hazardous plants according to the Norwegian planning- and building legislation (*Plan- og bygningsloven*). Provisions are determined for the consideration zones. While the consideration zones define a framework for which restrictions are to be implemented in a certain area according to the risk level, it is the municipal authorities that decide formal restrictions based on an assessment of all relevant factors for the area. Relevant provisions may include conditions for land use (prohibition of e.g. residential buildings etc.), sequential provisions, requirements for detailed regulation and requirements for further investigations before implementation of measures.

Risk management in the area around hazardous plants is hence mainly performed through municipal enforcement of plans and restrictions. Risk management of the plants themselves is regulated through the Norwegian legislation ("Brann- og eksplosjonsvernloven") and presumed to be handled through technical and organizational measures, possibly in combination with spatial restrictions. The focus of these guidelines is not on details regarding the risk picture inside the plants and how this should be assessed.

It is however important to note that the consideration zones and the associated provisions are not directly determined from the calculated risk contours, but these constitute an important basis of information for the work with area plans where major accident risks are relevant. In practice, the plants' risk analyses are often used as expert reports as a basis for the more general risk- and vulnerability studies (in Norwegian: ROS-analyse) that follow the planning work. The work with this guidance report is mainly justified by established practice with use of risk contours for plants defined as major accident plants according to the Seveso III regulation, but the guidance is considered relevant for all hazardous plants independent of size and level of risk. In this connection, it can be pointed out that the guidelines have been used as a basis for calculating safety distances for typical (generic) small and medium-sized facilities, given in DSBs proposed guidance on the topic which was on hearing in the turn of the year 2019/2020.

In the hearing statements, several methodological issues were pointed out related to the use of the guidelines, especially for different types of energy gas facilities. Among other things, it was commented that the methodology entails considerable variations in the results for small and medium-sized energy gas plants, even with small changes in the calculation/design basis. Questions were asked as to whether the data sources for leak frequencies referred to in the guidelines are representative for the types of plants included in the study. Furthermore, it was pointed out that when calculating risk contours in accordance with the guidelines, there is little effect of risk-reducing measures (e.g. systems for automatic detection and shutdown) and conservative tolerance limits have been used for explosion loads.

The changes in the revised guidelines are a remedy for some of these conditions, as indicated in the overview of changes from the last version. In the overview, reference is made to changes in the recommended tolerance limit for explosion overpressure, a new simple ignition model (recommended reduction factor as a function of distance from leak point to areas outside of the plant), and that changes have been made (additions) for leak frequency data source for hydrogen gas plants and leak frequency data for transfer of LNG.

In addition, the experience from the mentioned work with proposals for safety distances has initiated work to describe a simplified, scenario-based methodology for a number of simple small and medium-sized facilities. Chapter 5 of the guidelines lists the types of facilities for which this is currently relevant. The work of describing a simplified methodology has begun but is so far not included in the guidelines.

DSB expects that the revised guidelines will be used in the preparation of new quantitative risk assessments for calculating risk contours, as well as in updating (changing) existing risk assessments, e.g. as a result of significant changes on 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 plant or enterprise, i.e. all relevant plant sections, activities and incidents shall be included in risk assessments. Moreover, sources of external impact (natural hazards, domino effects from other enterprises, etc.) shall be included in risk assessments.
>
> "Best estimate" calculation of risk contours shall be performed, based on the information available and the chosen method for the risk assessment (i.e. risk assessments should 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. Risk assessments should therefore use 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 risk assessments are not based on assumptions that can be easily changed or are uncontrollable. This is especially true of 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 and will stay put and not seek cover. In reality this will not be the case, but it is considered more important that the risk contours are not unduly affected by assumptions regarding the protection the public may have or how they may react in an incident. The same applies to assumptions about the activity level in the surroundings and its impact on the probability of ignition of a gas cloud that extends to areas beyond the plant boundary. For example, consideration zones should not be dependent on traffic density, housing density or recreational activities in the area. Consequently, it must be assumed that a flammable gas cloud that reaches areas beyond the plant boundary, where there is no requirement for ignition control, will be ignited.
>
> The possible effects of implementing risk-reduction measures or (other) significant changes or activities in the plant shall be reflected in the risk contours.
>
> Uncertainties relating to the available information level of knowledge and the choice 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. The guidelines mainly relate to the analytical part of the standard; and are not intended to cover the entire risk assessment process.

The main focus of the guideline is clarifying the factors that to the largest extent affects risk contours, see Figure 1.1.

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

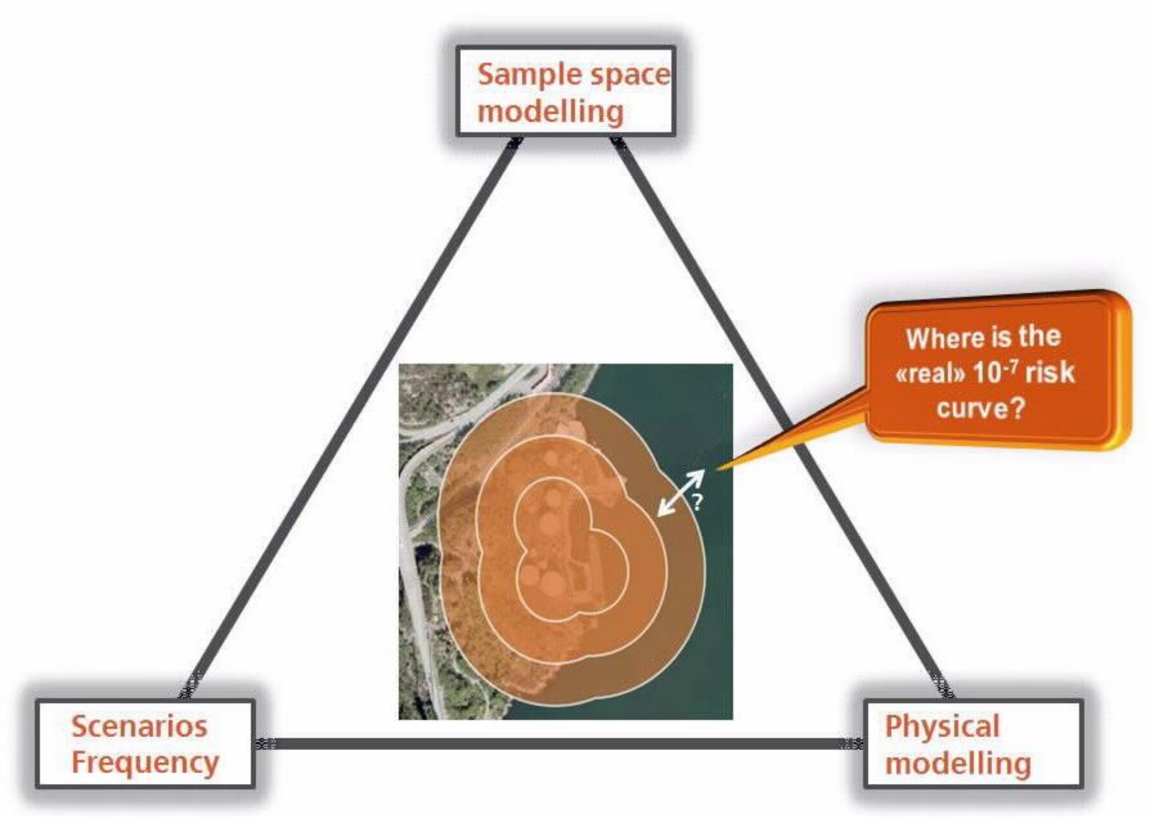

Figure 1.1 – Main drivers for establishing best estimate risk contours

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: 2008.

Iso-contour:

An iso-contour is a line or surface through all points in space that represent the same outcome level. For example, an iso-contour for an individual risk of 1E-7 per year represents the limit of the consideration zones in the theme report (2013), ref. /1/.

Risk contour:

Risk contours are used in risk assessments to express fatality risk levels in areas around plants handling hazardous substances. Risk contours are calculated by combining frequencies for possible accident scenarios with the associated fatality probability for an individual within the consequence region. The risk contours thus show geographical individual risk, by showing the risk to a hypothetical person at the location, independent of whether there are people at that location. Therefore, the presence of people, i.e. how many people and for how long these people stay within the affected area, shall not be taken into consideration. How exposure time is used in probit functions in this context is described in Chapter 4.

Consideration zone:

Plans for land use shall, to the extent necessary, show considerations and restrictions that are relevant to use of the land. This shall be indicated in the plan for land use as consideration zones, with associated guidelines and regulations. The provisions and guidelines that apply, or will apply, to the consideration zones in compliance with the Planning and Building Act, or other acts, shall to the extent necessary be specified. 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 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. This may affect the ability to conduct effective land planning. Risk assessments should therefore use best estimates in assumptions (e.g. expected leak frequency) and the most realistic interpretations of the expected extent of consequences for the scenarios assessed.

Top event:

The hazard identification (HAZID) will provide an overview of all events with hazard potential that may occur at a given plant. Some of these will, for different reasons (typically low consequence severity or low frequency), not be included in the 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 event and is usually an unwanted 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 and consequences), such as "unignited leak", "fire" or "explosion". In the guidelines, "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. This makes the picture complex and difficult to get an overview of, and one should therefore identify 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 only small variations in, for example, leak location, leak direction, leak rate, wind conditions, temperature, atmospheric class, mechanical conditions (obstructions), timing of ignition, etc.

By "expanding a sample space" we mean to cover the entire sample space, or as much as practicable, with specific scenarios so that the analysis is as far as possible representative of the complete range of consequences of each top event for a plant.

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).

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 independent of the tools used and the person performing the analysis.

The execution of a risk analysis follows the steps defined in NS 5814:2008. The risk analysis process is not reproduced in its entirety in the guidelines, but the process is summarized in Table 2.1.

Table 2.1 – Main steps in the process for risk assessment from NS 5814:2008

	Main steps in the process for risk assessment covered by NS 5814:2008, ref. Figure 1 in the standard
Not covered by NS 5814:2008	Define the framework conditions
Not covered by NS 5814:2008	Establish risk acceptance criteria
Planning	Kick-off, problem description and formulation of objectives
Planning	Organisation of work
Planning	Selection of method and data sources
Planning	Define system description
Risk analysis	Identification of hazards and unwanted events
Risk analysis	Cause analysis and frequency analysis Consequence analysis
Risk analysis	Risk calculation
Risk evaluation	Comparison with risk acceptance criteria
Risk evaluation	Identification of possible control measures and their effectiveness in reducing risk
Risk evaluation	Discussion, documentation and conclusion
Not covered by NS 5814:2008	Implementation

2.1 Understanding the plant

Appendix A (Chapter 1) can be used for mapping the plant, and contains elements considered important to be clarified in the initial phase of the project. The checkpoints in the list will normally identify what documentation is required for further work, as well as providing guidance on assumptions and methodology selection.

In case there have been modifications or extensions to an existing plant, it is important to collect operational and maintenance experience from the plant. In addition, documentation from incidents, accidents, audits, internal audits, etc. may be relevant. The person(s) who is to perform the analysis must have a good knowledge of the analysis object and a site visit should be made at the start of the analysis, if the local conditions are not sufficiently well known beforehand.

2.2 Selection of approach and methodology

Based on an initial mapping of the complexity and extent of the plant, surrounding conditions and overall assumptions for the task, further activities, methodology and tool selection are planned. All assumptions and decisions taken and considered to affect the methodology selection should be justified and documented. This also applies to later phases of a project to ensure traceability of decisions taken as the project progresses that are relevant to the outcome of the analysis.

2.3 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 discharge of hazardous substances shall be included in the calculation of the risk contours.

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

2.4 Design and barriers

The plant's design and barriers must be considered to the greatest possible extent in the risk assessments, both to provide the most accurate risk picture possible, but also to provide an incentive for the facilities to follow ALARP. An example is detection with automatic shutdown and possible pressure relief, which results in a reduction in the duration of the discharge (and the discharged amount). Reduced duration of the discharge will reduce the consequences of the incident, including the probability of ignition outside of the plant's own area (see Chapter 3.6.6).

Errors or failures of barriers must be included if it 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 on the plant. These events are then assessed in an event tree analysis, bow-tie analysis or similar (ref. NS 5814 and ISO 17776). In addition to systems and equipment, organisational and operational conditions must also be assessed. Poorly executed or lack of maintenance, operator errors, etc. are examples of causes and initiating events that may also be critical. 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 plant into subsystems and use a selection of relevant guidewords. Fault tree analyses and HAZOP reports or similar can also be used as inputs in a HAZID process.

The risk analysis should clarify how the transport of hazardous substances in to or out from 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 inside the facility must be included in the risk analysis. This may include evets 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 most, but all hazards associated with transport at the facility must be qualitatively assessed whether they can contribute to the risk figures.

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.

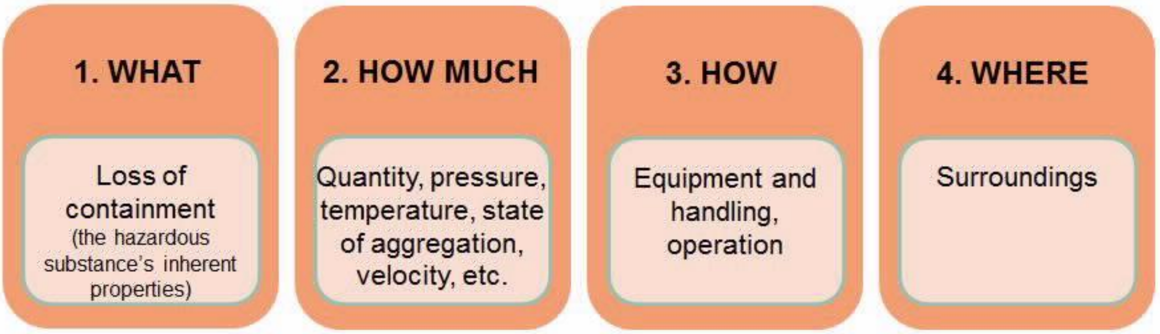

Figure 3.1 – Example of questions when establishing a top event

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 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 on the basis of SIL analyses or similar types of reliability analyses. 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 plant analysed. If the company has specific and well documented experience data for leak frequencies that are more relevant than the generic models, these should be used. If there are special conditions that indicate that leak frequencies will differ from the generic models used, the leak frequencies can be adjusted, provided that the adjustment can be documented. Human, operational and organisational conditions can affect the expected value for the frequency of the top events, and these can be taken into account as long as the effect can be documented or substantiated.

Figure 3.2 illustrates how the risk contours are affected by the estimated frequency for the top events. The black circle illustrates the resulting risk contour at a specified frequency. Here the frequency decreases with increasing leak rates (and associated representative spreading). If one increases the frequency of all leak scenarios with the same factor the resulting risk contour will be larger, as represented by the orange dotted line.

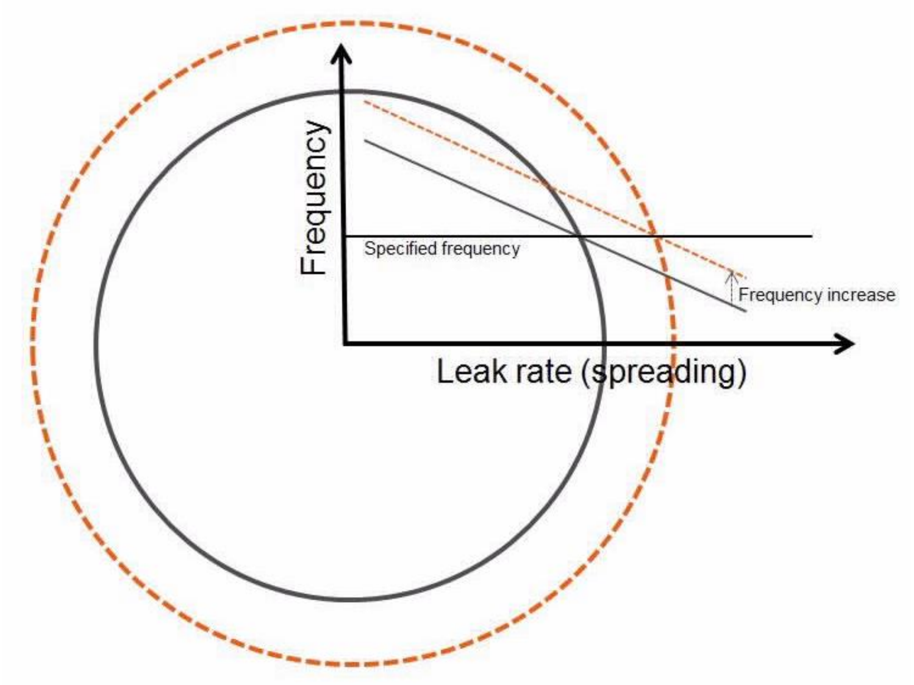

Figure 3.2 – Illustration of how the selection of frequency model affects risk contours

There are different models for the calculation of leak frequencies. These can be used to calculate frequencies for top events, which will normally be leaks with different leak rate classes. 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 are mainly distinguished by:

- The level of detail of the plant information required to use the models, i.e. does it only include information about the main equipment in the plant (such as pressure tanks, 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 resolution granularity of the subsequent analysis, i.e. whether the model provides either frequencies for different scenarios in terms of rates and durations or discharged volumes, or frequencies for different hole sizes.

Use of the more advanced models requires more detailed information about leak sources. For example, in an early phase of a design process - before P&IDs are completed - one will need to adjust the parts count (quantification of leak sources), alternatively, using experience data from similar units from other plant to derive leak frequencies that are representative for the planned plant. For a plant in operation, this is not necessary as all equipment will be known.

To a limited extent, the use of a simple model will reflect the design conditions in the plant and the corresponding scenarios will be correspondingly simplified. By using a model that provides hole-size distributions, one can use the fluid type, pressure and temperature to calculate a frequency distribution of leak rates. The leak frequency model will therefore reflect the design conditions more accurately. In order to take advantage of this, the subsequent analysis will also need to be more detailed.

The selection of leak frequency model can be determined from:

- How simple or comprehensive an analysis one wants to perform. The need to evaluate the effect of risk reduction measures must be considered; more advanced models generally provide greater opportunities for assessing the effect of these measures.

- The level of detail that is available for the plant.
- How site-specific the analysis should be. The complexity of the leak frequency model must be balanced against the analysis model in which it will be used.

3.4.2 Leak frequency models

The following leak frequency models are considered relevant to analyses of land-based plants and are further discussed in these guidelines:

- RIVM
- HSE
- OGP
- PLOFAM
- HyRAM
- Shell (transfer hoses for LNG)
- BLEVE

RIVM and HSE are the most widely used leak frequency models for land-based plants in Europe. OGP and PLOFAM originate from the offshore industry but are also used for downstream activities such as for terminals and petrochemical industrial plants. At present, data from offshore facilities are significantly better and more comprehensive than for land-based industries. It is desirable that in the longer term, more comprehensive and better data from land-based industries should be obtained.

For special fluids that are likely to affect the leak frequency (for example, due to known corrosion or other damage mechanisms), it should be considered whether the standard leak frequencies need to be adjusted. HyRAM is an established model for hydrogen leaks based on the work at Sandia National Laboratories in California.

Note that the leak frequency models provide frequencies for different types or classes of leaks, and that they can also provide different frequencies even for the same type of leak. Since frequencies and consequences are to be combined, it is important to use the right model for the for the different types of scenarios. For example, there are different models for process equipment, tanks, cylinders and hoses. If the frequency of a tank rupture is chosen, but the event is modelled as a leak from process equipment, the risk analysis will not be consistent.

