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A method to judge the internal risk of establishments with dangerous substances

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Abstract

Here, an assessment method is described for judging the acceptability of the internal risk of an establishment, as presented in the safety report. The starting point is an establishment with an adequate safety management system. The assessment method consists of checking to see whether the information required is given, comparing the risk and risk-acceptance criteria of the establishment with a set of normative risk criteria and verifying the correctness of the calculated scenario probability and the consequences for a sample set of scenarios. The assessment method represents a first step towards a complete and more rigorous method for judging the internal risk of an establishment.

Samenvatting

Op grond van het ‘Besluit Risico’s Zware Ongevallen 1999’ moet de Arbeidsinspectie een oordeel geven over de aanvaardbaarheid van de risico’s voor werknemers ten gevolge van zware ongevallen, zoals beschreven in het veiligheidsrapport. Om tot een oordeel te komen moet de inspecteur zowel nagaan of de risico’s correct zijn berekend en weergegeven en de berekende risico’s vergelijken met een set van normen. In dit rapport wordt een methode beschreven voor het beoordelen van de aanvaardbaarheid van de risico’s voor werknemers. De beschreven methode is complementair aan de AVRIM2 methode en richt zich op de technische voorzieningen.

Het uitgangspunt van de beoordelingsmethode is een inrichting met een goed veiligheidsbeheerssysteem. De eerste stap is na te gaan of de benodigde informatie is opgenomen in het veiligheidsrapport. Het risico voor de werknemers moet goed beschreven zijn, evenals de interne criteria van het bedrijf.

Vervolgens moeten het risico voor de werknemer en de interne criteria beoordeeld worden aan de hand van een risiconorm. Echter, een risiconorm voor de arbeidsveiligheid bestaat momenteel niet. In het rapport wordt daarom achtergrondinformatie gegeven die nuttig is bij het komen tot een goede set van risiconormen. Op basis van de beschikbare informatie lijkt een redelijke limiet voor het individueel sterfterisico van werknemers ten gevolge van zware ongevallen in de orde van $1 - 10 \times 10^{-6}$ per jaar te liggen voor de groep met het grootste risico.

In de beoordelingsmethode worden de kans van optreden van een scenario en de effecten, zoals beschreven in het veiligheidsrapport, geverifieerd aan de hand van een steekproef. De volgende methode wordt hierbij gehanteerd. Eerst wordt een standaard installatie gedefinieerd die niet beïnvloed wordt door de stof en door de omgeving. Aangenomen wordt dat alle standaard voorzieningen aanwezig zijn. Vervolgens wordt nagegaan wat de invloed van de stof en van de omgeving op het falen van de installatie is. Indien de stof dan wel de omgeving leidt tot een verhoogde kans van falen, dienen er additionele voorzieningen aanwezig te zijn die hiertegen beschermen. Wanneer deze additionele voorzieningen ontbreken wordt aangenomen dat de kans op een scenario groter is dan bij het standaard systeem en de kans van optreden van een scenario wordt verhoogd met een straffactor. Vervolgens wordt nagegaan of er extra voorzieningen, zowel preventief als repressief, aanwezig zijn en wat de invloed is op de kans van optreden en de gevolgen van een scenario. Op basis van de straffactoren en de beoordeling van de extra voorzieningen wordt tenslotte de plaats van een scenario in de risicomatrix bepaald. De verschillende stappen van de methode worden geïllustreerd aan de hand van een pilot studie.

De methode, zoals beschreven in dit rapport, vormt een eerste stap in de ontwikkeling van een complete methode voor het beoordelen van de aanvaardbaarheid van de risico’s voor werknemers.

Summary

Under the 'Hazards of Major Accidents Decree 1999', the labour safety inspector has to pass judgement on the acceptability of the risk to employees due to major accidents, as presented in the safety report. In order to form an opinion on the acceptability of the risk, the labour safety inspector should both assess the correctness of the calculation of the risk to employees and compare the risk calculated with normative risk criteria. Here, a procedure is described for judging the acceptability of the internal risk of an establishment. This is a method complementary to AVRIM2, the management system evaluation tool, and focuses on the hardware lines of defence.