3.4.2.1 RIVM model

The RIVM (Reference Manual Bevi Risk Assessment) model (ref. /4/) is mainly based on the TNO Purple Book. It is the simplest of the leak frequency models, as it provides leak rates for equipment groups and not for smaller components (such as flanges and valves). RIVM is therefore most useful for plants where there are a limited number of leak sources outside these equipment groups (without necessarily implying that there are few leak possibilities in the plant). Furthermore, the frequencies for 3 different discharge scenarios are given by amount, rate or hole size:

- Instantaneous discharge of the entire content
- Discharge of the full content at a constant rate over 10 minutes
- Continuous discharge through 10 mm holes.

For pumps and compressors, frequencies for hole sizes are specified in relation to the pipe diameter (10% of diameter).

The frequency is independent of the equipment size and pipe dimensions for pipes below the ground. For pipes above the ground, the frequency is dependent on the pipe size. As only large equipment is included, the number of leak points is easily counted. The RIVM model is suitable for simpler analyses where design-specific conditions that affect the leak frequency are only taken into account to a limited extent.

A comparative study between RIVM and HSE (ref. /5/) shows that an important prerequisite RIVM sets for the use of the leak frequencies for pressure tanks, is that the leaks assessed are not due to external causes (collision, shock), corrosion, fatigue due to vibration or operator error, as it is assumed that the plant has control over this. If such conditions exist, either a special assessment must be made using the RIVM frequencies for pressure tanks (as the RIVM frequencies are basically dominated by conditions such as design defects, aging, wear, etc.), or the HSE or PLOFAM models should be used.

The background for the hose fracture frequencies in this model is very unclear (ref. /6/), and these are therefore not recommended for use.

3.4.2.2 HSE model

The HSE model (UK Health and Safety Executive, ref. /7/) is based on data from facilities in the United Kingdom (UK). It is a model for failure frequencies for equipment where leakage is the failure mode. It is more detailed than the RIVM model, as it includes data for components such as flanges and valves. The HSE model also provides frequencies by hole-size for some equipment, mostly between 3 and 5 hole-sizes depending on equipment type, while a generic hole size is provided for valves, flanges and pumps. The HSE model is therefore better suited than the RIVM model if more design-specific and detailed frequencies for top events are required. The frequencies for an item of equipment are independent of the size of the equipment, except for large storage tanks (two size classes) and pipes where frequencies are provided by hole-size for pipes in different size ranges. 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 separate flanges.

The HSE model is suitable if one wants a more detailed analysis, where design-specific conditions that affect leak frequencies are taken into account to a greater extent, both because of a better resolution regarding the number of leak sources and because the effect of process conditions (pressure, temperature, fluid density) can be taken into account.

The HSE model has leak frequencies for loading/offloading with hoses to transport tanks based on fault tree analysis of the operation and associated barrier systems, see ref. /8/.

As there is a significantly greater resolution regarding leak sources, the counting of leak sources will be significantly more extensive than by using the RIVM model. The advantage is that the top event frequencies will more accurately reflect the facility.

3.4.2.3 OGP model

The OGP model (ref. /9/) is also based on a data collected by the UK HSE, but is structured differently than the HSE model. The primary differences are:

- The OGP model has data for significantly more process components than the HSE model
- The OGP model distinguishes between:
  - full leaks (the entire segment content is released from initial full pressure)
  - limited leaks (part of the segment content is leaking, pressure is lower than full, but not negligible)
  - zero pressure leaks (the pressure is in practice 0, i.e. <0.01 barg)
- 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, while the HSE model only has one frequency (not continuous as in the PLOFAM model).

- OGP provides frequencies for tank ruptures but is coarser than HSE's model (HSE has a more detailed resolution for tank types and events) and it is often somewhat lower in frequencies than HSE.
- OGP also has a model for cylinder leaks ("small containers"). This can be used to calculate the leak frequency for smaller containers such as e.g. industrial gas cylinders and propane cylinders.

3.4.2.4 PLOFAM model

PLOFAM (Process Leaks for Offshore Installations Frequency Assessment Model, ref. /10/) is regarded today to be the most comprehensive, advanced and best validated model for calculating leak frequencies for process plants. However, it has less detail for different tank types than, for example, the HSE model. PLOFAM is based on offshore experience data from the entire UK (data from HSE) and NCS (Norwegian offshore sector, data from the Petroleum Safety Authority Norway) from 1992 to 2015. With HSE and PSA requirements with regard to the format of incident reporting, it has been possible to assess and classify each event thoroughly.

The equipment components included are as in the HSE model, but with some additional classes. What most sets PLOFAM apart from the other models are:

- Frequencies are provided by equipment dimension
- For each equipment size, 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, thus avoiding all effects associated with transition between classes. However, for the calculation of risk contours, only major leakages are relevant
- PLOFAM is validated using the model on leak-source counts from 62 platforms on NCS and compared to observed leak frequencies on the corresponding platforms.

Although PLOFAM is based on UK and NCS offshore data, a review shows that there is no reason to assume that the frequencies are not equally applicable for land-based facilities 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 for petrochemical plants, refineries, larger LNG plants and the like.

PLOFAM is the leak frequency model that to the largest extent enables the design conditions of a plant to be modelled but is also the one that is the most time-consuming to use. The amount of work to count leak sources will be of the same level as with the HSE model.

PLOFAM covers about the same equipment components as the OGP model, but it has both a significantly more comprehensive database and is methodically more correct. Therefore, use of PLOFAM is recommended rather than the OGP model where applicable.

3.4.2.5 HyRAM model

HyRAM is an established model for hydrogen leaks based on the work of Sandia National Laboratories in California, ref. /11/. Sandia has worked out these frequencies in connection with IEA expert group work in the years of 2005-2010, with the participation of strong technical communities in the world, including HSE, TNO, INERIS, DNVGL, TELTEK and GEXCON.

HyRAM has been used by the industry for many years, but it is still considered uncertain. By comparing HyRAM with PLOFAM (see Figure 3.3), it can be seen that they are relatively similar for small equipment, but that the difference becomes larger when the equipment size increases. The figure compares valves, but the same trend can also be seen for other equipment such as flanges and filters. The difference is partly due to the fact that HyRAM provides frequencies based on relative hole size and does not adjust for the size of the equipment. Note that for filters, HyRAM is considered to be significantly on the conservative side. The frequencies from HyRAM for filters should therefore be adjusted down by a factor of 10-25 when calculating risk contours. An assessment of filter types should be made before the down-adjustment factor is determined.

Although HyRAM differs from PLOFAM, this is not in itself proof that HyRAM is not applicable to hydrogen leaks. PLOFAM has only been validated for offshore process leaks in the North Sea, and there is uncertainty related to how well it represents onshore process plants (see also Chapter 3.4.2.4). Neither is PLOFAM validated against hydrogen leaks. However, there is reason to believe that HyRAM is more uncertain for larger equipment components than for smaller ones (where most of the validation has also been performed).

Even though there is uncertainty associated with the use of HyRAM, it is recommended to use for hydrogen plants. There are no other frequency models that stand out as more validated for hydrogen leaks, and it is considered an advantage that HyRAM is easy to use and thus consistent between the various users.

HyRAM is also recommended for hydrogen leaks in liquid form, although it can be argued that the uncertainty for liquid leaks is even greater than for gas leaks. However, no other models have been established that appear to be better than HyRAM for hydrogen leaks in liquid form, and it is considered an advantage that the risk analyses can use the same model for gas and liquid leaks.

In the long term, a more validated model for hydrogen leaks is desirable, and these guidelines will be revised when a new and more validated model is available.

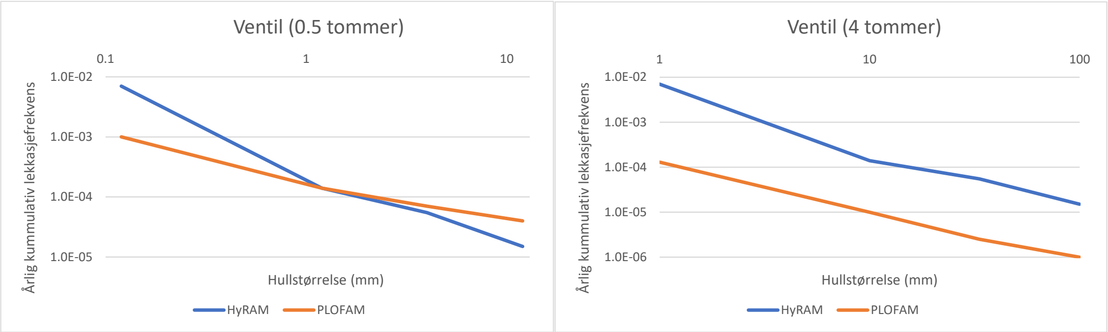

Figure 3.3 – Comparison of leak frequencies for valves from HyRAM and PLOFAM (figure in Norwegian)

3.4.2.6 Leaks from transfer hoses

HSE is generally recommended for leaks from transfer hoses, see Chapter 3.4.2.2.

Shell has presented data for hose ruptures for stainless steel LNG hoses based on experience from plants in the USA and Europe, ref. /12/. These frequencies are lower than the generic frequency 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 leak frequencies (from Shell) are therefore recommended:

- Full rupture: 9.7E-08 per operation
- 25 mm diameter leak: 1.9E-07 per operation

Hose ruptures for LPG hoses is 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. /13/. Leakage data from this database suggest that the frequency of leaks from LPG transfer hoses may be similar to those for LNG transfer hoses. However, on the basis that 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 above LNG, but not as high as the frequencies given in HSE. If no special assessments are made for the analysed LPG system, it is recommended to set the leak frequency for LPG hoses halfway between Shell (LNG) and HSE (generic). Assessments regarding LPG frequencies shall be discussed under uncertainties, see also Chapter 3.11.

3.4.2.7 Frequency of BLEVE

Although some frequency models provide generic frequencies for BLEVE (e.g. HSE), it is considered inaccurate to use generic frequencies for these events.

Instead, assessments should be made in each case for 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 single event tree should be set up that assesses frequencies for prolonged fires and the probability that these expose tanks. OGP also recommends basing the frequencies for BLEVE on event trees and the probability of long duration fire exposure.

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

Cold BLEVE can be considered as a pressure vessel rupture, and the HSE model (Chapter 3.4.2.2) is recommended for such events.

3.4.2.8 Use of historical data for facilities or companies

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

If you have historical leak frequency data that are considered relevant for the analysed system, these can be included in the assessment of the expected leak frequency. In that case, it must be proven that the historical data have sufficient reliability to be used for the purpose.

If there are well-documented historical data available, the historical frequencies can be weighted equally with the generic frequencies (discussed in Chapter 3.4.2.1 to Chapter 3.4.2.7).

3.4.3 Other leak causes

Unintentional releases of flammable or toxic substances that may represent a societal risk may occur without being a result of a leak with frequency covered by the models in section 3.4.2. For example, there could be runaway reactions or other abnormal process situations that cause overpressure with associated fracture 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 intermediate products.

It is therefore a prerequisite that HAZID and HAZOP studies are carried out adequately to reveal possible circumstances where such scenarios could occur. Such scenarios shall be included in the risk contour calculations if they are expected to give a significant contribution to the risk picture.

3.4.4 Summary

A summary of recommendations is given in Table 3.1.

All the leak frequency models discussed in Chapters 3.4.2.1 - 3.4.2.7 are in principle suitable for use in risk analyses. In addition, other models or experience 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 that should be used, and in each individual case an assessment must be made of which information is available and what level of detail is desired for the results. In this summary, a recommendation is given on the preferred model for different types of scenarios.

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

Table 3.1 – Recommended data for leak rates

Characteristics	Information available / requirements	Recommended models
Process areas	Only larger equipment and associated quantities. Dependency of pressure and equipment size is not relevant.	RIVM/TNO (not for pressure vessels, see Chapter 3.4.2.1)
	Limited information about components, but no dependency of equipment size. Larger equipment, valves, flanges, pumps, hoses and pipes must be counted. Process pressures are considered.	HSE
	Large facilities (refineries, petrochemical plants, large LNG plants, etc.). Information about components (these must be counted). Provides frequencies by equipment dimension and hole size (continuous distributions).	PLOFAM
Tanks	All tank types	HSE
Cylinders	Propane cylinders etc.	OGP
Hoses	Process hoses	PLOFAM
	Transfer hoses to road tankers	HSE
	LNG hoses	Gasnor (Shell)
	LPG hoses	See Chapter 3.4.2.6
Hydrogen	All hydrogen leaks	HyRAM (frequency for filters must be adjusted, see Chapter 3.4.2.5)
BLEVE	All types of BLEVE	Calculated from event tree (see Chapter 3.4.2.7)

3.5 Leak and dispersion analysis

3.5.1 Leak modelling

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

There are two stages in the leak process before a source of dispersion analysis can be identified. The first stage is to determine the leak rate out of the hole, the second stage is to determine the phase and thermodynamic state just outside the hole as the start of the dispersion analysis. The source in dispersion analyses in case of a gas release (whether using CFD or empirical models) is not the hole itself, but will be where the expansion of the released gas has reduced the pressure to ambient, i.e. at the so-called Mach disk (usually ≤ 1m from hole).

These stages require the use of different physical models, both in relation to the two stages and in relation to the phase (condition) of the fluid prior to release.

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

3.5.1.1 Leak rate through the hole

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

- If the fluid temperature exceeds the boiling point of the liquid at the operating pressure, the fluid will be a gas
- If the fluid temperature is between the boiling point of the liquid at the operating pressure and the boiling point at ambient pressure, the pressure drop during the leakage will cause the liquid to boil (gas bubble formation). Evaporation (conversion from a liquid to a gaseous state) requires energy, which is taken from the liquid, so the amount of gas bubble formation will depend on the difference between the temperature of the liquid and the boiling point of the liquid at ambient pressure, i.e. the degree of superheating. Depending on the degree of superheating, boiling will start in the fluid 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. These are complex physical processes that can be approximated with different calculation models. If the liquid has components with different boiling points, this must also be considered
- If the fluid temperature is lower than the boiling point at ambient pressure, the liquid will evaporate without boiling as the pressure falls in the leak. The amount of liquid that evaporates is determined by the vapour pressure curve of the liquid, but this evaporation takes some time.

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 dimensions of the pipe. For short pipes, some empirical models can be used. For long pipes, suitable calculation models for piping systems can be used to improve the accuracy of the calculated release rates.

Leak models assume unrestricted flow out of the hole. Certain conditions, such as high temperature drop and high humidity, can cause ice formation which may partially block the opening and reduce the leak rate compared to the rate calculated by the leak model. If the experience with the use of a fluid is limited, literature/accident databases should be reviewed to obtain better understanding of the leak characteristics for such a fluid. It is then necessary to consider whether this experience can be transferred to the current scenario.

3.5.1.2 Conditions immediately outside the leak – Near field

The situation is dependent on whether the scenario is a pure gas leak or a multiphase leak.

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

As the heat capacities for methane and for natural gas are higher than for air, some leaks may behave as heavy gas at a given mixing ratio with air and as a light gas at a different mixing ratio. This means that the gas can initially be lighter than air but subsequently become heavier than air by mixing. Humidity and temperature can affect these conditions. Therefore, the safety datasheet alone will not be sufficient to assess how a leak will spread.

In the case of a 2-phase or pure liquid leak, the liquid may be atomised and form a spray. Depending on the droplet size, a larger or smaller part of the liquid will rainout and form a liquid pool. There are several different mechanisms that 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 temperature in the surroundings. Atomisation and droplet sizes are determined by hole diameter, fluid velocity and density, surface tension and viscosity. For small holes, even relatively low pressures (the order of 1 bar) could cause spray formation. Liquid that runs down vertical profiles onto horizontal surfaces may also cause atomisation and formation of a gas cloud, ref. /14/
- Fractioning 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 part of the dispersion calculation is the amount of the released liquid that will form a liquid pool, and the amount of liquid that is atomised and accompanies the gas in the dispersion. The proportion of 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 should be undertaken in relation to the degree of liquid spray formation. Upon cooling of the gas, condensation may also contribute to droplet formation. Due to flashing, the temperature in the 2-phase cloud will reduce and the cloud (with or without droplets) will normally behave like heavy gas
- For liquids with multiple components with differing boiling points, special assessments must be made. Depending on composition, pressure and temperature, such releases could be a combination of a spray and a liquid pool where gas components boil off or an atomized spray with no or minimal rainout
- In the case of a release from a pressurized multiphase tank, the pressure drop as a result of the discharge can cause significant evaporation, so that the mass of gas released may be several times greater than the original gas content in the equipment
- Weather conditions may affect the rate of evaporation from liquid pools, so for scenarios where evaporation may be a significant factor, local weather conditions should be taken into account
- 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 spread 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. /15/ and /16/ 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. There are no detailed guidelines regarding model parameters here, but this should be considered in the modelling of individual releases.

3.5.2 Far field

In order for risk contours to represent reality as closely as possible, it is crucial that the modelling of a simulated scenario is as physically accurate as possible. Therefore, whether there are special conditions at the plant that require a given type of modelling tool for simulating far field effects to be selected must always be considered.

There are basically two types of simulation tools to calculate dispersion in the far field from a release: empirical tools and CFD tools:

- Empirical tools (also called integral tools or 2D tools) apply simplified physical models that are tuned to recreate experimental trials in the best possible way. These models are robust and very fast, but take little account of the actual physical conditions of the plant being assessed
- CFD tools attempt to simulate the physics (Navier-Stokes equations) in the releases, 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 approximate the effect of physics on a smaller scale than can be handled by the chosen resolution of the discretization model.

Neither of these 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 type of 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 remote field has no or minor obstructions that may affect gas dispersion (see ref. /17/). For facilities where this is the case, it will be possible to get good estimates of gas dispersion with both types of modelling tools.

If one is to analyse a facility where one of the following characteristics applies, CFD tools should be used to model dispersion:

- Terrain. If the plant is close to terrain that will significantly affect the dispersion of gas in the far field. This is especially applicable if the plant can produce heavy gas emissions that can be trapped and directed by the terrain, see Figure 3.4. For such scenarios, empirical tools may be non-conservative. Mountains and steep terrain can also constitute natural barriers that prevent the dispersion of heavy gas in certain directions. If empirical tools are used for such scenarios, this could result in excessive risk contours in certain directions
- Large buildings. If there are buildings or other obstructions that significantly affect the dispersion image (such as changes in local wind conditions, eddies, blockages, and directional changes in relation to what empirical tools would predict)
- Complex or large diffuse releases. If the release is from a bunded pool with a complex or large area, an approach that uses a point release could give significant inaccuracy in the results
- Releases in congested areas. If a large proportion of the kinetic energy of the release is absorbed by the gas flow (jet) hitting process equipment or buildings. When kinetic energy is absorbed by process equipment, the mixing of air will be reduced (the jet speed is stopped mechanically instead of by friction with air), and the flammable or toxic gas will therefore reach further before it is diluted. In such cases empirical tools can be non-conservative. If a high-speed discharge hits a small surface (building or similar), the pulse 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, local wind speeds may also be significantly lower than that outside the congested area and different to

the wind field at the nearest measurement station. This must be taken into account in dispersion modelling, 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 air (wind speeds <1m/s), where empirical tools can have limited simulation possibilities. Note that there may be areas where CFD tools also operate outside a domain where it is adequately tested.

Alternatively, if empirical tools are used, one must describe uncertainties related to assumptions about conditions as mentioned above, and possibly how one has sought to compensate for such conditions.

For the calculation of toxic gas concentrations over long distances in the far field, there may be some challenges when using CFD. Due to the calculation time, it can be a problem modelling the near field effects accurately, whilst at the same time adequately representing the far field effects. When modelling such scenarios, the person performing the study should know 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 replicate with CFD (Pasquill A, B, C stability), and CFD tools usually provide conservative hazard distances in such situations. Empirical tools can be more robust and easier to use for such situations, even if they also fail to model the local effects of, for example, small obstructions and varying heat transition figures from the substrate. However, when using empirical tools, one must ensure that there are no important elements of modelling close to the release that are omitted and that there are no low wind scenarios that cannot be modelled. Empirical tools produce accurate results for the scenarios they are calibrated for, but the accuracy reduces significantly as soon as the parameters differ from the calibration scenarios. Therefore, for the calculation of toxic concentrations in the far field, there is uncertainty related to the results for both CFD and empirical tools, and this uncertainty must therefore be discussed in the risk analysis (see also Chapter 3.11).

The choice of the type of modelling tool for the far field could have a major impact on the risk contours, and it must therefore be documented that this is considered in the risk analysis.

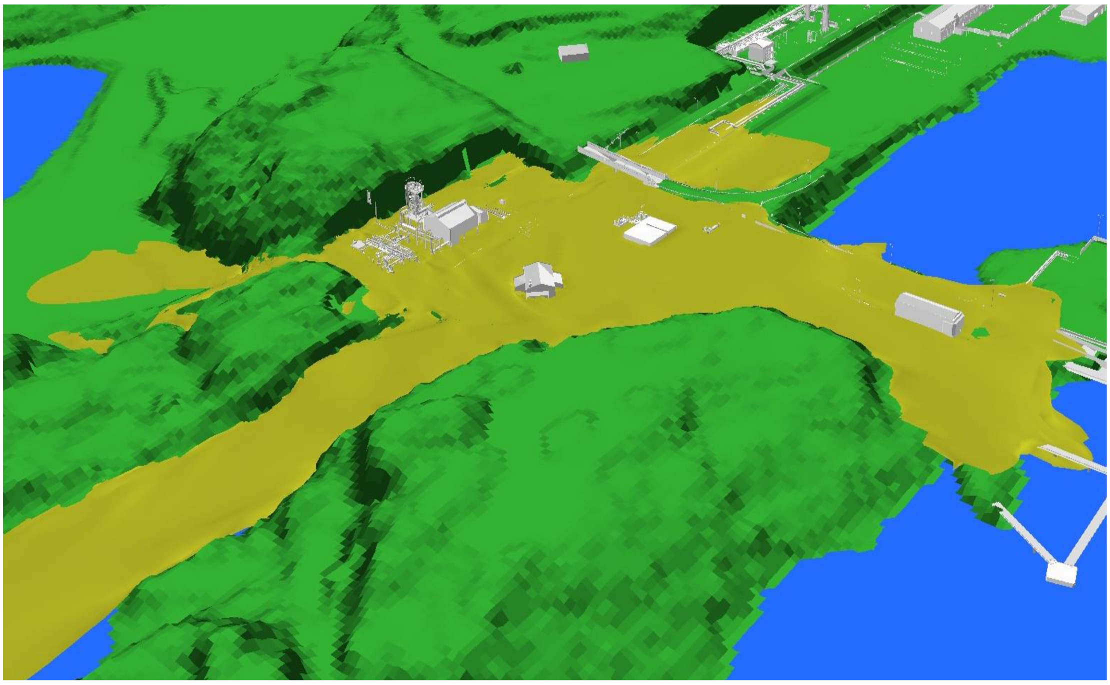

Figure 3.4 – Release of heavy gas (yellow colour) in area of uneven terrain. The figure shows that the field of impact is heavily affected by the terrain for heavy gas emissions

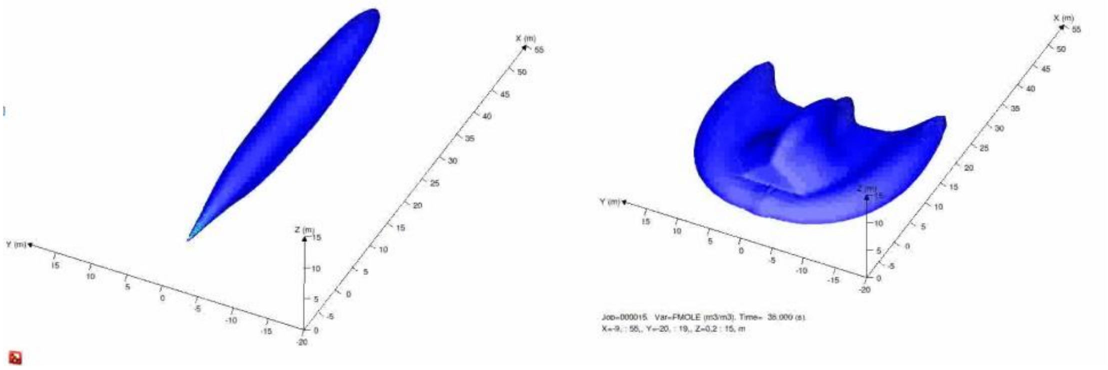

Figure 3.5 – Non-obstructed release (left) and same release with 3x3 metre obstruction (right). The figure illustrates that if a leak hits an obstacle, the dispersion field could change significantly

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 a long simulation time. 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 unbiased risk contours, it is therefore recommended to use a steady state solution as a basis for to calculate fatality (50% fatality should be used as a threshold value, see Chapter 4.2.1).

For flammable clouds, it is therefore recommended to use LEL of steady-state condition as a basis for calculating fatality.

3.6 Ignition analysis

3.6.1 General

Ignition assumes that there is a flammable concentration of gas, either as a result of a gas discharge or as vapour evaporation from a liquid, exposed to an ignition source. For liquids, this means that they are at a temperature that provides sufficient evaporation. Normally, liquids with a high flash point (above 60 ˚C) will not be regarded as flammable without being heated. Note, however, that spray leaks of this type of liquids 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 factors:

- The likelihood that the cloud of flammable gas reaches an ignition source. In reality, the leak rate will decrease over time and, in combination with wind or ventilation conditions, the cloud size and thus the probability of exposure to ignition sources (i.e. a flammable concentration of gas at a location where there is an ignition source) will also vary with time, i.e. it is transient
- The probability of ignition given exposure to ignition sources, usually called ignition intensity.

Ignition can either occur immediately after the release, resulting in a fire, or it may occur after a time delay, resulting in an explosion or flash fire followed by a fire for as long as the leak lasts. Probability models handle the relationship between immediate and late ignition in different ways. This affects the likelihood of delayed ignition to a greater extent than for immediate ignition, which is significant for the risk of explosion but less so for fire frequency.

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

- Ignition sources inside the plant. This is the main focus of all models. There are historical databases, although limited, and these ignition sources are therefore included within ignition models (though in different levels of detail). The ignition probability of special ignition sources, such as fired units, are very dependent on design detail and should therefore be considered on a case-by-case basis. In the case of self-ignition, the ignition probability is set to 1.0.
- Ignition sources outside the plant. For assessment of ignition outside the facility, different assessments must be made for different uses of the risk contours:
    - For calculation of risk contours for use in land use planning, the total ignition probability is set to 1.0. Otherwise, the ignition probability will be dependent on the activity level, density of housing, etc., and it is not expedient for the consideration zones to depend on such factors. In reality, the ignition probability is likely to be high in urban areas, as there is no requirement for ignition control outside the plant boundary. Note that using an ignition probability of 1.0 does not directly coincide with the principle of unbiased risk analyses (see Chapter 1.5). Guidance on how to consider ignition outside the plant boundary as accurately/unbiased as possible is given in Chapter 3.6.6).
    - For calculating risk contours which are not to be used for land use planning, an ignition probability ≤ 1 outside the plant boundary may be used if it can be argued as more unbiased. An example may be when calculating risk contours for a facility located in an industrial area where there are requirements regarding ignition source control, and the risk contours do not extend beyond the industrial area.
    - Quantification of ignition outside the plant boundary must be given considerable uncertainty. There is great variation in the type of ignition sources outside a plant, there is a lack of 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 plant is also not covered by the standard ignition models discussed in Chapter 3.6.2 – Chapter 3.6.5. Separate assessments of ignition sources must therefore be made, where it is important to consider the probability of exposing them, since the ignition intensity in any case will be high.

A release of liquid at a temperature above the self-ignition temperature may ignite when they come in contact with air. This is especially relevant for refineries, where parts of the process have high temperatures.

There are 4 principal ignition models that are commonly used:

- RIVM
- OGP
- MISOF (revised version of the OLF model)
- HyRAM (for hydrogen).

These models handle the probability of exposure to ignition sources and ignition intensity in different ways, require different degrees of information and therefore entail different degrees of simplified or comprehensive analysis. The model selection must therefore be based on the complexity level of the risk analysis. For scenarios involving flammable gases such as hydrogen, the ignition probability should be specifically considered.

There are also other very basic models where the ignition probability is determined by the area of a region with ignition sources where there is a flammable concentration of gas, but the OGP model is recommended in preference to these models as it is as easy to use, better validated, and gives a more detailed picture of ignition probability.

3.6.2 RIVM ignition model

The RIVM model (ref. /4/) is very simple, but nevertheless accounts for the probability of exposure to ignition sources and a factor representing ignition intensity:

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

The ignition intensity inside a plant is only given for boilers and ovens and is therefore invalid for most plants. The model also provides ignition intensities for third-party ignition sources:

- Neighbouring construction plant
- Houses and offices (per person)
- High-voltage power lines
- Ships
- Vehicles and trains.

However, for the calculation of risk contours for land use planning purposes, the probability of ignition, given exposure outside the boundaries of the plant should be set to 1 (see Chapter 3.6.5).

3.6.3 OGP ignition model

The OGP model (ref. /18/) refers to the UKOOA model (ref. /19/) developed by the Energy Institute in the UK in 2006 based on HSE data from onshore and offshore facilities, and therefore explicitly covers both onshore and offshore facilities. The probability is given as curves or correlations as a function of leak rates for:

- Various types of facilities and areas of onshore (and offshore) facilities
- Gas, oil, and LNG
- Various ventilation conditions in the areas
- To some extent for different density of equipment.

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 leak rate 0.1 kg/s. The ignition probability decreases with time, mainly because the gas cloud will not reach more ignition sources once it has reached its maximum size.

The OGP/UKOOA model is simple in the sense that it does not require modelling of the probability of exposure of ignition sources, but gives a total ignition probability directly.

As the OGP/UKOOA model does not take into account the transient conditions of a leak, it is suitable for use in analyses that do not include transient cloud models. Therefore, the ignition probability of a given leak rate can be determined without calculating any cloud size, though in order to calculate consequences, the cloud size for each leak scenario must still be calculated.

The OGP/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 /rotary equipment, the OGP/UKOOA model generally gives slightly higher total ignition probabilities than MISOF, which is reasonable given that it is a simpler model than MISOF. If there are special sources of ignition in the area, OGP/UKOOA is generally expected to give a slightly lower ignition probability than MISOF.

Note that the OGP/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 due to catastrophic 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 OGP's "Storage incident frequencies". See Chapter 3.1 in OGP/UKOOA for further information.

OGP is sometimes referred to as IOGP (International Association of Oil & Gas Producers). Note that OGP also refers to several other ignition models (MISOF, OLF, TDIIM, RIVM and CCPS) which are not all mentioned in these DSB guidelines.

3.6.4 MISOF ignition model

MISOF (Modelling of Ignition Sources on Offshore Oil and Gas Facilities), ref. /20/, is a revision of the former OLF model. It differs from the other models because it:

- Is the most comprehensive model
- Is the only model that takes into account the transient nature of a gas cloud
- Is based on a comprehensive statistical basis from the UK and NCS
- Is matched with PLOFAM such that an analysis combining PLOFAM and MISOF reproduces the historical frequency of ignited process leaks offshore
- Can take into account specific ignition sources such as the number of rotary equipment, air intakes for gas turbines and diesel engines, hot work and different levels of Ex-protection
- Can take into account emergency shutdown and isolation of ignition sources.

MISOF applies to process areas with a typical equipment density for an offshore facility, not to a widely spread facility with relatively empty regions between discrete process areas where the density of potential ignition sources is low.

For exposure of non-Ex equipment in unclassified areas, MISOF has a simple correlation between the ignition probability and the volume of the exposed area. It can be used in all areas that have comparable density of electrical equipment as an unclassified area offshore.

MISOF has no model for ignition sources outside the plant boundary, only for standard process equipment and hot work (except for air intakes for diesel engines and turbines). Such sources of ignition must therefore be considered separately.

The level of detail in MISOF requires a comprehensive analysis in which transient clouds need to be modelled. The advantage is that it provides a significantly more design-specific ignition probability than RIVM or OGP/UKOOA. Hence, it provides a significantly greater opportunity to investigate the effect of various measures for reduction of ignition probability in a plant.

It should be noted that MISOF is based on offshore process modules where the equipment density can be assumed to be higher than for typical onshore facilities (which often have more area available), and it is therefore expected that MISOF on average gives a somewhat conservative estimate for classified areas on land.

3.6.5 Hydrogen ignition model

Hydrogen is highly flammable over a large 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 (HyRAM-model, ref. /21/) recommends a model for ignition of hydrogen. In this model, 2/3 of the total ignition probability is immediate ignition and 1/3 delayed ignition. Immediate ignition leads to fire, while delayed ignition leads to explosion (with a subsequent fire).

However, HyRAM states the ignition probability in step functions and has no refining of leaks above 6.25 kg/s (all leaks above 6.25 kg/s have the same total ignition probability of 35%). In addition, the literature, see for example ref. /22/, 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. In ref. /23/ a new ignition model is presented which is based on the DNV model for small leak rates, while it is improved by being made continuous as a function of leak rate and it takes into account that large leaks may have a significantly higher ignition probability than that as the HyRAM model suggests. The same model is later presented in /22/, which in contrast to /23/ is also publicly available. This new HYEX model in ref. /22/ and /23/ 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 instantaneous ignition and delayed ignition is the same as for the DNV model (2/3 instantaneous ignition). Note also that the model presented in ref. /22/ and /23/ 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. /22/ and /23/) is therefore recommended as an ignition model for hydrogen leaks.

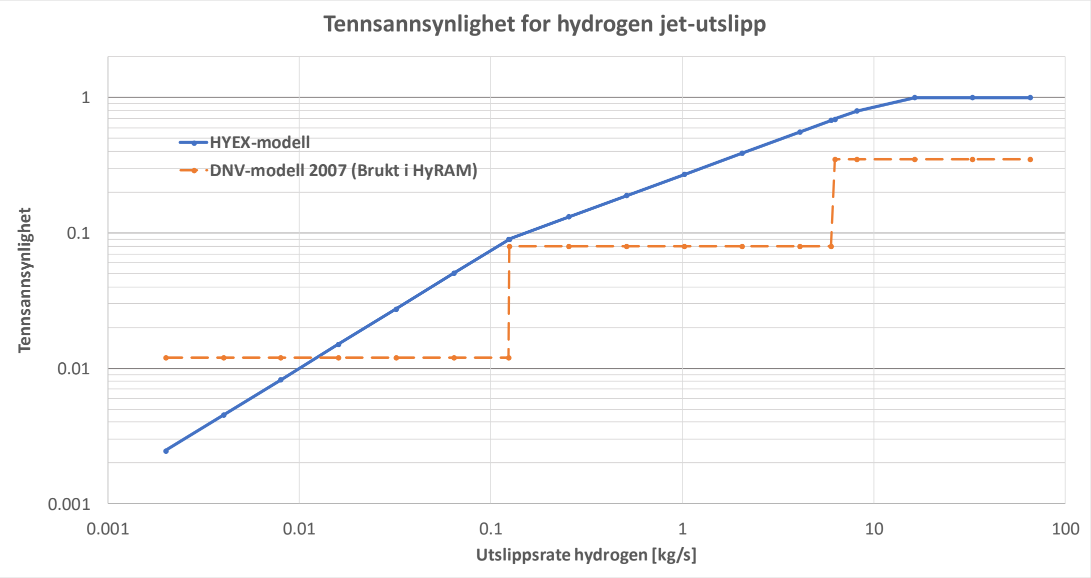

Figure 3.6 – Recommended total ignition probability for hydrogen leaks, ref. /22/ and /23/ (figure in Norwegian)

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

In the event of a tank rupture, however, 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 is to be used for explosion calculations. Here, HYEX recommends keeping 1/3 delayed ignition probability and explosion corresponding to 20-50% of the energy until experiments indicate otherwise. 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 (LH2), the back pressure and thus the kinetic energy in the leak is lower than for unobstructed jet leaks. Due to lower emission torque and lower temperature, it is not unlikely that the ignition probability will be lower. On the other hand, a discharge of liquid hydrogen will result in slower dilution in air, and thus longer hazard distances. In addition, the cloud will show heavy gas behaviour (heavy referring to the gas being heavier than air) and stay along the ground up to several hundred meters for large emissions. As an example, DNV GL performed experiments on behalf of the Norwegian Public Roads Administration with emissions of liquid hydrogen in 2019/2020, where 22-23% hydrogen concentration was measured 30 m from releases of 0.8 kg/s LH2 (ref. /24/). 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 LH2 emissions and ignition, the model can be considered adjusted, 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 for leaks that can fill the entire room to concentrations above 8% to adjust delayed ignition probability in the following way:

$$\begin{aligned}&Delayed\ enclosed\ ignition\ probability\\ &\qquad = Minimum(1.0 - P(early\ ignition); 0.018\ x\ Room\ volume^{0.35})\end{aligned}$$

In this equation, $P(early\ ignition)$ 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 leak rate, while delayed ignition is a function of 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 .

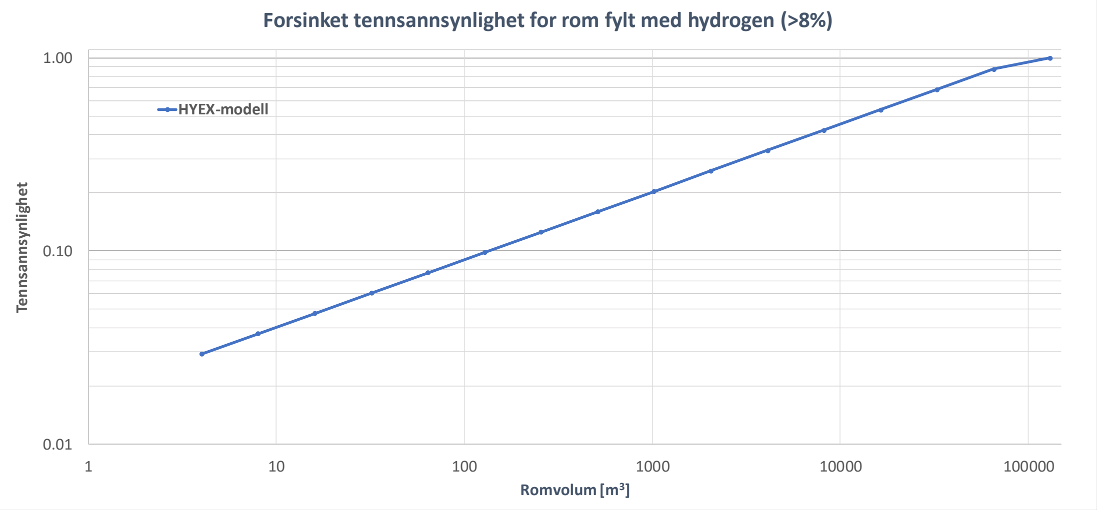

Figure 3.7 – Recommended conditional contribution from delayed ignition indoors (figure in Norwegian)

3.6.6 Ignition outside the plant boundary

In order for the consideration zones to be expedient in spatial planning, they must be independent of what is outside the facility boundary.