The starting point for the assessment method is an establishment having an adequate safety management system. The first step is to check whether the information required is given in the safety report. The risk to employees should be adequately communicated, along with the risk acceptance criteria of the establishment.

Next, the risk and risk acceptance criteria of the establishment should be rated against a set of normative risk criteria. However, this set is currently lacking, so background information is given here to facilitate the definition of normative risk criteria. Based on the data available, an individual mortality risk limit in the order of $1 - 10 \times 10^{-6}$ per year for accidents with dangerous substances for the group running the highest risk would seem to be acceptable.

In the assessment method, the probability of the scenario and its consequences occurring, as presented in the safety report, is verified for a sample set of scenarios. To verify the correctness of the scenarios, the following method is applied. First, a standard installation, which is not influenced by the substance or its surroundings, is defined. In the standard installation, all standard lines of defence are taken to be in place. Next, the influence of the substance and of the surroundings on the system is evaluated separately. For each influence, additional lines of defence should be present. If required additional lines of defence are missing, the probability of occurrence of a scenario is assumed to be higher than for the standard and a penalty factor on the frequency of a scenario is introduced. Finally, if any additional lines of defence, both preventative and repressive, are present, their influence on the probability and consequences of a scenario is determined. The location of the scenarios in the risk matrix is determined using the various penalty factors and the valuation of the extra lines of defence. To illustrate the various steps, a pilot study is carried out.

The assessment method described here represents a first step towards a complete and more rigorous method to pass judgement on the internal risk of an establishment.

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Glossary

ALARA	ALARA is the principle that the risks should be **A**s **L**ow **A**s **R**easonably **A**chievable. The principle requires a process of judging risk-reducing measures by balancing the risk reduction received and the sacrifices needed.
casualty	A casualty is the harm done to people including injury and fatality.
dangerous substances	Substances, mixtures or preparations named in Annex I, Part 1, or belonging to a category specified in Annex I, Part 2, of Hazards of Major Accidents Decree 1999 and present as a raw material, product, by-product, residue or intermediate product, including those substances, mixtures or preparations which it is reasonable to suppose may be generated during loss of control of an industrial chemical process
destructive failures	Failures resulting from damage to the equipment, like corrosion, external impact, weld faults. Non-destructive failure results e.g. from erroneously opening of valves and making incorrect connections.
direct failure cause	Incident that initiates a loss of containment (corrosion, erosion etc.)
employee	Employee as referred to in Section 1, subsections one and two, of the Working Conditions Act
employer	Employer as referred to in Section 1, subsections one and two, of the Working Conditions Act
establishment	The whole area under the control of an operator where dangerous substances are present in one or more installations, including common or related infrastructures or activities
external risk	Risk to members of the public outside the establishment
external safety	Safety relating to members of the public outside the establishment
FN curve	Graphical representation of the group risk, where F, the frequency of N or more persons suffering an effect (e.g. mortality), is shown as a function of N.
group risk	The probability of a specific effect occurring within a specified period to a specified number of persons simultaneously. If the number of persons is not specified one or more persons are meant. For instance, a group risk of 10^{-3} per year means that the group has a probability of 0.001 that at least one person of the group suffers the effect in a time

	period of one year.
individual risk	The probability of a specific effect occurring within a specified period for an identifiable person (or function). For instance, an individual risk of 10^{-3} per year means that a person has a 0.001 probability of suffering the effect in a time period of one year.
installation	Technical unit within an establishment, in which dangerous substances are produced, used, handled, processed or stored. It shall include all the equipment, structures, pipework, machinery, tools, private railway sidings, docks, unloading quays serving the installation, jetties, warehouses or similar structures, floating or otherwise, necessary for the operation of the installation.
internal risk	Risk to employees
internal safety	Labour safety, safety relating to employees
labour safety inspector	The inspector of the labour safety department whose duty is to assess the safety report
line of defence	Technical and procedural measures in place to prevent loss of containment (preventive) or to reduce the effects of a loss of containment (repressive)
major accident	An occurrence resulting from uncontrolled developments in the course of the operation of an establishment and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances
operator	Any individual or corporate body who operates or holds an establishment or installation
penalty factor	Arbitrary factor used to increase the probability of a loss of containment. In the report use is made of default loss of containment frequencies based on a standard system with standard lines of defence. If additional failure causes are present, e.g. due to the corrosive nature of a substance, the probability of a loss of containment is likely to increase if no additional lines of defence are present. The increase in the probability of a loss of containment is determined by multiplying the default loss of containment frequency by a penalty factor.
random failures	Failure occurring at random places in the system, e.g. corrosion failure of a pipeline. Non-random failures occur at specified places in the system, e.g. leakage at flanges.