It is nevertheless desirable that the consideration zones reflect the design of the facilities and associated safety systems. Since there is no ignition source control outside the plant boundary, the assessment of ignition outside the plant must be based on whether the plants have safety systems that can reduce how far outside the plant the flammable cloud can reach, and how long the flammable cloud will remain widespread before the leak is stopped. That is, the type of ignition sources (discrete and continuous) and their ignition intensities (probability of ignition given exposure) cannot be part of the assessment.

The total cumulative ignition probability shall be equal to 1.0 for all leaks that result in a flammable cloud outside the plant's own area (see also Chapter 3.6.1). But this does not mean that all leaks should ignite immediately when they reach outside the plant. A recommended way to distribute the ignition probability in the area surrounding the plant, so that the total (cumulative) ignition probability is 1.0, is described below. This is intended as a simple mathematical approach to prevent all the gas clouds from igniting at the plant boundary and that the longer the flammable cloud persists at the largest extent, the greater the proportion of fatality occurring closer to the maximum extent.

The main principle in the mathematical model for ignition outside the plant given in this chapter is thus that total ignition probability is equal to 1.0, but the lethality in any point is proportional to the fraction of the scenario duration this point is located inside a flammable cloud.

Leaks must be fully calculated as a steady state (where the cloud size no longer changes), and the distribution of ignition at different cloud sizes must then be calculated on the basis of the time it takes to reach a steady state compared to how long the leak remains at the steady state. If a leak is detected and stopped quickly, the gas cloud will be at the steady state size for a short time and a larger proportion of the ignition must be expected to occur before the leak has reached its largest extent (steady state). A reduction in lethality furthest from the leak can thus be determined.

To determine the reduction in lethality as a function of distance from the leak point, one can generally assume that the area is a power function of the length from the leak point. For diffusive leaks (from bunds and for jet leaks pointing straight down) a square dependence is a good approach, but for larger horizontal jet leaks the area of the flammable cloud will be more proportional to the length, see also Figure 3.5. Area proportional to the square of the length is conservative and is therefore used in the model for reduction in lethality. If one had assumed that the flammable cloud was proportional to the length (and not the square of the length), one would get the same formula as given below, but the result would be straight lines of lethality between release point and maximum extent in Figure 3.8 . Note that the formula below does not in principle discuss ignition sources outside the plant, as this in any case is outside of the operator’s control. The cloud is always assumed to ignite, the point is only to distribute the ignition probability over different cloud sizes. This is done by assuming that the flammable cloud spreads at a steady velocity from the leak point and that ignition is at all times proportional to the area x time from the start of leakage of the flammable gas.

The distribution of fatality is determined by the distribution of ignited cloud sizes, which in turn are calculated from the leak point by integrating the area over time. Assuming that the spreading rate is linear, i.e. $x = v \cdot t$, this corresponds to integrating over distance corrected with the scaling factor $1/v$. This is in practice easier than integrating over time because one does not have to take into account the spreading velocity (and thus time) as this is shortened away in the ratio between the integrals. The expression for fatality rate at a point (x) can then be calculated as:

$$Fatality\ rate(x) = 1.0 - \frac{1}{(1+RV)\int_0^{X=max} A(X)dX} \int_0^{X=x} A(X)dX$$

where

x	= horizontal distance from the leak point
$A(X)$	= area of flammable cloud when it is X meters from the leak point (equal to the square of the distance from the leak point), assuming $A(X) = x^2$
$\int_0^{max} A(X)dX$	= the sum of all the areas in the model (for example, if you divide the reduction model into max =100 distances from the leak point to the maximum extent, $\int_0^{max} A(X)dX$ will be the sum of the 100 areas formed between the discharge and the 100 distances).
RV	= relative duration x (n+1) where n is the power that the area depends on the distance, which is expressed by (duration where the leak is at steady state) / (duration from start of leak to steady state) x (n+1). For a square area dependence (n = 2), RV = 3 implies that it is assumed that the duration at the steady state is equal to the time it takes to reach the steady state.

The distribution of cumulative fatality rate is illustrated in Figure 3.8 where the distance from the discharge to maximum extent of the cloud is divided into 100 equal distances (which means that it can be read as a proportion of maximum extent). This figure shows that the total ignition probability for the scenario is 1.0, but since not all clouds ignite at maximum extent (steady state), the areas furthest from the discharge will have less lethality than the areas closest to the discharge. The figure also shows that the longer it takes before the leak is stopped, the higher the lethality at the largest extent of the cloud. If the relative duration is high, the lethality approaches 1.0 in the entire steady state cloud. If you do not know the duration of the discharge, you can simply assume that the duration is long and that the consequence can thus be modelled by igniting the cloud at its longest extent and setting the lethality equal to 1.0 in the entire area covered by the steady state cloud (i.e. no reduction in lethality due to rapid shutdown of the leak). If you have safety systems that stop the leak immediately after the stationary cloud is reached, one must still assume that the flammable gas will be close to its maximum extent for about as long as the time it took to reach the steady state (only that the gas is thinned from the discharge and beyond towards the largest extent). In these cases, it is recommended to set relative duration = 1 (this is also why this curve is given in orange in Figure 3.8).

Note that the model used for the distribution of fatality rate per scenario in principle stipulates that the main part of the ignition sources in the remote field can be assumed to be discrete ignition sources (they come suddenly and randomly). If one could assume that all ignition sources were continuous, the flammable cloud would ignite at 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 .

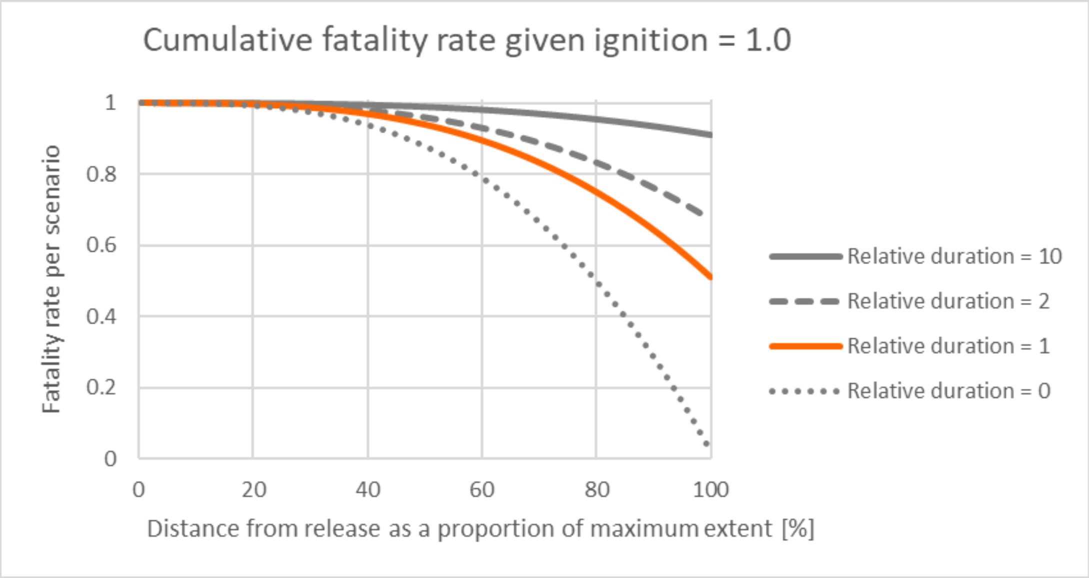

Figure 3.8 – Fatality rate distribution per scenario as a function of relative duration of the leak

With a total ignition probability equal to 1.0 and using a fatality rate distribution as shown in Figure 3.8 , the outermost 1% of the flammable cloud will have a lethality of

2% at relative duration = 0,

51% at relative duration = 1,

67% at relative duration = 2, and

91% at relative duration = 10.

The innermost 1% of the cloud (at the discharge) will in all cases have a lethality of 100% when the combustible gas cloud is ignited outside the plant.

The values 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 equations above directly, or one can interpolate between the characteristic lengths in Table 3.2 .

Table 3.2 – Lethality at characteristic relative lengths of the cloud (given ignition)

Relative duration:	**Relative distance from leak to longest extent of 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 the same procedure as one uses for probit functions and give different lethality for different locations for the same scenario (see also Chapter 4.1).

3.6.6.1 Ignition at sea

Ignition over 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	Model
Within the plant boundary	No calculation of exposure probability. No time-dependent ignition probability, alternatively time-dependent for a constant cloud size	OGP (with adaptations for diffusive leaks, see Chapter 3.6.3)
	Calculation of exposure probability. Time-dependent exposure probability. Operating regime as for a large plant or offshore	MISOF for process areas in the plant
	Explicit consideration of special ignition sources (gas turbines, diesel engines, pumps)	MISOF (requires exposure probability calculation)
	Fired units	Considered specifically for each device, RIVM for easier analysis
Outside the plant boundary	Cumulative ignition probability = 1.0	See Chapter 3.6.6
Special substances	Hydrogen leaks	HYEX, 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 (atomized 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 switch to a detonation that gives an overpressure in the range 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 approx. 15-20 times higher than the initial overpressure.

The size of the flammable cloud is usually significantly smaller than the distance to the plant boundary, and it is therefore mainly the overpressure propagation beyond the flammable cloud that decides the societal risk contours. The overpressure outside the cloud is determined by the explosion overpressure inside the cloud and the size and shape of the cloud. However, the overpressure reduces outside the cloud in such a way that when the overpressure inside the cloud exceeds 0.5 - 1 barg (50-100 kPa), additional increase in overpressure has only moderate impact on the overpressure outside the cloud (except quite close to the cloud). This means that for the assessment of strong explosions it is important to control the size of the cloud during ignition, as this determines how quickly the overpressure decreases outside the cloud.

In cases where rupture of equipment due to explosion can result in a significant escalation of the incident, such as the release of toxic substances or large quantities of hydrocarbons, the explosion analysis inside the plant must be sufficient to assess the extent to which equipment may rupture. The required extent and methodology for such analysis depends on the ratio of the expected explosion loads to 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 range of leak rates. NORSOK Z-013, Annex F, recommends that at least 9 leak rates are used for analysis 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 insignificant consequences to the largest clouds that may occur. The aim 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 plant, 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, detonates more easily than other substances, and in such cases, it is especially important to consider the energy from the entire flammable cloud (and not just the one within an obstructed area).

For events inside a building or process equipment, the cloud size will be limited by the size of the building or equipment. For such scenarios, a significantly smaller release will be required to achieve hazardous gas clouds/dust clouds capable of causing significant localised damage. However, the far field pressure wave energy will be limited.

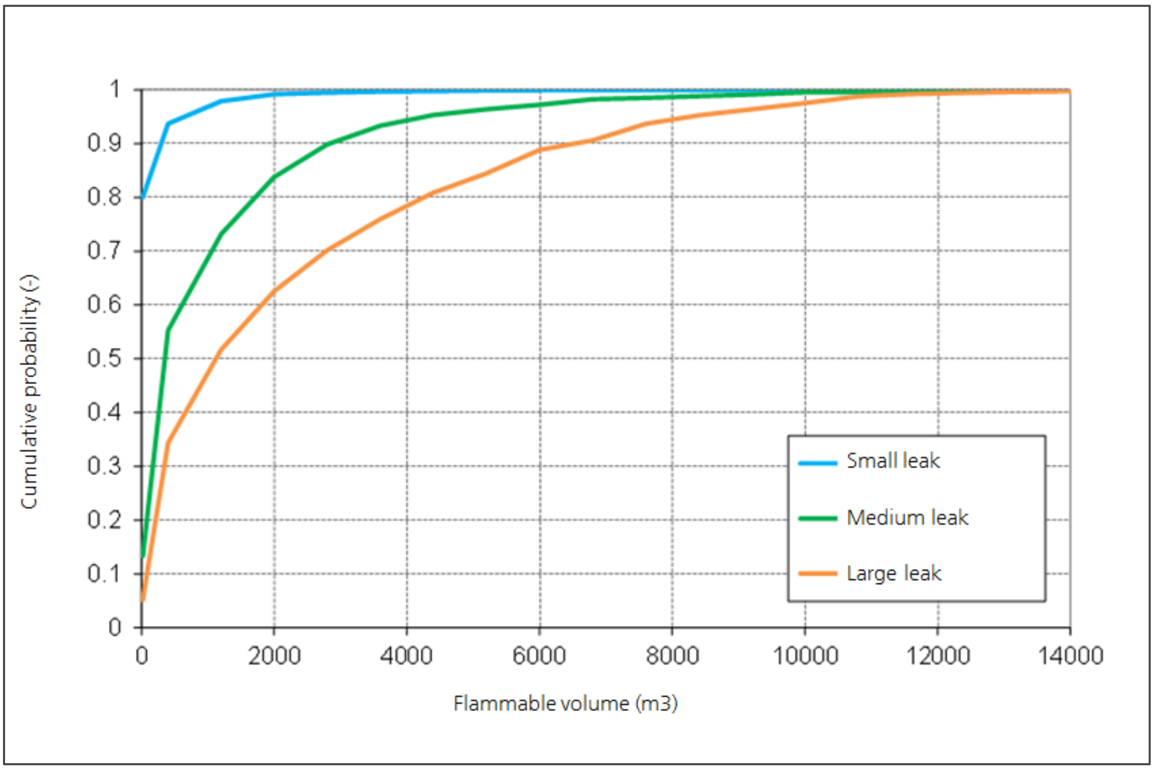

Figure 3.9 – Example cumulative probability distribution of flammable cloud size, by leak size. In this figure there is a 78% probability that a large leak will result in a flammable cloud size of 4,000 m^3 or less (and a 90% probability of a cloud size of 6,500 m^3 or less)

By combining information about flammable cloud sizes and ignition sources (see section 3.6), a relationship between ignited cloud size and frequency of occurrence can be established, see Figure 3.10.

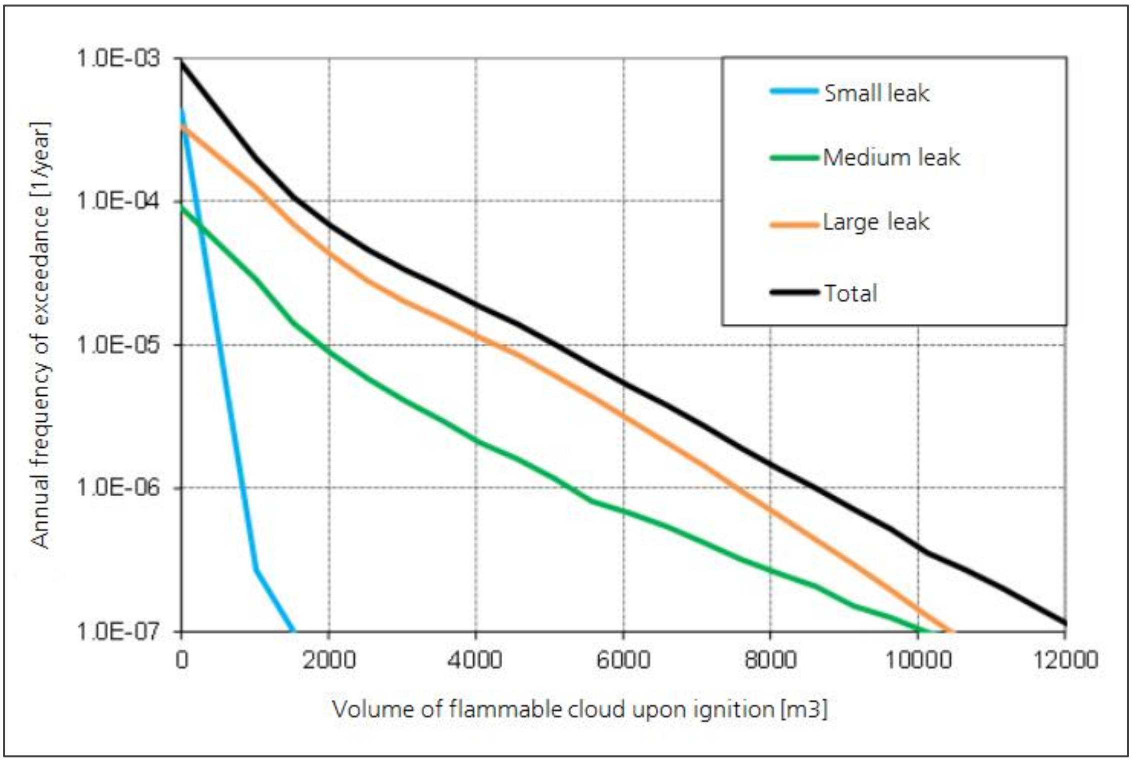

Figure 3.10 – Example ignited cloud size exceedance frequency graph, by leak size. In this figure the total frequency for igniting a cloud greater than or equal to 5,000 m^3 is 1E–5 per year. The total ignited release frequency is 1E–3 per year

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

3.7.3 Calculation of explosion overpressure within a flammable gas cloud

For determining the risk level outside the flammable cloud, the overpressure within the cloud (source overpressure) can be estimated by simpler models, for example as described as source strength in ref. /27/. This gives an overpressure irrespective of the size and shape of the cloud and is used in the so-called multi-energy method for overpressure propagation outside the cloud.

Alternatively, the source overpressure within the flammable cloud can be determined more precisely taking into account possible cloud sizes and associated frequencies. A recommended standard for establishing an overpressure-frequency distribution within a flammable cloud is NORSOK Z-013 (ref. /25/), this requires the use of CFD simulations for both gas dispersion and explosion overpressure. This methodology provides an estimate of the relationship between cloud size and explosion overpressure. When using CFD for input to the Multi-energy method, it is recommended to use a representative source overpressure from each simulated CFD scenario corresponding to 50% of the highest overpressure measured in a control volume for that scenario.

When using CFD to calculate explosion overpressure it is very important to have a good 3D description of geometry, if the geometry model's detailing degree is too low, this will non-conservatively provide too low explosion overpressure. In addition, it is important to evaluate a variety of scenario variations (cloud location and ignition points) to adequately expand the output space.

3.7.4 Calculation of explosion overpressure in far field

When the frequencies of different ignited cloud sizes and associated overpressures are known, the associated explosion loads can be established in the far field by calculating the overpressure propagation outside the cloud. This can either be simulated by CFD or calculated with simpler models like the multi-energy method (see for example ref. /34/, ref. /27/ and ref. /26/).

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

A key parameter in the multi-energy method is the efficiency factor ("Efficiency factor" in ref. /27/). This indicates the amount of combustion energy in the cloud that, in practice, contributes to the generation of an ideal pressure wave and effectively reduces the cloud size accordingly. This factor therefore has a significant impact on how quickly the overpressure decreases outside the flammable cloud. Guidance on selection of efficiency factor can be found in ref. /27/ based on ref. /28/. The efficiency factor will in principle increase with overpressure, and for detonations, it is 1.

As the overpressure in the far field becomes less dependent on the source overpressure in the flammable cloud if it is over approx. 1 barg, the far field overpressure in such situations is determined only by the cloud size and 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 overpressure in the cloud is > 1 barg and using a high efficiency factor.

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

See Chapter 4.2.4 for tolerance limits for explosion loads.

3.8 Fire analysis

With regard to simulation of fires, the choice of scenarios will have a big impact on the size of risk contours. When the scenarios are defined the energy of the combustion will also be established, and the fire analysis results are less dependent on the choice of simulation tool than for dispersion modelling, see Chapter 3.5.2. As a result, this Chapter provides only a high-level description of fires.

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 rise during combustion, the air in the flame will expand and can push the unburned flammable cloud outwards to approximately double 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, lethal heat intensity will extend slightly 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. /29/), 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. Unbiased models for flash fires require best estimate models of the flammable cloud. When assessing the lethality of flash fires outside the facility, it can be assumed that those inside the flammable cloud will die, see Chapter 4.2.3.

- Diffuse fires. If a liquid leak collects in a bund where the liquid can evaporate (either by boiling or by vapour pressure-driven evaporation), the vaporized gas can reach flammable concentrations that can ignite. In such cases, the fire will be controlled by the availability of flammable gas, and by the area inside the bund. Geometric factors regarding the bund, other than the area (which determines the flame height and extent), are usually of minor importance, but it is necessary to consider whether there are factors at the plant that can act as shielding of heat load towards the surrounding environment. Diffuse fires will continue to burn for as long as there is a supply of flammable gas and can therefore last for a long time and radiate large amounts of heat to the surrounding environment. 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 amount of smoke upwind and hence the radiation in that direction will be higher.
- Jet fires. A high-pressure gas or liquid release will generate a high momentum jet or spray with a high discharge velocity. This jet will result in a high degree of mixing of the gas or liquid droplets with air and can therefore burn with very high intensity and emit large amounts of heat to the surrounding environment. Jet fires can continue to burn for as long as the supply of flammable material is sustained and can therefore last for a long time. There is usually not much difference in heat loads generated by gas jet fires and spray fires.

Typical heat loads for different fire types are given in NORSOK (ref. /30/) and FABIG (ref. /31/). Hydrocarbons have higher combustion energy than most other flammable substances and therefore normally represent a higher fire risk. For fire properties of substances other than hydrocarbons, reference is made to ref. /32/.

In addition to heat load, smoke from the fire must be taken into consideration, as this may affect the size of the risk contours. This is particularly important where the combustion process generates toxic gases. For example, chlorinated hydrocarbon fires will produce hydrochloric acid. Another example is a fertilizer fire, which results in the generation of nitrous gases. FABIG (ref. /33/) has stated 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. Lethal concentrations of CO outside the hot areas will normally only occur in fires in enclosed spaces where there is limited access of oxygen and limited ventilation (smouldering fires).

Note that fire calculations, to a lesser degree than explosion calculations and dispersion calculations, depend on the selection of simulation tools (see Chapter 3.5.2), but if the characteristics and consequences of a fire are significantly affected by obstacles, CFD should be considered (see guidelines in Chapter 3.5.2). In particular, this applies to the assessment of escalation barriers and risk exposure for the public immediately outside the facility.

3.9 BLEVE and other events

3.9.1 BLEVE

BLEVE (Boiling Liquid Expanding Vapor Explosion) normally occurs when a pressure vessel with fluid significantly above the boiling point temperature ruptures. This can result in different scenarios and could generate significant heat loads, projectiles and possibly overpressure waves. However, because the term BLEVE is often used to describe a wide range of incidents, it is important to consider what may actually happen when a tank ruptures.

Rupture can occur either if the tank is weakened impaired due to exposure to heat (for example, an external fire) or due to failure of the tank for other reasons (without an external heat source), such as impact resulting from train derailment and collision. A BLEVE is often characterized as physical if the explosion is purely mechanical (expansion of gas due to phase transition resulting from pressure drop) or as chemical if a chemical reaction (fire or explosion) further contributes to the consequence severity. Therefore, the different constituents of a tank rupture scenario must be considered separately to get a complete consequence picture, see for example. ref. /34/ Chapter 6.5.7, ref. /35/ and /36/. The formulas in ref. /34/ apply to LPG, for fluids with other molecular weights, corresponding formulas in ref. /37/ can be used.

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

- In a tank with pressurized gas, the expansion of the gas at rupture will generate a pressure wave in the environment. This primary pressure wave is not normally considered as part of the BLEVE phenomenon, but it can generate the highest pressure if the storage pressure is high, the gas phase to liquid phase volume ratio is significant, and the distance to the public is small or there is considerable degree of enclosure around the tank
- If the liquid temperature at rupture is above the boiling point at atmospheric pressure, but not superheated (i.e., the temperature of the liquid when rupture occurs is higher than the boiling temperature of the liquid but lower than the superheated temperature, where $T_{Superheated} \sim 0.89\ T_{Critical}$), liquid will boil when the tank ruptures, but not rapidly enough to generate a strong pressure wave (so-called "cold" BLEVE). However, 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 and will not 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 due to instantaneous expansion will set up a strong shockwave ("hot" BLEVE), in addition to a fireball if the liquid is flammable and ignites. This secondary pressure wave can often occur simultaneously with or soon after the primary pressure wave from the gas cap. This scenario is most often associated with BLEVE, and there are standard formulas for height, diameter, and duration of fireball, such as in ref. /34/. If the pressure generated in a BLEVE is calculated, one must take into account the pressure, temperature, and volume of the liquid in the tank and the size of possible gas cap.

Note that it is the liquid temperature at rupture that determines if a cold or a hot BLEVE will occur. For example, rupture of a tank with propane at ambient temperature will give a cold BLEVE, but if a fire around the tank heats the propane to more than about 50 ˚C it will become superheated and a hot BLEVE will occur.

In addition to overpressure and heat radiation from a BLEVE, large and small fragments of the tank shell will be expelled as projectiles and could constitute a significant societal risk factor, for data see for example, ref. /36/.

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 a BLEVE (BLCBE - Boiling Liquid Compressed Bubble Explosion), although the liquid is not superheated (ref. /38/). 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 of the amount of liquid that will atomise into droplets and not rainout in the event of tank rupture must be made. This can be estimated by calculating what amount of the liquid can boil at rupture. Multiplying this by the tank pressure gives an expansion factor E. Analysis of the RELEASE experiments with different fluids, ref. /39/, shows that the proportion of liquid that is atomised into droplets is roughly proportional to E, where all liquids can be assumed converted into liquid droplets at E ~ 100. The potential pressure wave can be calculated for rupture of a tank based on total gas volume = initial gas volume + volume of released gas, all at the pressure of the tank.

3.9.2 Roll-over and boil-over

In tanks with low-temperature liquids like LNG and ammonia, layer splitting may occur due to evaporation or refilling of liquid with different density. If the bottom layer is heated, the density decreases until the layers mix. The evaporation rate then increases far beyond normal, and if this has not been adequately considered in dimensioning the tank safety valves, the tank may be over-pressurized.

The risk of roll-over is difficult to determine but should be checked by having operational control of factors that lead to stratification in tanks; primary composition, temperature and density of liquid being loaded, as well as aging (density change through evaporation). There are several models for monitoring the state of the liquid and predict roll-over with associated evaporation rate, see for example ref. /40/.

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

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. If the fire heats the tank for a prolonged period, the water will eventually start to boil and expand, and subsequently atomise the oil into droplets. The result is a huge increase in fire intensity, often in the form of a fireball, with an increase in associated hazard distances. The risk of boil-over is best controlled by minimizing or removing water at the bottom of storage tanks at all times. A comprehensive overview of the phenomenon and related calculation models for time to boil-over and residual volume of liquid is given in ref. /41/. Similar issues may occur in pressurized separator tanks (water, oil, gas) if the content is heated above the atmospheric pressure boiling point for water before tank rupture.

The likelihood 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, do not directly affect societal risk contours. However, it is important to consider whether a small event can escalate to a larger one that can affect the surrounding environment. Typically, this may be a limited fire or explosion, which causes rupture of equipment and release of toxic substances or greater amounts of flammable material. Important factors to be considered are 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 3.4.2.7.

3.10 Establishing risk contours

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

By using symmetry considerations and simplified physical modifications, one can reduce the number of scenarios one actually needs to simulate. 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 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).

Although the leak frequency distribution can be considered to be representative of the plant (see Chapter 3.4.2) and the simulated scenarios are performed with the correct simulation tool in relation to the guidelines in Chapter 3.5.2, it is still crucial that a sufficient number of incidents is 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.

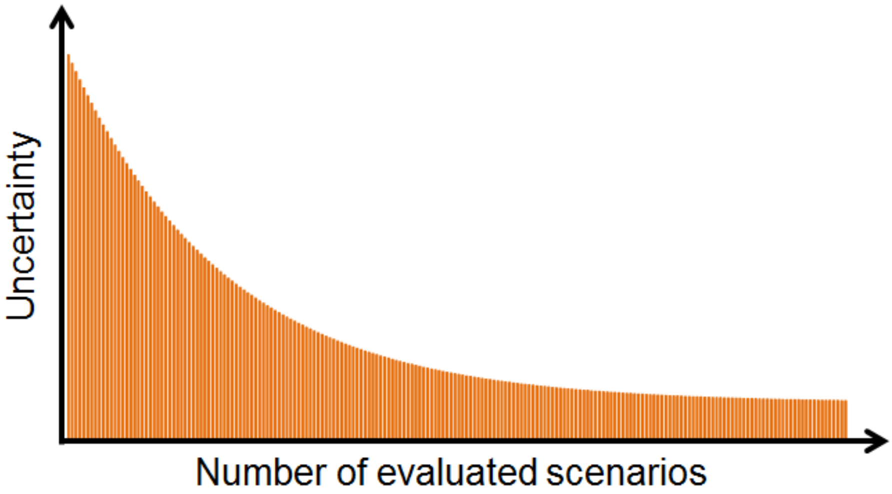

Figure 3.11 – Uncertainty as a function of the number of evaluated scenarios – illustration

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 amount of calculations needed for the various impact assessments (fire, dispersion and explosion) will also vary.

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

- First, sufficient 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 because the contours have tags/arms associated with the simulated individual scenarios), the simulated scenarios can be used to estimate scenarios that are considered sufficiently similar to those 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 preserve the physics directly, but only represent a smoothing of the result field.

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

- Effect of number of simulations
- Interpolation of simulated scenarios
- Number of leak points
- Number of simulated rates

- Smoothing of the risk contours
- Refine the risk contours in critical areas

3.11 Description of uncertainties

All assessments that significantly affect 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 unbiased (best estimate) risk contours:

- Frequency evaluation. The frequency of the top event represents the analysed facility with all relevant physical attributes and barriers to reduce leaks, see Chapter 3.4. An assessment must be made as to whether the selected frequency model is representative for the plant to be analysed and how any deviations are compensated for.
- Physical modelling. The physical models must adequately assess the physics, see Chapter 1.2. Selection of physical models and calculation tools shall be discussed in relation to whether they adequately model the physics of the scenarios. Uncertainties related to the use of probit functions and threshold values shall be discussed when relevant.
- Modelling of possible outcomes. The assessment shall discuss 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 considered such that convergence cannot be demonstrated, the effect on the risk contours should be discussed.

Sensitivity analyses should be used to identify the parameters or assumptions where the uncertainty has the largest impact on the risk contours, ref. Chapter 3 of the DSB report «Sikkerheten rundt anlegg som håndterer brannfarlige, reaksjonsfarlige, trykksatte og eksplosjonsfarlige stoffer» (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 should therefore be selected amongst parameters and assumptions that have not already had variations applied in the analysis.

In addition to frequency, physical modelling and possible outcomes, special assessments that are expected to give rise to uncertainty in risk contours shall be discussed. An example of this is the ignition model, see Chapter 3.6. If this has a significant impact on the risk contours, the uncertainty related to the ignition model should also be discussed in the risk analysis. The same applies to uncertainties related to tolerance limits for lethality, see in particular Chapter 4.2.2 for toxicity. However, it is not necessary to quantify uncertainties relating to the risk contours. Sensitivity analyses and uncertainty assessments should initially be described qualitatively. However, there will be benefit to quantifying sensitivity analyses for alternative plant designs or risk mitigation measures at the plant, such as safety systems or physical barriers, if they change the risk contours.

4 Vulnerability criteria

4.1 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 representing "all" events that may occur and the associated exposure levels (concentration of toxic substances, flammability, heat load and explosion load). But before one can establish a fatality risk contour, one must have a model that indicates the exposure level that is considered to be fatal. Choosing thresholds for fatalities will affect the size of the risk contours. Below are recommendations for choice of vulnerability criteria.

Figure 4.1 illustrates how the choice of vulnerability criteria (for toxicity) affects risk contours for the same event. The concentration of toxic substance decreases with the distance from the leakage point, and if one sets the fatality criterion level at a low concentration (orange curve) or at a slightly higher concentration (green curve), one gets different risk contours for the same scenario simulation.

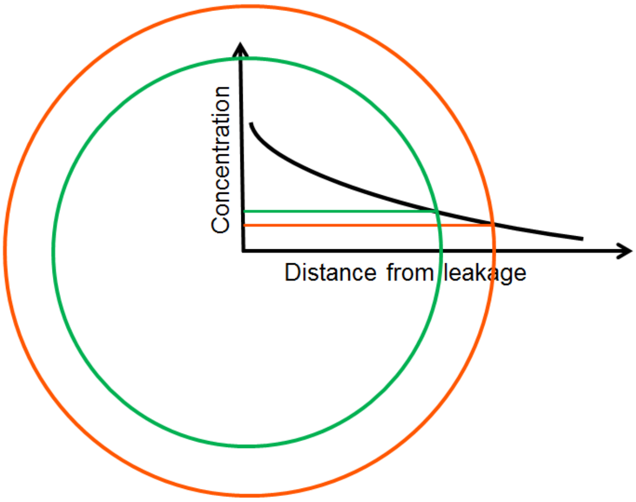

Figure 4.1 – Illustration of how vulnerability criterion for toxicity affects risk contours

There are two types of vulnerability criteria: threshold values and probit functions. Threshold values are binary in the sense that they say that for values below the threshold value there is no lethality, while for values above the threshold value 100% fatality rate is assumed. For probit functions, a gradual transition is assumed where fatality rate for doses below a low threshold is set to zero, and then there is an increasing probability of fatalities at increasing doses. For doses above a high threshold, 100% fatality rate is assumed. An advantage of using probit functions is therefore that a single scenario will have a gradual transition between 0% fatality rate and 100% fatality rate, and this will give smoother risk curves when adding the frequencies for all simulated and assessed scenarios. The use of probit functions therefore makes the risk contours less sensitive to the choice of which scenarios to simulate (because lethality is not binary but is distributed over a larger area). It is therefore recommended to use probit functions as much as possible when calculating risk contours. 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). This means that time for escape and evacuation must not be taken into account (see also Chapter 4.2.1).

If threshold values are used to calculate the consequences of simulated scenarios, the 50% fatality rate shall be used to determine the threshold value. This is in keeping with the goal of generating best estimate risk contours (for a probit function that is normally distributed the 50th percentile is the same as the mean value). If a threshold value is based on a probability function with a fatality rate of more than 50%, the risk contours will be non-conservative and, conversely, if a threshold value is based on a probability function with a fatality rate less than 50% it will lead to conservative risk contours.

If one uses the 50% fatality rate as a threshold for estimating fatalities for a single scenario, one also finds that a Gaussian smoothing of this scenario will result in a similar fatality distribution as would be obtained if one used the probit function to calculate fatalities. The reason for this is that both probit functions and Gaussian smoothing are normally distributed. This is illustrated in Figure 4.2.

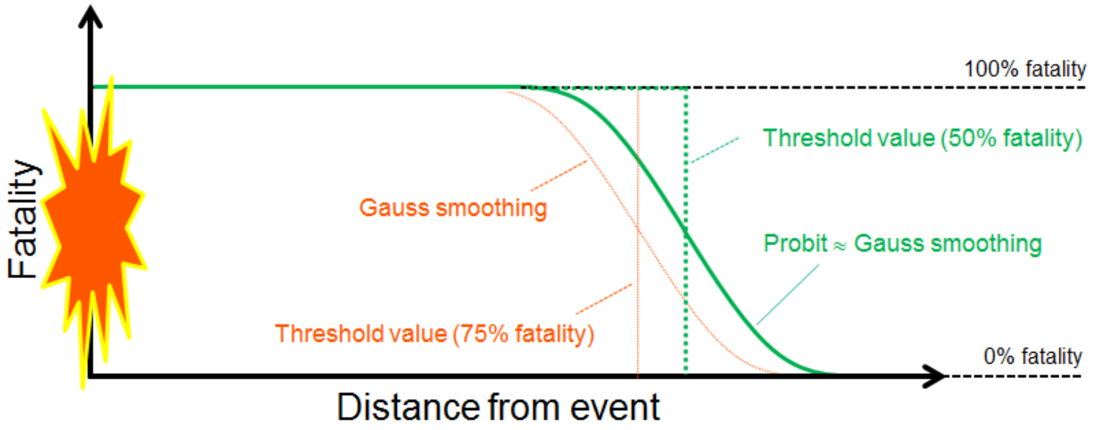

Figure 4.2 – Illustration that using the 50% fatality rate threshold value gives a similar curve to that for a probit function (see also Appendix B). If a threshold value with a fatality rate other than 50% is used, the smoothed curve will shift relative to the probit function (orange curve)

4.2 Recommended vulnerability criteria

4.2.1 General

It is recommended to use probit functions when calculating risk contours, see Chapter 4.1. Use of probit functions implies maximum exposure time for different probabilities of death. As it is not taken into account for how long any persons 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 thus be a limit for the duration of the scenario.

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 most unbiased (best estimate) risk contours as possible, a threshold value representing 50% lethality shall be used as a basis for the analysis, see Chapter 4.1.

If there are special uncertainties in the use of probit functions or threshold values, theese shall be described, see also Chapter 3.11.

4.2.2 Toxicity

DSB has on its website (www.dsb.no) an overview of recommended probit functions for the most commonly used substances in Norway. The probes recommended on DSB's websites shall be used to calculate risk contours.

If the substance is not in DSB's list of probit functions, it is recommended to use probit functions defined by RIVM. Current probit functions can be found in the Guidelines for Quantitative Risk Assessments "Purple book", ref. / 35/, published by the National Institute for Health and the Environment in the Netherlands (RIVM). RIVM has developed a general method, ref. /42/**.** 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 a probit functions status overview (ref. /43/). For most substances given in the overview, new probit functions are specified, with the status "interim" or "to be updated".

The Norwegian Defence Research Establishment (FFI) has on behalf of DSB, conducted a review of new and old probit functions from RIVM for a number of common gases with toxic properties ref. /44/. An excerpt from the summary of the report is reproduced here:

> *Probit functions are used as part of a quantitative risk analysis (QRA) of hazardous events, such as acute releases of hazardous substances. A probit function describes the relationship between the concentration of the hazardous substance, the duration of the exposure to the substance, and the proportion of the exposed population who suffer a certain effect, such as illness or death, as a result of the exposure. The National Institute for Health and the Environment in the Netherlands (RIVM) has developed a new method for deriving probit functions. Changes in probit functions as a result of the new method can have consequences when risk contours are established, which in turn can affect land use plans and have economic consequences for society. In this assignment, the Norwegian Defence Research Establishment (FFI) has assessed the basis for the establishment of the new probit functions. The new and old probit functions for the substances sulphur dioxide (SO2), ammonia (NH3), hydrogen fluoride (HF), chlorine (Cl2), carbon monoxide (CO), hydrogen chloride (HCl), hydrogen sulphide (H2S) and sulphuric acid (H2SO4) have been evaluated and compared. Probit curves for different exposure times based on the new and old probit functions have been calculated. FFI considers that the basis for the establishment of the new probit functions from RIVM is well and truly founded. The new method uses safety factors to deal with uncertainty. These are based on criteria within the quality of the data base, nominal concentration, and variation between species of test animals. The comparison of the new and old probit functions showed that the new method had a relatively large effect on substances where the data base was deficient. FFI sees that there is a need to deal with uncertainty in the data base, but it should be considered whether the use of safety factors on probit functions is the most appropriate way to deal with the uncertainty. The new method leads up to a worst-case approach. Such an approach will provide a risk contour that is very safe for society, but very costly, and probably far from reality.*

New and old probit functions are reproduced in the report, and probit functions have been derived without the use of a safety factors for some of the substances. Recommendations have also been made on further work for a better basis regarding the use of the new probit functions and the assessment of uncertainties.