risk	Probability of a specific effect occurring within a specified period or in specified circumstances
risk matrix	A set of scenarios, along with their probabilities and consequences
safety management system	The safety management system as required in Article 5 of Hazards of Major Accidents Decree 1999
scenario	A scenario is a course of events that ends in a loss of containment and the subsequent events. A scenario refers to both the fault tree, ending in a loss of containment and the subsequent event tree. The scenario description includes the initiating events (corrosion, erosion, operator error,…), the failure of the lines of defence to prevent a loss of containment, the loss of containment, the actions to minimise the consequences of the loss of containment and the consequences.
standard system	A system containing an inert substance, i.e. a gas or liquid at ambient pressure and temperature, non-flammable, non-reactive and non-corrosive or -erosive, and situated in an environment not conducive any external failure causes.
standard lines of defence	Lines of defence given in prescriptive legislation, regulatory guidance and the standards produced by standard-making organisations
value / valuation	The process to evaluate and rate, for instance, a line of defence

1. Introduction

The 'Hazards of Major Accidents Decree 1999' [1] applies to all establishments where dangerous preparations or substances are present or are believed to be generated during loss of control in quantities equal to or in excess of the appropriate threshold. The Decree recognises a lower and an upper threshold limit value, each with its own obligations for establishments exceeding those thresholds. The main obligations for establishments exceeding the lower threshold limit values are the notification to the competent authority and the preparation of a prevention policy. Establishments exceeding the upper threshold limit value are also obliged to prepare a safety report. The operator of an establishment should demonstrate in a safety report the risks of an operation, both for external safety as well as internal safety, and that they are adequately reduced. The labour safety inspector has an obligation to accept or reject the safety report and to pass judgement on the acceptability of the internal risk as described in Article 16 of the Decree [1].

> Article 16
> 1. The administrative authorities referred to in Article 15, paragraph three, and the official designated by Our Minister of Social Affairs and Employment as referred to in Section 32 of the Working Conditions Act shall evaluate the safety report and shall, through the competent authority, inform the operator of the establishment in writing, within six months of receipt of the safety report, of their assessment of the acceptability of the hazards identified in the report.

Criteria are needed to decide on the acceptability of the internal risk. This report discusses the possibility of defining internal risk criteria. The various phases in the judging of the acceptability of the internal risk are described and criteria for the various phases are discussed. Chapter 2 outlines the method to assess the acceptability of the internal risk, and the various steps in the assessment method are elaborated in the subsequent chapters.

The labour safety inspector already uses the AVRIM2 inspection tool [2]. AVRIM2 focuses on the organisation of an establishment and evaluates the management system. The criteria described in this document focus on the 'hardware' lines of defence and are therefore complementary to AVRIM2. Both systems should be used jointly in judging the risk of an establishment.

2. Procedure for judging the acceptability of risk

In the safety report the operator of an establishment presents both the risk and his evaluation of the acceptability of this risk. The labour safety inspector has to judge the acceptability of the risk presented. In order to form an opinion on the acceptability of the risk, the labour safety inspector should both assess the correctness of the calculation of the risk to employees and compare the risk calculated with normative risk criteria. The procedure to assess the acceptability of the internal risk of an establishment is outlined in this chapter and elaborated in the subsequent chapters.

The starting point for the assessment method is an establishment having an adequate safety management system. After determining the adequacy of the safety management system, the assessment method starts with a check whether the information required is given in the safety report. The risk to employees should be adequately communicated, along with the risk acceptance criteria of the establishment. Next, the risk and risk acceptance criteria of the establishment should be rated against a set of normative risk criteria. Finally, the probability of the scenario and its consequences occurring, as presented in the safety report, are to be verified for a sample set of scenarios.