In line with the objective of calculating unbiased (best estimate) risk contours (see also Chapter 4.2.1), DSB recommends that safety factors not be used when using probit functions. This presupposes that the uncertainties associated with the use of the probit functions are described in the risk analysis, see Chapter 3.11. Furthermore, reference is made to Chapter 1.3, where as one of several overriding principles, it is assumed that "uncertainties related to the information basis and use of methods shall be assessed, but not quantified."

If the probit function is not available, LC50 can be used as threshold values. LC50 is used for the concentration (lethal concentration) of a chemical in air that gives 50% fatality rate at a given exposure time, normally 4 hours. The largest database of threshold values is RTECS (Registry of Toxic Effects of Chemical Substances), ref. /45/.

If LC50 is also not available, one can use AEGL-3 values, ref. /46/. When using AEGL-3, one must be aware that these values are not meant to represent concentrations that give 50% fatality rate, they represent the smallest concentrations that give fatalities in a population. Exactly what this means may vary, but it can generally be assumed that AEGL-3 represents in the order of 1% fatality rate. This means that it is significantly on the conservative side if it is used directly to create risk contours. According to the US National Research Council, ref. /47/, 50% fatality rate is typically in the range of 1.1 to 6.5 times the AEGL-3 value. Furthermore, they found that the 90th percentile is at 2.9 and the 95th percentile is at 3.5. If the association between AEGL-3 and 50% fatality is not stated, it is recommended to use a factor of 3 on AEGL-3 when calculating risk contours.

Inert gases such as N_2 are not toxic in the toxicological sense but can still be lethal by displacing O_2. Ref. /48/ provides the following probit function for low O_2 level based on data in ref. /49/:

$$\mathrm{Pr} = -65.7 + \ln\left(C^{5.2} \cdot t\right)$$

where C is the concentration in ppm and t the time in minutes.

CO_2 also displaces O_2 and in addition, it is toxic at higher concentrations and may therefore be fatal even though the O_2 level is not. The recommended probit function for CO_2 is given on DSB's website, together with probit functions for some acutely toxic substances.

4.2.3 Fires

Clothing will provide a degree of thermal radiation protection, depending on the amount and type of clothing. TNO also provides a probit function for fatalities resulting from ignition of clothing. However, there will be significant uncertainty associated with the proportion of the public that will be adequately protected by clothing. Furthermore, it will complicate the risk calculations considerably if probit functions or threshold values are required for both unprotected and protected members of the public, or for ignition of clothing. Risk contours will also be dependent on the assumption of degree of protection, which is not appropriate. It must therefore be assumed that the public do not have protection against heat radiation.

For the calculation of risk contours for fires resulting from ignition of a gas cloud, the threshold value for fatalities is set to be the lower explosion limit (LEL). For emergency scenarios, it may in some cases be necessary to use the distance to ½ LEL.

For heat radiation, TNO, ref. /34/, Chapter 1, Eq. 3.5, gives the following probit function for fatality due to exposure with bare skin:

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

where the received dose is

$$D = t\, q^{4/3}, \qquad q\left(\frac{kW}{m^2}\right), \mathrm{t(s)}$$

The correlation between heat flux and duration corresponding to the 50% fatality rate (i.e. Pr = 5) is shown in Figure 4.3. A lower limit of 1.5 kW/m^2 has been set corresponding to the threshold for unmanageable pain in TNO (ref. /50/, Chapter 1, Section 2.6).

If threshold values are used to assess the consequences for the simulated scenarios, account needs to be taken of the fire duration (t) associated with the fire scenarios simulated and the heat load equivalent to a 50% fatality rate from the probit function used as a threshold value. The threshold values for different durations are indicated in Table 4.1 (figures can also be read from Figure 4.3).

Note that the highest heat flux given in Table 4.1 is 15 kW/m^2, with a corresponding exposure time of 28 seconds. However, it is advisable to use a higher threshold value than 15kW/m^2 and/or shorter exposure time than 30 seconds when determining the 50% fatality rate threshold value for heat radiation.

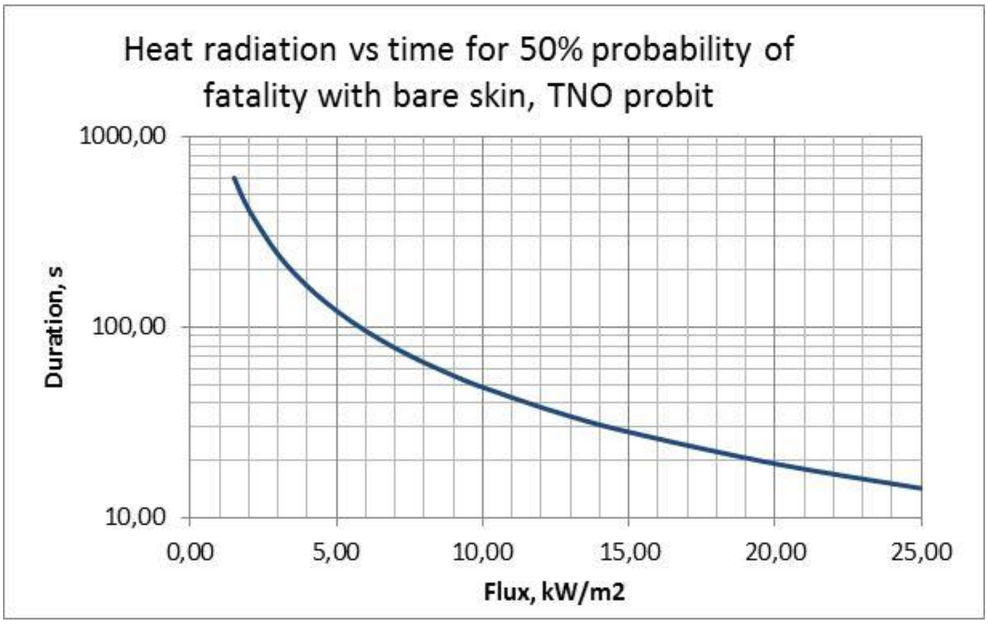

Figure 4.3 – Correlation between heat flux and associated duration for 50% fatality rate for unprotected exposure (bare skin)

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

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
49 seconds	10 kW/m^2
28 seconds	15 kW/m^2

In addition to the heat load, the flue 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 largest consequence (of heat and smoke) is chosen 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 flue gas (for example, chlorinated hydrocarbons can emit hydrochloric acid and fertilizers can emit nitrous gases). In the case of toxic gas emissions during fires, this must be considered 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 spread in the far field. For fatality rates, probit function is used if it is available, if not, the threshold value for 50% fatality rate is used.

For flash fires, it can be assumed that those who are inside the flammable cloud will be killed, while those who are outside survive. This is a simplification that both contributes to simpler analyses, but which 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 unbiased. In the non-conservative direction, the most important factor is the fact 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 area of the plant (see Chapter 3.6.6).

4.2.4 Explosions

4.2.4.1 General

The tolerance limit for explosion depends on many factors that are not easily summarized; effect of projectiles, collapse of buildings, broken windows, people being thrown against hard surfaces, etc. These indirect effects of explosion can therefore lead to fatality for far lower pressure than that which results in direct death in the event of lung collapse. Because the 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 fatality as a result of explosion pressure.

In a note published together with the guidelines on DSB's website (www.dsb.no), ref. /51/, the various consequences of explosions are discussed. This note concludes that the most appropriate use for calculating risk contours for consideration zones is to link fatality rate to the collapse of buildings. Threshold values associated with 50% fatality rate 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

In determining threshold values, in accordance with Chapter 4.2.1, the starting point shall be 50% fatality rate in order to make the consideration zones as straightforward as possible. According to this, the threshold value is set equal to 50% fatality rate as a result of the collapse of a building from ref. /51/.

The recommended threshold values for calculating risk contours are presented in Table 4.1.

Table 4.1 – Threshold value for fatality due to explosion (50% fatality rate)

Duration of pressure waves	Threshold 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 modelling tools (both CFD and empirical tools).

In such cases, one must document how the special substance is modelled and how the uncertainty surrounding this can be assessed (see also Chapter 3.11).

These substances need to be evaluated specifically each time, but the following guidelines may be helpful in estimating the risks associated with these substances:

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

5 Simplified methodology

For some types of plants, 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. Further guidelines must be prepared before such a methodology can be used.

Table 5.1 show types of plants that are currently considered relevant:

Table 5.1 – Types of plants that are currently considered relevant for a simplified methodology

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

Different types of plants are defined in the guidelines for registration of hazardous substances /52/. The guidance states that "a plant unit can be an assembly of tanks, pipes and equipment that make up an entire plant or part of a plant". The list above is somewhat more detailed than in the guide. In addition, reference is made to relevant standards for the plant types.

6 Presentation of results

6.1 Communication of small frequencies

It is recommended that risk analyses try to give the reader a perspective on how to interpret the risk results and how the plant's calculated risk level compares to risk levels for everyday hazards found in society. One way of doing this is to compare the individual risk values in the areas around a facility with general fatality rates in society, see Figure 6.1. This figure shows that for the age group in Norway with the lowest individual risk (5- to 10-year-olds), the average fatality rate is 1.0E-4 per year, which means that in any given year there is on average about one fatality for every 10,000 people in this group. Comparing this to the individual risk criterion for the outer consideration zone (where the exposure probability for fatal loads is less than 1.0E-6 per year), this means that the plant represents an additional risk of less than one percent of the individual risk for members of the public. For areas beyond consideration zones (individual risk requirement of less than 1.0E-7 per year), the plant represents an additional individual risk factor of less than one in a million.

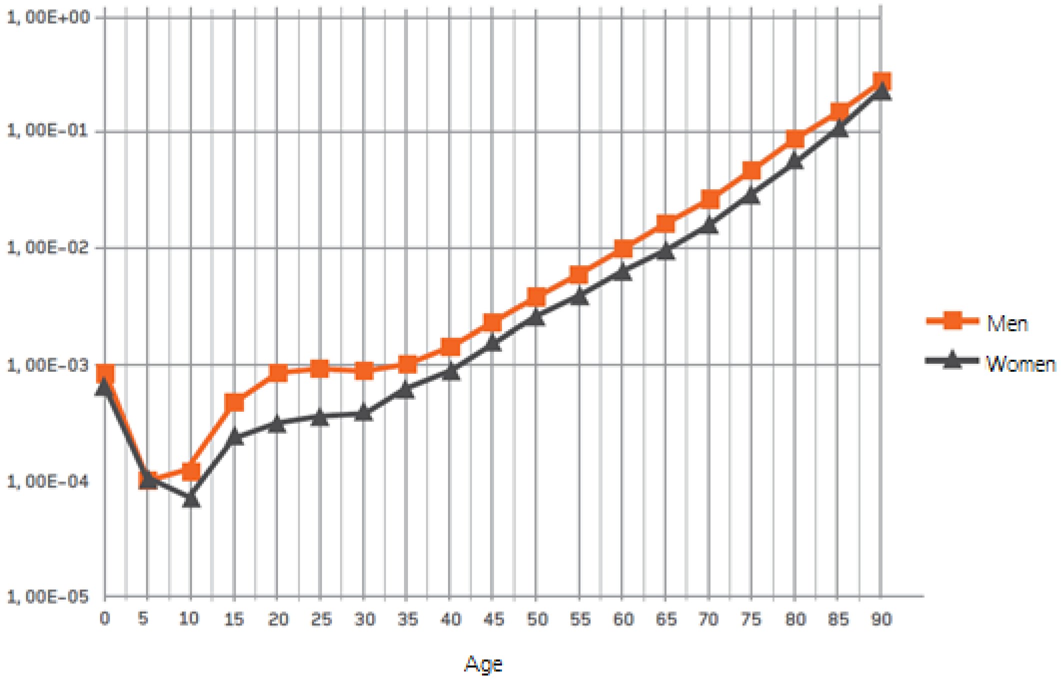

Figure 6.1 – Age-dependent fatality rates in Norway, 5-year groups (2006-2010). The figure is taken from the Template report (ref. /1/), based on values from "Statistics Norway"

6.2 Primary results and intermediate results

As well as the primary results, intermediate results that may contribute to the land use planning shall be presented. Any results that increase traceability and the ability to check and assure the quality of analysis shall also be presented.

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

- Frequency distribution of top events must be presented as a function of leak size and as a function of area (iso-contours are not required, but a minimum requirement is a table providing the areas where the release scenarios are located)
- Ignition probabilities, both as a function of leak size and area
- Individual risk contours
- Examples of all major events considered relevant for external emergency preparedness (Chapter 7).

In addition, the following intermediate results are considered useful for communicating risk contributors and for emergency preparedness (for example, in emergency preparedness planning, it may be beneficial to present fatality areas separately for toxicity, heat load and explosion, as well as the combined overall fatality area):

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

For clarity, risk contours should be plotted on a map or photo. Figure 6.2 shows an example of risk contours plotted on a map, and 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. These risk contours are plotted using the same coordinate system used by the maps, eliminating the potential errors associated with manually reproducing the contours on a map.

When analysing future facilities, risk contours should be plotted on the current local development plan/ spatial plan (or the planning permission map if the area is not regulated). This also applies to affected development plans in the case of extensions or other significant changes to existing facilities.

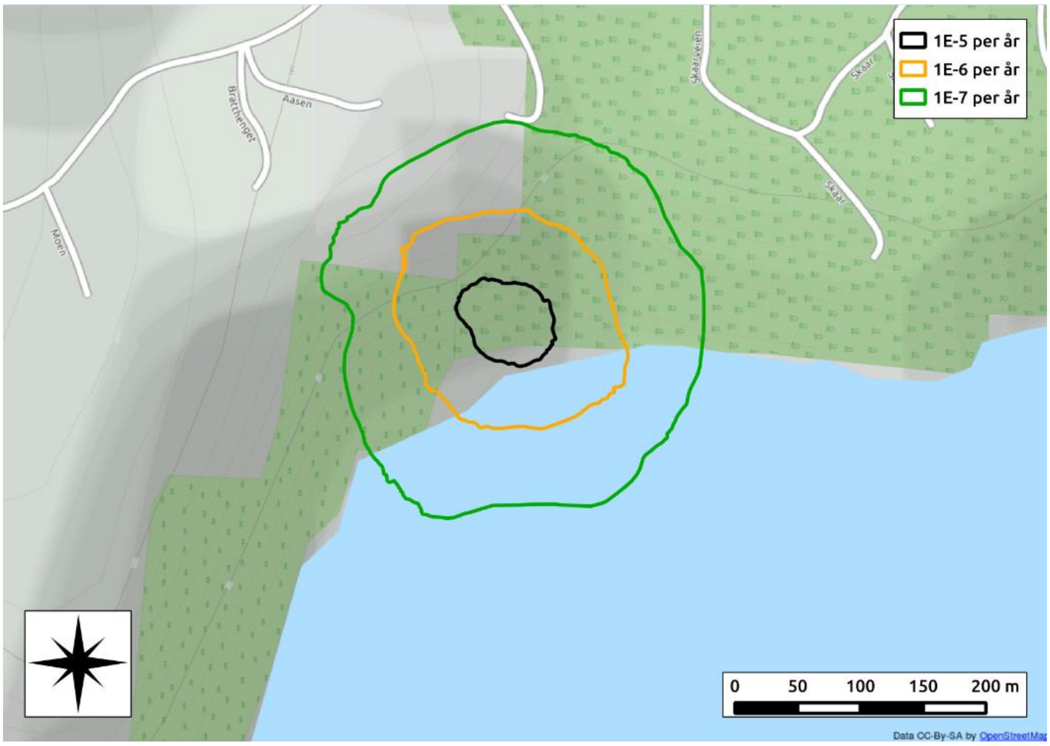

Figure 6.2 – Illustration of risk contours plotted on a map (location randomly selected)

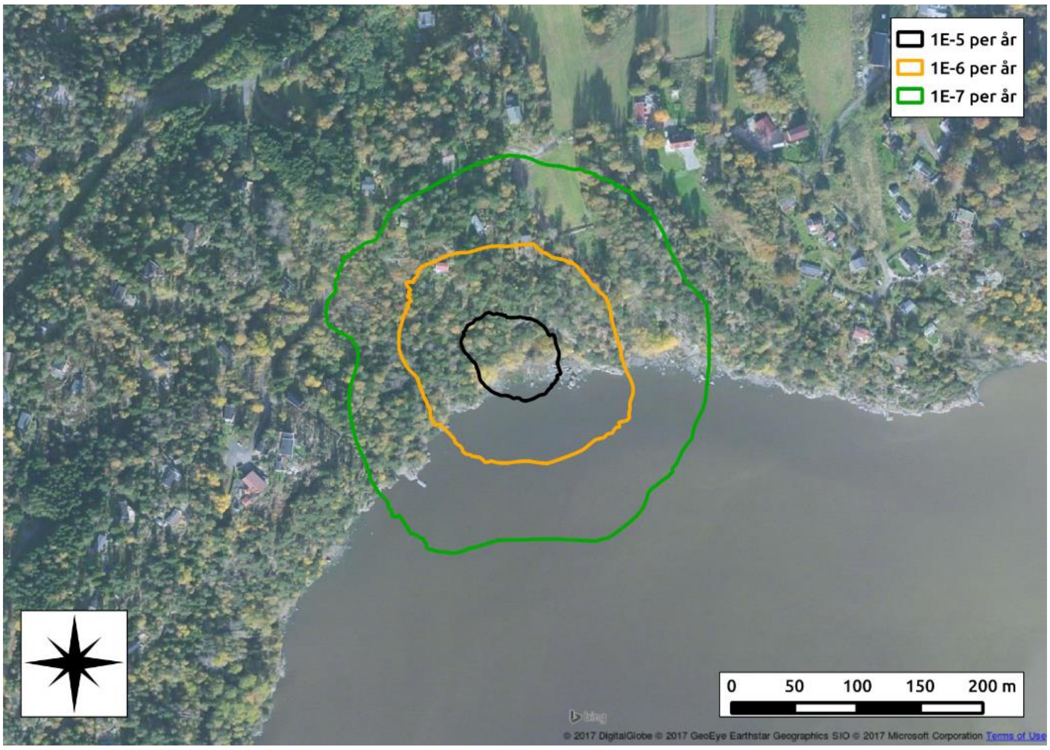

Figure 6.3 – Illustration of risk contours plotted on an aerial image (location randomly selected)

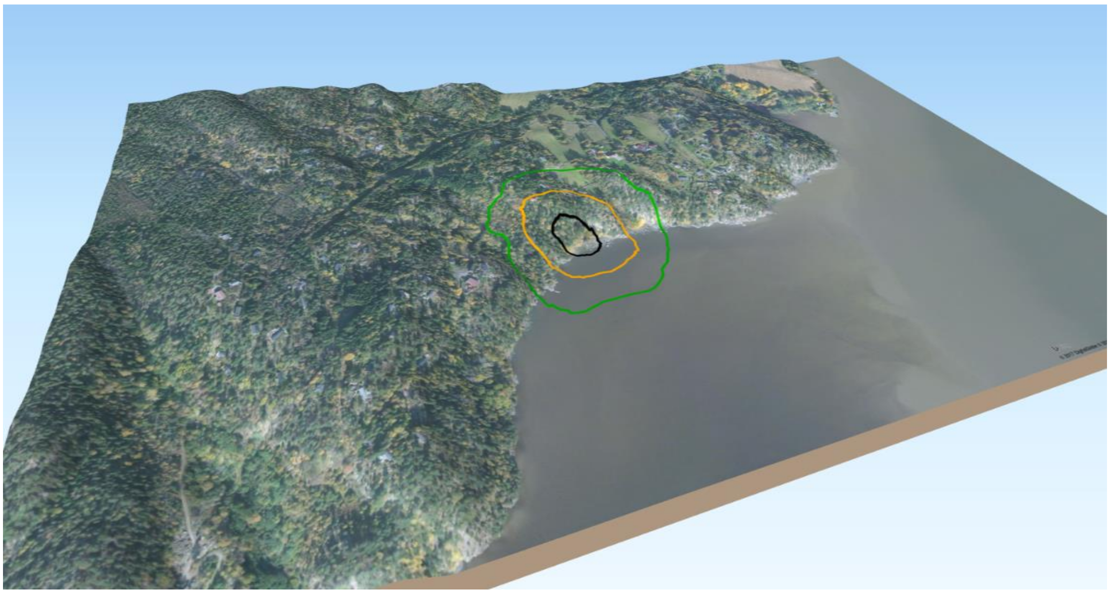

Figure 6.4 – Illustration of risk contours plotted on a 3D map (location randomly selected)

6.3 How far above the ground do consideration zones apply?

Risk contours can be presented as a maximum projection or as contours that vary with elevation above ground. The maximum projection contour is obtained by taking the worst-case value for any height (z values) for each position in the horizontal (x, y) plane. In a projected representation, the variation in risk level with elevation is not provided, but the advantage of this is that all iso-contours can be presented on a single diagram (at the largest extent). The alternative to a projected representation is to plot risk contours for different elevations. In the example illustration in Figure 6.5, it can be seen that the flammable gas exposure varies with elevation. If one wishes to reproduce this effect on a 2D drawing, one can create risk contours at different elevations. If this is not required, one can project the furthest point in the z-direction onto the ground.