The various steps in the procedure for judging the risk of an establishment are shown in Figure 1 and described below.

1. *Safety management system*
   The operator of an establishment is obliged to have a safety management system. If the safety management system is not adequate, the risks are deemed unacceptable and the judging procedure ends. A tool used to judge the acceptability of the safety management system is the NIVRIM checklist [3], which is not further described in this report.

2. *Presentation of the risk*
   The safety report should present the risk of an establishment. If the risk is not presented adequately, the safety report is not acceptable and the judging procedure ends. Criteria for judging the acceptability of the presentation of the risk are outlined in Chapter 3.

3. *Presentation of the risk acceptance criteria*
   The safety report should indicate the risk acceptance criteria adopted by the operator of the establishment. If the risk acceptance criteria are not presented adequately, the safety report is not acceptable and the judging procedure ends. Criteria for judging the acceptability of the presentation of the risk are outlined in Chapter 4.

4. *Tolerability of the risk acceptance criteria*
   The risk acceptance criteria adopted by the operator of the establishment may be less demanding than the risk acceptance criteria adopted by the Ministry of Social Affairs and Employment. In this case, the risk acceptance criteria of the establishment are deemed intolerable and the judging procedure ends. Guidelines to define risk acceptance criteria are given in Chapter 4.

5. *Scenarios presented in the safety report*
   The risk of an establishment is presented using only a limited number of scenarios. If the scenarios selected do not give a good description of the risk and the lines of defence, the safety report is not acceptable and the judging procedure ends. Chapter 5 gives background information for evaluating the scenarios presented in the safety report.

6. *Selecting a sample of the scenarios by the labour safety inspector*
   The safety report presents the probability and the consequences for each scenario. The labour safety inspector should verify the operator's assessment. However, since it is not worthwhile to verify all scenarios presented in the safety report, a sample of scenarios should be selected for verification. Chapter 6 gives background information to select a sample of scenarios.

7. *Verifying the operator's assessment of the probability and consequences*
   For the sample of scenarios selected, the labour safety inspector verifies the operator's assessment of the probability and the consequences. The robustness of the lines of defence is also checked. If the operator's assessment is not correct, the risks are not correctly presented in the safety report and the judging procedure ends. Chapter 7 outlines a method to verify the probability and the consequences of the scenarios.

8. *Verifying the use of best available technique*
   Finally, the labour safety inspector investigates whether the operator of an establishment is using the available standards and the best (practically) available techniques. Even if the risks are calculated correctly and are acceptable according to the operator's criteria and the acceptance criteria adopted by the Ministry of Social Affairs and Employment, the operator of an establishment is obliged to meet the standards and apply the ALARA (As Low As Reasonably Achievable) principle by balancing risk reduction and sacrifices.

Chapter 8 includes a pilot study demonstrating the evaluation of the scenarios (steps 5-7).

In the flowchart (Figure 1), the judging procedure is terminated as soon as one of the steps is not carried out. For instance, if the safety management system – checked against the NIVRIM checklist – is adequate (step 1), but the presentation of the risk is not (step 2), the procedure ends without carrying out the steps 3 – 8 and the safety report is then deemed not acceptable. It should be noted that continuation of the judging procedure if one or more criteria are not met may be construed as that the inspector accepts this. This may later lead to indefinite situations and legal consequences that are indistinct.