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

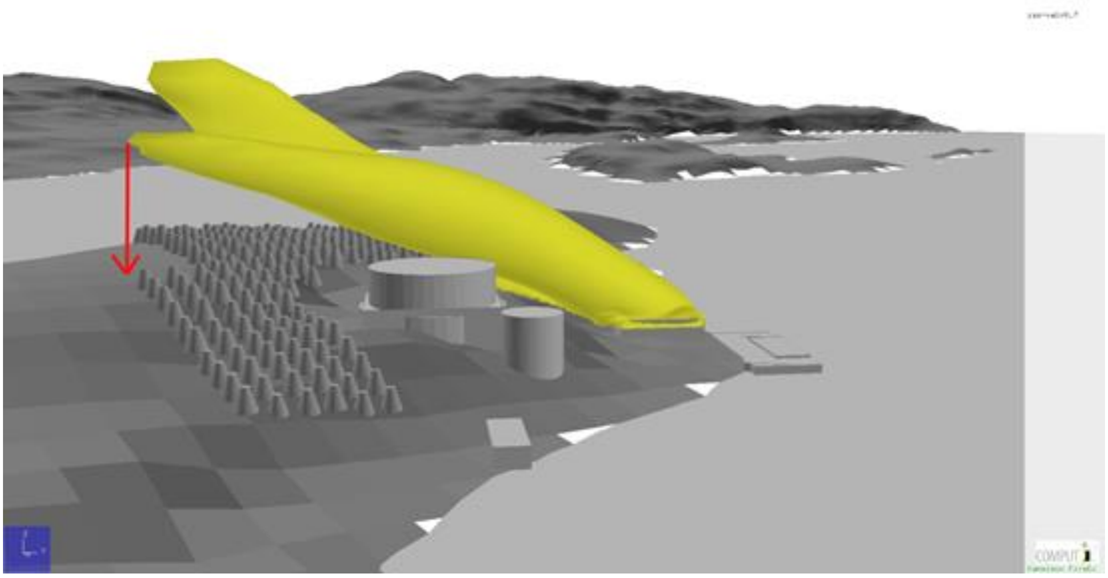

Figure 6.5 – Example demonstrating that flammable gas exposure varies with elevation

6.4 Consideration zones and individual risk

The theme report (ref. /1/) defines consideration zones for use in land planning, and it is therefore emphasized that the risk level in the consideration zones is geographical, and not associated to individual people who may be in the consideration zones. This means that one cannot use an occupancy factor to reduce the risk level.

However, an occupancy factor (exposure time) can be taken into consideration if individual risk is to be calculated for a specific group of people. This is not discussed further in this report.

7 Scenarios for emergency preparedness

Risk contours do not show individual scenarios, only total risk exposure for third parties summed up from all possible scenarios. There is also no requirement that scenarios for external emergency preparedness considerations be linked to the criteria for acceptable risk, cf. the report from DSB, ref. /1/. However, the risk analysis makes it possible to select contingency 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 emergency situations 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 displayed as plots for exposed areas at worst possible event/consequence

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

8 References

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Appendix A

Check list for activity definition and guidewords for hazard identification

Table of contents

1 Tables for use in initial mapping of the business

1.0	Purpose of the analysis	References
	Enrolment of new building, new establishment	
	Enrolment of changes to existing business	
	Review of accident in business or in neighbouring businesses	
	Update of existing analysis and/or safety report, ref. Major Accident Regulations ("Storulykkeforskrift"), Paragraph 9	
	Changes in area planning, the business itself or neighbouring business, the municipality	
	Special requirements from authorities	
	Other	

2.0	What kind of hazard substances does the business handle	References
	Pressurized substances	
	Flammable gas	
	Oxidizing gas	
	Toxic gas	
	Flammable aerosol container	
	Water vapour or hot water under pressure	
	Flammable substances	
	Flammable liquid	
	Diesel and fuel oils	
	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 fluid	
	Self-igniting solids	
	Self-heating substance	
	Oxidizing solid	
	Oxidizing liquid	
	Self-reactive substance	
	Organic Peroxide Type	
	Reactive substances	
	Substance that develops toxic gas	
	Refrigerated toxic gases	
	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	

3.0	Available documentation, degree of accuracy	References
	Deviation, report from supervision, best practices, experience transfer from the industry etc.	
	Other	

4.0	Stored amounts of hazardous substance	References
	Notifiable in accordance with Hazardous Substance Regulations (“Forskrift om farlig stoff”)	
	Major Accident Regulation (“Storulykkeforskrift”) §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 tanks	
	Forming/processing	
	Processing/storage/temporary storage	
	Internal transport	
	Mixing/racking/transmission	
	Emissions to ground, water, air	
	Other	

6.0	Environment - Where is the business located	References
	Built-up area, city/village, with/without harbour	
	Open landscape, scattered settlement with/without harbour	
	Hilly landscape, scattered settlement with/without harbour	
	Neighbours?	
	Special vulnerable items: School, kindergarten, hospital, nursing home, community centre, sports facilities	
	Hotel, accommodation, business, restaurants	
	External emergency preparedness, Emergency Service	
	Will unintentional/uncontrolled events that may occur in nearby businesses (industrial enterprises, etc.) pose a risk to the business (domino effect)? - Are there potential sabotage/terrorist targets nearby?	
	Other	

7.0	Infrastructure near business	References
	Trafficked roads; private roads, county road, highway etc.	
	Bus, train, tram, lane ferry, air plane	
	Hiking trails, pedestrian and cycle paths	

7.0	Infrastructure near business	References
	Power	
	Other	

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

9.0	Emergency preparedness	References
	Does the loss of access to the following services cause disadvantages to the business? -electricity, telecommunications services, water supply	
	Water supply? Does the area have insufficient fire water supply (quantity and pressure)?	
	Access to external firefighters, response time, etc. Arrival route for fire truck?	
	Automatic firefighting inside/outside, deluge system, water cannon, foam system, water curtain etc.	
	Fire alarm, gas alarm	
	Illegal sabotage and terrorist acts: is the business itself a sabotage/terrorist 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 - leakage/spillage or cross contamination. Process vessel failure. Heat exchanger pipes leak or break. Process line failure	• Hazardous chemicals (including hydrocarbons) • Other chemical hazards • Explosives • Unexpected reactions • Incompatible materials • Thermal uncontrolled reaction (runaway) • Air inlet • Corrosion • Erosion • Brittleness (chemicals, low temperature)

Category	Guideword
	• External collision • Fatigue • Abnormal vibration • Mechanical collision • Overloading
High/low pressure High/low temperature systems	• Warm process/superheat • Steam • Condensate • Cold processes/cryogens • Thermal combustion • Safety valves • Torches
Buildings	• The effect of external hazards
Escalation	• BLEVE • Consequence of other events • Fire and gas detection, fire extinguishing equipment, water curtains etc. • Evacuation routes
Transportation	• Events with rail/railroad carriage • Dock/navy events • Vehicle traffic events • Tanker trucks
Mobile equipment	• Heavy machinery • Light-weight vehicles
Lifting equipment	• Dropped/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
Marine vessel	• Ship collision with dock

Category	Guideword
	• Loading/unloading • Emissions
Fabrication and installation	• Complexity • Modulisation • Transport • 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	• Earthquakes • Fundamentals (insertion, scouring) • Corrosion • Fatigue • Weight control • Primary structure • Secondary constructions • Temporary constructions
Auxiliary system failure	• Cooling water • Fire in cooling tower • Hypothermia • Power • Steam • Air • Inert gasses • Heating, ventilation and air conditioning system • Communication system • Firefighting system • Internet • Wastewater removal/treatment • Vacuum • Contained bunding
Nature and environment	• Seismic activity • Weather:

Category	Guideword
	○ Strong wind ○ Flooding ○ Extreme cold or heat ○ High or low humidity, fog ○ Earthquake/tsunami ○ Hurricane/tornado ○ Lightning • Impact of marine environment on equipment • Recess/unstable terrain/soil and snow • 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 a part of “Guidelines for quantitative risk analysis of facilities handling hazardous substances” and describes good principles for establishing unbiased (best estimate) risk contours.

2 General

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

In reality, there are infinite different scenarios (end events) that can occur at a plant, and in practice one must discretize the outcome of the top events (ref. Chapter 3.2 in the main report) to assess an adequate number of variations of these top events. This must be done by selecting a finite number of leak points, leak rates, leak directions, wind directions and wind speeds. In addition, one must select a limited number of ignition times and ignition points since all variations of this will have different consequences. This may end in many different scenarios being analysed. 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, one will end up with 36 million scenarios, and it will be necessary to distinguish between simulated and evaluated scenarios.

By using symmetry considerations and simplified physical modifications to scenarios already simulated, one can significantly reduce the number of scenarios one actually needs to simulate. It is thus possible to evaluate a large number of scenarios and significantly reduce the number of simulated scenarios.

If symmetry calculations are made to reduce the number of simulated scenarios, it is important to simultaneously assess the accuracy of the physics of the scenarios, according to the principles discussed in Chapter 3.4.2 in 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 of the scenarios it is necessary to capture (thus being able to calculate representative risk contours).

Although the leak frequency distribution can be considered representative for the plant (see section 3.3.2 in main report) and the simulated scenarios are performed using the correct simulation tools in relation to the guidelines in Chapter 3.4.2 in main report, it is still crucial that an adequate number of events are considered such that the possible outcomes are modelled 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 the extent to which this 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 a limited number of evaluated scenarios. One does not know whether this risk contour is conservative or non-conservative unless one knows if the simulated scenarios are more or less severe than those around the "actual" risk contour. The difference between the calculated risk contour and the "actual" risk contour decreases with an increase in number of scenarios evaluated, see Figure 2.1. Note that even if one simulates several scenarios such that in practice a wide range of events are simulated, the uncertainty related to the frequency picture does not disappear (how likely are scenarios that are different to those evaluated).

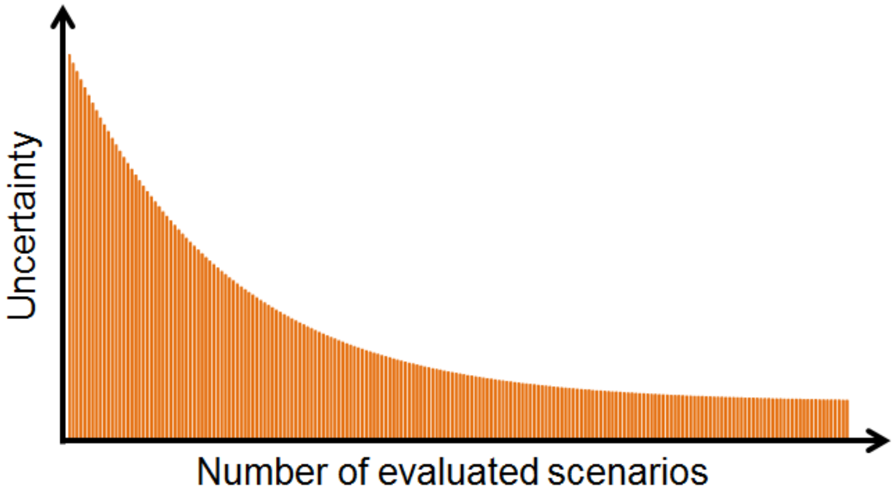

Figure 2.1 – Uncertainty as a function of the number of evaluated scenarios – illustration

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

For example, in the event of a liquid fire in a bund, there will be no need to vary the number of release locations or use a large number of release rates; and with the use of an empirical tool it may be sufficient for a few different wind speeds to be used to simulate the possible outcomes for the top event. However, with the use of CFD, there may be more need for more simulations (for example, assessing different wind directions).

For gas explosion top-event assessments, 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. Since it is unrealistic to consider too many scenarios in detail, it may be necessary to minimise the effort on the scenarios and scenario variations that have little impact on risk. Some examples of simplifications:

- For leak rates that do not form flammable cloud sizes that can generate significant explosion overpressures, there is no need to evaluate a variety of wind directions and wind speeds. All of these scenarios can be represented by the "calm wind" calculation
- It may be necessary to simplify the analysis by decoupling the dispersion and explosion studies so that the dispersion study with subsequent transient ignition estimation 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, an analysis with a large number of scenarios can be reduced to a manageable amount, by focusing the effort on the leak rates that have the biggest impact on the 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 relevant sample space of outcomes for the risk contours to be representative for the analysed plant. 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 release location, will have a significant impact on the shape and location of the risk contours. This can be illustrated by the following simplified example of variation of leak direction (wind conditions are assumed to be calm):

From the leak rate exceedance frequency graph, one can determine the leak rate for a given frequency (for example 10^{-7} per year, or less). If one simulates this critical leak size (m_{kr}), one will get a length and width of flammable (or toxic) concentration region for this leak rate, see Figure 3.1.

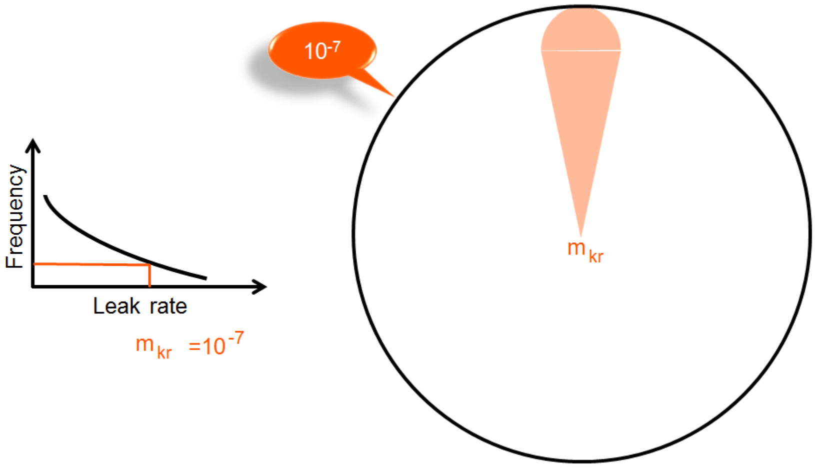

Figure 3.1 – Concentration envelope (risk contour) generated by rotating a single scenario with critical leak rate (m_{rk}). The figure indicates that all points within the circle have the same exposure frequency (>10^{-7} per year)

In reality, a leak may occur in any direction, and the frequency is therefore distributed between each of these directions. If the single scenario, for example, is divided into 10 directions and the frequency is assumed equally distributed between these directions, each of these will represent 1/10 of the original frequency, i.e. 10^{-8} per year. If one generates a risk contour by drawing a circle around the tips of these regions, one will get another result. The regions have the same length and width as before, but they have a frequency that is 1/10 of the single scenario (see Figure 3.1). The risk contour has the same dimensions as that in Figure 3.1 but, whereas the contour in Figure 3.1 represents an estimate of 10^{-7} per year, the equivalent contour in Figure 3.2 represents a frequency of 10^{-8} per year.

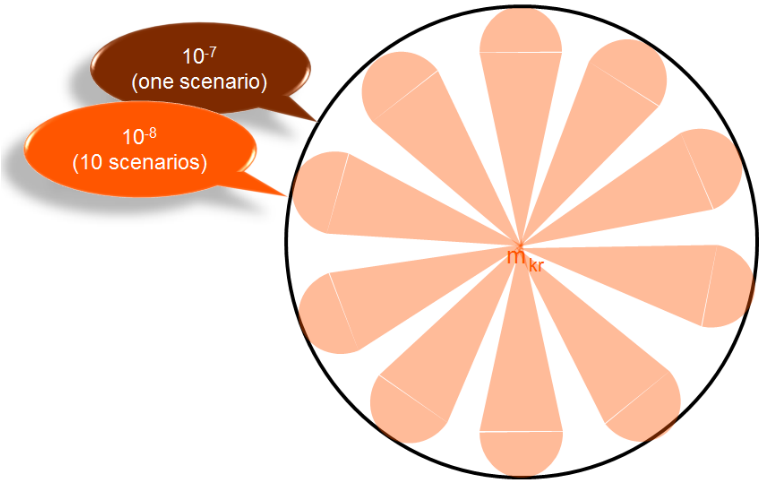

Figure 3.2 – Risk contours from distributing a single critical scenario equally in 10 directions. The figure indicates that all points within the circle have the same frequency of exposure ($>10^{-8}$ per year)

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

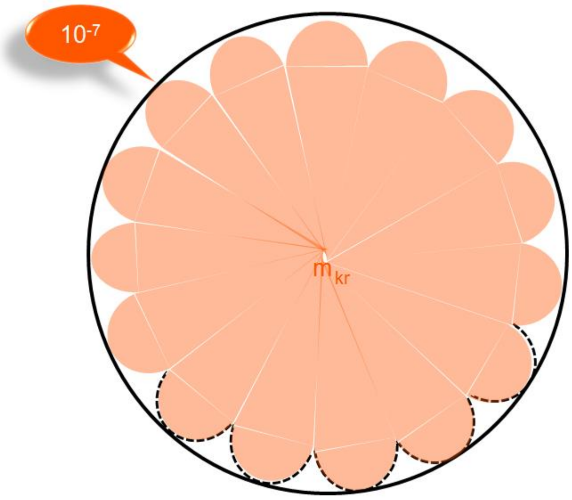

Figure 3.3 – Risk contour with frequency 10^{-7} estimated for a total of 15 different leak directions. Note that the iso-contour is often defined as the edge along the scenarios (dashed line), but in this example illustrating the effect of considering several directions, the iso-contour is defined as the circle that touches the extremes of the scenarios

If one doubles the number of assessed directions (i.e. 30 directions), the frequency for each of the scenarios will be halved, but these regions will start to overlap so that most of the field will still have an aggregate frequency of 10^{-7} per year. At the very end of the field, it can be seen that the overlapping regions have a slightly shorter radius than the non-overlapping regions, see Figure 3.4, but the difference in frequency is significantly smaller than seen earlier (Figure 3.2) where there were no overlapping scenarios. One can now see that the critical scenario is divided into enough directions for the iso-curve to begin to converge.

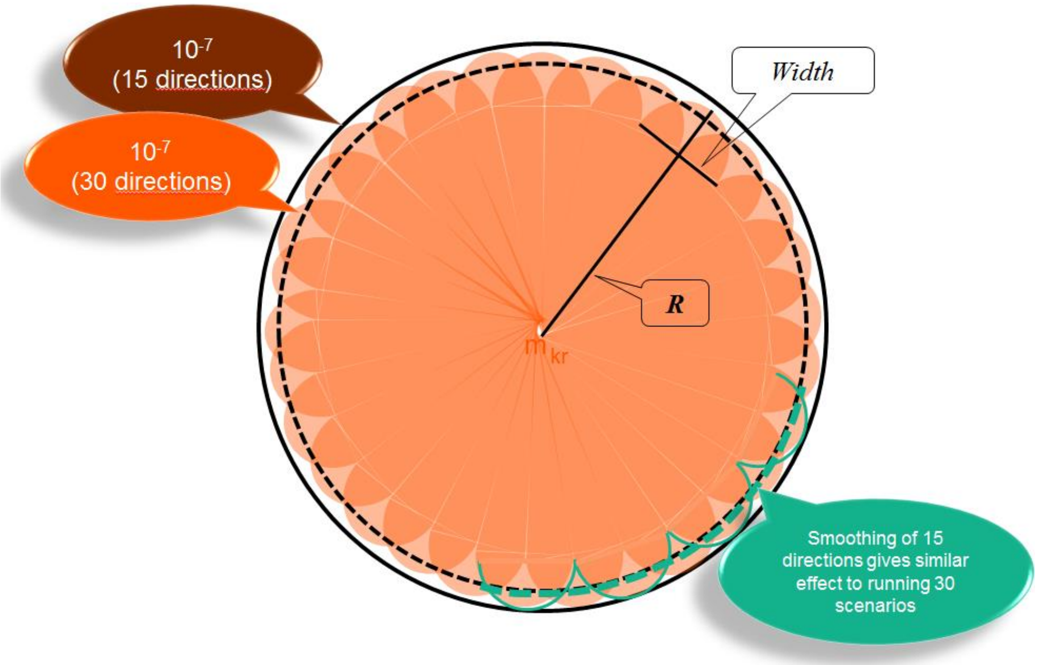

Figure 3.4 – Risk contour with frequency 10^{-7} per year estimated for a total of 30 different leak directions

Figure 3.4 shows that sufficient scenarios have been simulated when the number of directions modelled is proportional to *Width/2πR.*

A risk contour that is aggregated or smoothed will be more representative than using the outermost "bumps" in a jagged contour.

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, there will be smoothness in the field, as well as interaction with dominant buildings or terrain, which indicates whether one have run enough scenarios.

From the above figures it can also be concluded that using few scenarios could lead to larger risk contours than by using a more refined analysis with multiple scenarios.

4 Interpolation of simulated scenarios

If one has simulated the necessary number of scenarios to get the physical characteristics that one considers essential to the outcome of a top event, one can estimate the consequence of similar scenarios using symmetry, rotation, and scaling. The frequency must then be distributed across the total number of evaluated scenarios. Rotation can be used, for example, when a small change in wind direction is expected to give the same effect distance, but in a slightly different direction. In such cases, one can rotate the simulated region around the release point to evaluate an almost identical scenario, see Figure 4.1. The uncertainty increases the more one rotates a scenario, but some types of scenarios can be rotated considerably and still be considered to be unbiased. An example of a scenario that can be rotated a lot and still considered as unbiased is evaporation from a bund located in a flat area without significant obstructions. Conversely, a high momentum release scenario in an area where both wind and jet momentum are influenced by objects (building terrain, etc.) cannot be rotated much before the physical characteristics of the release become very different.

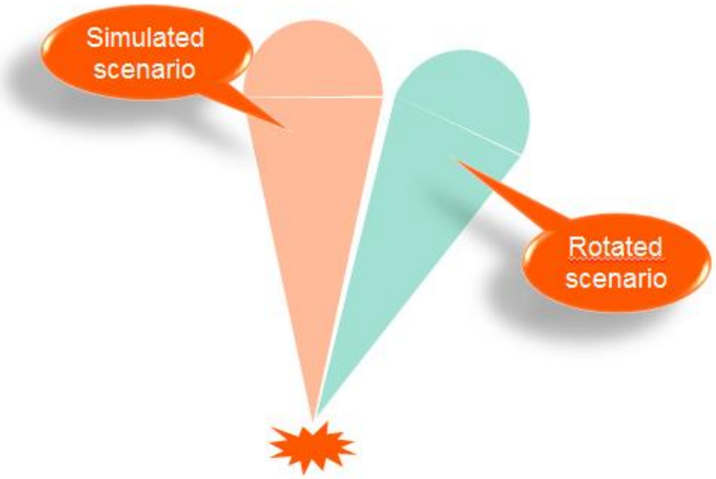

Figure 4.1 – Rotation of a simulated scenario to evaluate a similar scenario

Scaling 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 scaling, one can adjust the concentration in each control volume to evaluate how a scenario with a slightly different release rate may look. For example, if the gas concentration in all control volumes in the result field is doubled, this may represent simulating a release that has twice the mass release rate. The methodology is inaccurate and must be used with caution. It is not recommended to use this scaling methodology for rates more than double or less than half of the simulated rate.

Common to all types of transformations 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 places in a processing plant. In the risk analysis one must select a finite number of scenarios, and thus a finite number of leak points, to model "everything" that can happen in an area. The number of leak locations one selects may have an impact on the resulting risk contours. However, the error made by selecting too few leak points can be estimated to be at most in the order of a magnitude equal to the dimension of the process area, see Figure 5.1 (where the process area is marked with a black square).

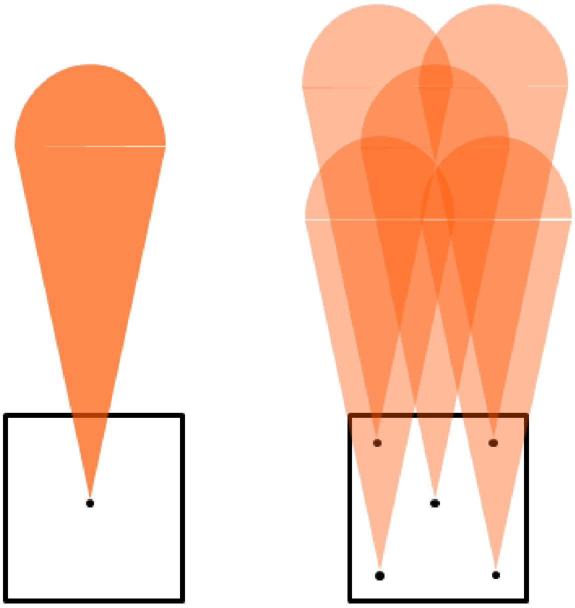

Figure 5.1 – The effect of selecting a leak point relative to 5 leak points in an area

6 Number of simulated leak rates

If the subdivision of simulated rates is too coarse, the rate representing critical modelled leak scenario (e.g. 10^{-7} frequency) could be either slightly smaller or slightly larger than the actual critical rate. Risk contours will thus have a corresponding error in the frequency of the resulting risk contours. This error is limited by the difference in frequencies for the simulated rates above and below the actual critical rate, see Figure 6.1.

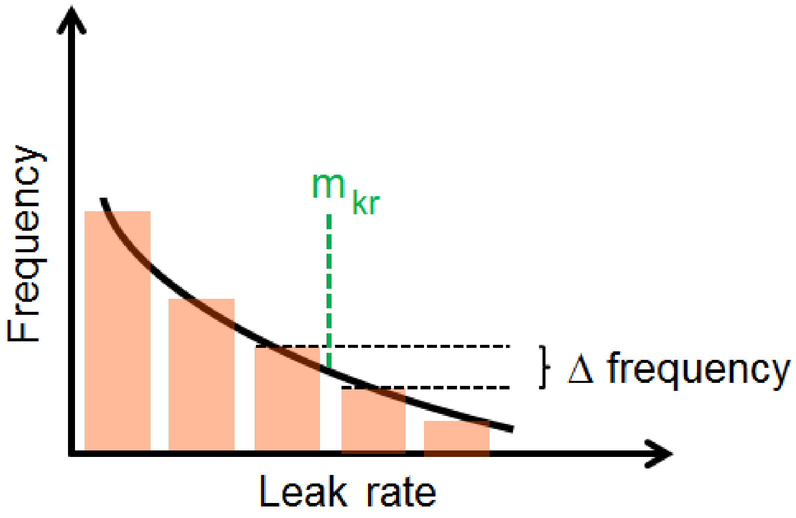

Figure 6.1 – Estimated errors in iso-contour frequencies are limited by the difference in the frequencies for the simulated rates above and below the critical rate (requires that one knows critical rate before assessing errors). Simulated rates are marked in orange

7 Smoothing of risk contours

If a calculated risk contour is jagged, without this being explained by specific conditions related to the plant, it is probably because the contours are based on too few simulated scenarios. From Figure 3.4, it can be seen that smoothing of the contours must be performed to make these more in line with expectations, and therefore smoothing is recommended for contours that are jagged without this being related to the plant.

Smoothing of a jagged contour has a similar effect as running multiple scenarios with slightly different input parameters. Figure 7.1 illustrates this by distributing the frequency of a single scenario over 3 different scenarios with slightly different leak rates. This is compared with the effect of smoothing the single scenario using a normal distribution smoothing function. Note that the shape of the smoothed curve (green curve) is determined by the chosen standard deviation in the normal distribution smoothing function (Gauss). The shape of the orange contour is determined by how much the parameters that determine the scenarios vary.

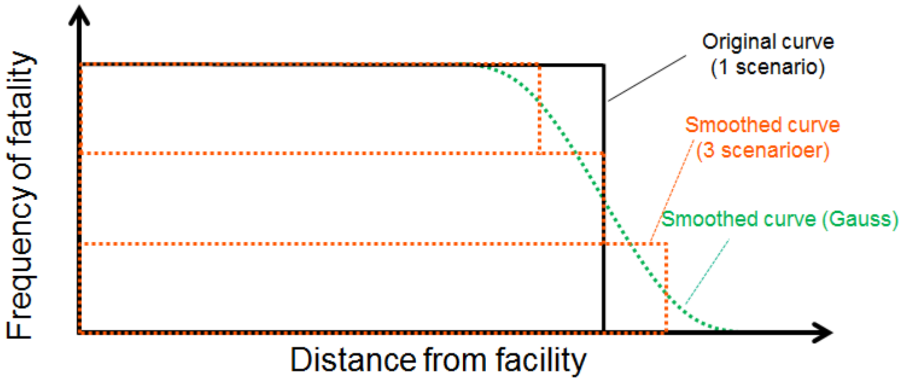

Figure 7.1 – Illustration showing that if one only runs a single scenario representing all frequency of fatality (where fatality is set by threshold value, see Chapter 4 in the main report), the frequency contour can be smoothed either by running more scenarios (the orange contour shows the same frequency spread over 3 slightly different scenarios) or by using a normalized smoothing function (Gaussian smoothing, see green curve)

Figure 7.2 shows a risk contour that is smoothed using a normal distribution smoothing function (Gauss distribution with standard deviation 1.0). Such a function smooths the frequency contour by adjusting each point from the value of the surrounding points in all directions with a weighting according to the normal distribution based on distance to the evaluated point. The standard deviation determines the weighting for each point in the smoothing as a function of distance from the point being smoothed. The smoothed contour (green curve) follows the main trends of the original risk contour but smooths out the small irregularities in the contour. Note that, even if smoothing makes the risk contours more in line with expectations, in situations where the small irregularities in the contour are not linked to the analysed facility, smoothing will cause the contour to expand (in practice, the contour will expand slightly outward from the plant in all directions), see Figure 7.3. A Gaussian smoothing with standard deviation between 1.0 and 4.0 is considered acceptable to remove small irregularities in contours.

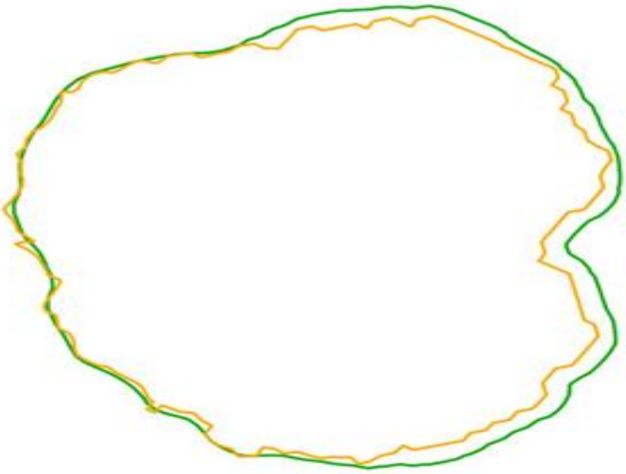

Figure 7.2 – Example of risk contour (orange) smoothed by a normal distribution (Gauss) with standard deviation = 1.0 (green curve)

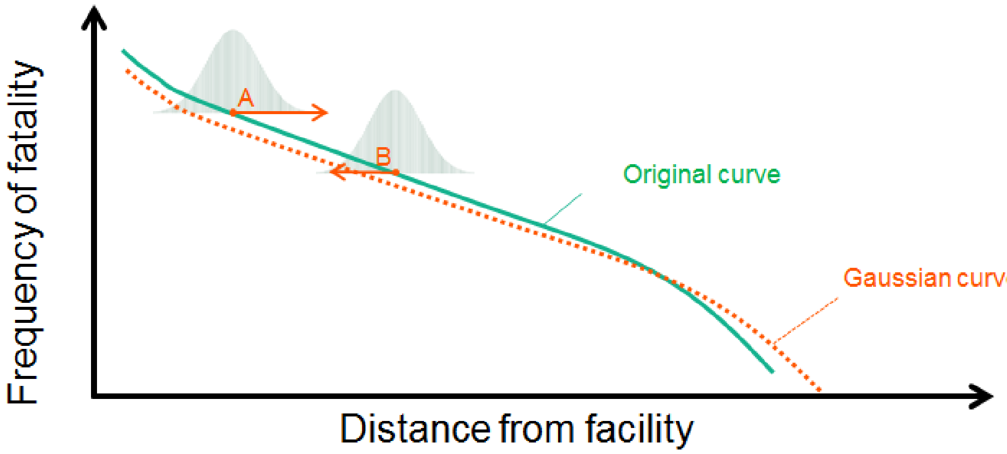

Figure 7.3 – Illustration showing that a smoothing function will move curves from higher frequencies to lower frequencies. Using a normal distribution result in more scenarios moving to lower frequencies (A) than to higher frequencies (B) – simply because point A has a higher frequency than point B

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 will not normally be used in the dispersion calculations performed in a risk analysis, although this is partly included in the calibration of the simulation tools, especially in the calibration of empirical tools. Smoothing of the risk contours can also be said to represent a similar effect as would be achieved by using dynamic wind conditions in the simulations.

8 Refining risk contours in critical areas

Risk contours can be more detailed in certain areas of particular interest. Through refinement, the purpose is for the contours to be more in line with expectations 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 only running additional simulations where the scenarios affect the area one wishes to refine (target area).

In order to assess whether a sufficient number of additional simulations have been run in the target area, refer to the principles discussed in Chapter 3.9 in the main report.

9 Summary – risk contours

In order for the risk contours to be in line with expectations, the analysis needs to evaluate a sufficient selection of top events. The following three steps are recommended as a robust way of achieving risk contours that in line with expectations:

- Firstly, a sufficient number of simulations /calculations are conducted to capture the principal characteristics for all relevant scenarios. This is done by modelling a series of individual scenarios and using modelling tools that accurately reflect the relevant physics for the scenarios, see Chapter 3.4.2 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 scenarios simulated can be used as the basis for estimating additional scenarios where the additional scenarios are sufficiently similar to those already simulated. Here one will typically transform (rotate or manipulate) the simulation output to estimate the additional scenarios. Making such transformations will lose some of the accuracy of the physics for the simulated scenarios (for example, flow around large objects will not be simulated correctly), but it will have the effect of smoothing the frequency of multiple events
- If the risk contours still have small irregularities after the transformations are performed, one can further smooth the result field (e.g. with a Gaussian smoothing as shown in Figure 7.2). Such a smoothing will not reflect the physics accurately but will result in a smoothing of the risk contour. Smoothing out minor irregularities in the risk contour (which are not associated with conditions related to the plant) will make the risk contours more in line with expectations, see Figure 3.4.

An example of the above process is shown in Figure 9.1. The orange risk contours represent a given frequency based on the scenarios modelled by CFD simulations of flammable gas only. From the shape of the orange contour one can see that an insufficient number of wind directions have been taken into account (there are 12 "fingers" on the contour, corresponding to the 12 wind directions simulated). In the green contour, each CFD simulation is used to evaluate 3 additional scenarios with wind direction close to that used in the simulation by rotating the simulated scenario around the release location. The leak frequency of the simulated scenario is divided equally between the 4 scenarios. Thus, the green risk contour is based on 48 wind directions instead of 12 (12 simulated scenarios and 36 transformation scenarios). The green curve is smoother and hence more in line with expectations than the orange. The black curve is obtained by smoothing the green curve (Gaussian smoothing with standard deviation 2.0). Note that it is not the green contour that is smoothed directly, but the entire 3D frequency field.

However, when the entire 3D frequency field is smoothed, the iso-contours for a given frequency move accordingly. The smoothed contour is more in line with expectations than both the orange curve (12 wind directions without smoothing) and the green curve (48 wind directions without smoothing).

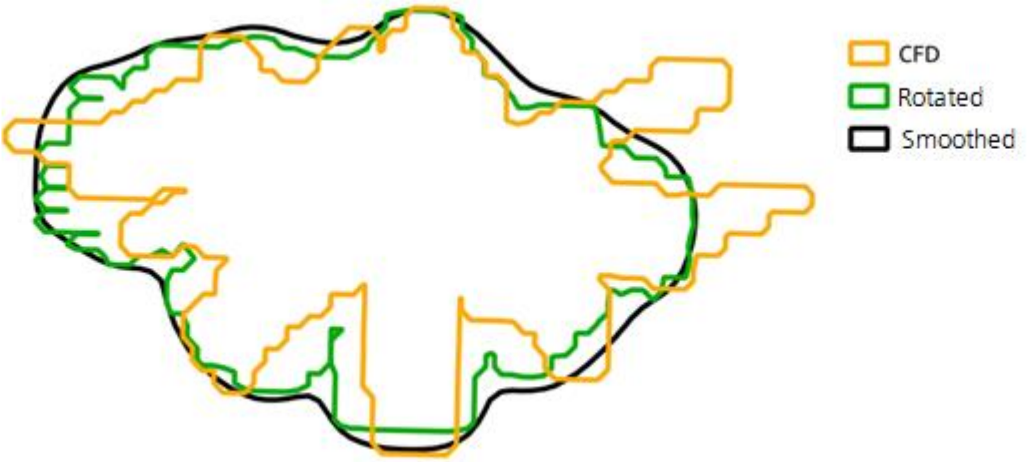

Figure 9.1 – Example of simulated (CFD), evaluated (rotated) and smoothed risk contours