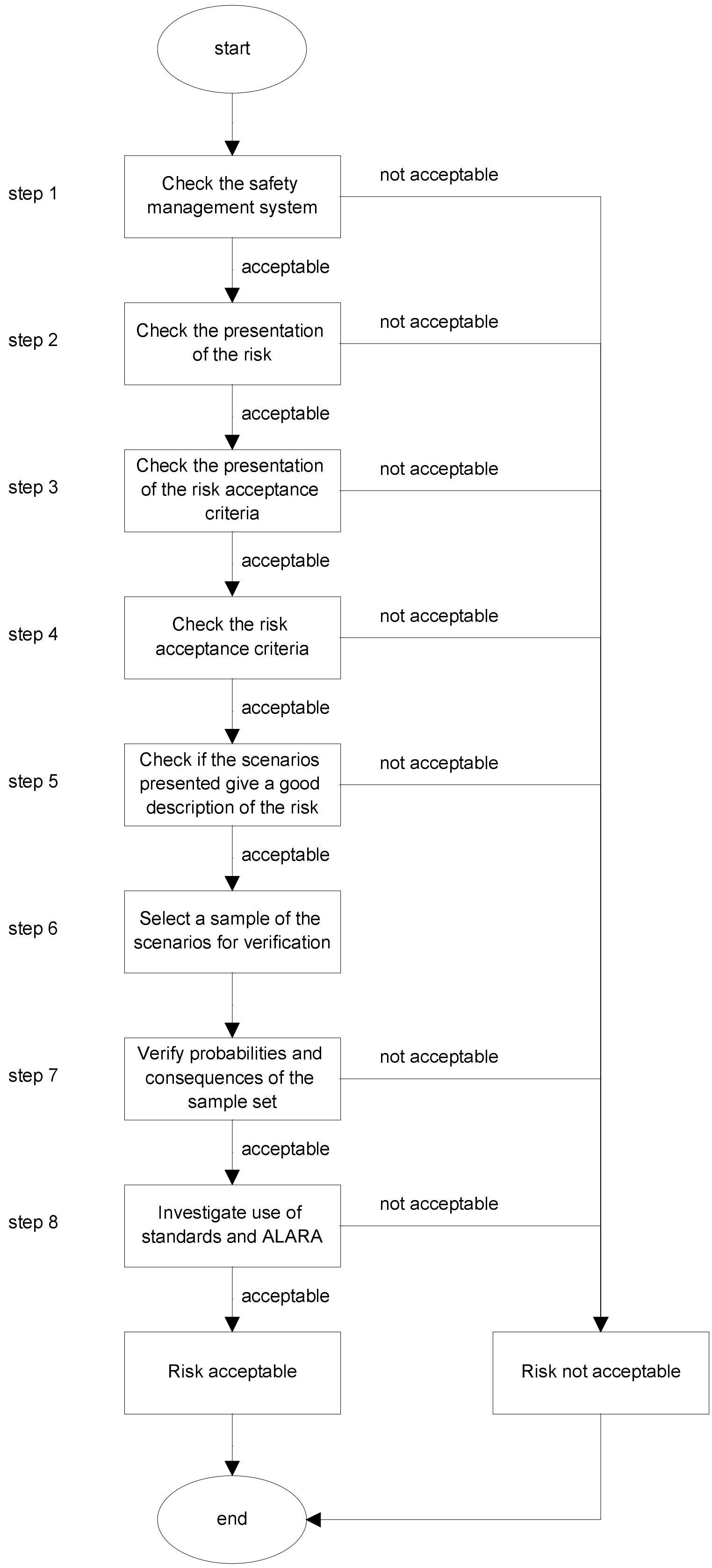

Figure 1 Outline of the procedure for judging risk.

3. Presentation of the risk (step 2)

The safety report should give information on the risk of an establishment. In step 2 of the judging process (see Figure 1) there is a check done to see whether the risks are shown in the safety report and whether the presentation of the risk is satisfactory.

The information required in the safety report is described in the 'Hazards of Major Accidents Regulations 1999' [4]. The safety report should contain a set of scenarios for each (part of the) installation where risks of a major accident are greatest. Elements to be included in the description of the scenarios are described in Article 5 of the Regulations [4].

> Article 5
> 1. The description of the scenarios referred to in Annex III, at 1 (k), to the Decree shall relate to the parts of installations with which the greatest risks of a major accident are associated. The parts of installations concerned shall be identified using a method described in the safety report.
> 2. In describing the scenarios referred to in paragraph one, consideration will at least be given to which of the following incidents can initiate such scenarios: corrosion, erosion, external loading, impact, overpressure, underpressure, low temperature, high temperature, vibration, human error during use, alteration or maintenance.
> 3. The qualitative probability and the effects should be given for each scenario, as well as the measures which have been taken to prevent the scenario from occurring. Furthermore, so that the acceptability of the hazards can be assessed, a coherent account should be given, allowing for the measures already taken, of:
> a. the residual probability of occurrence of a major accident;
> b. the severity of the consequences of the accident in that case;
> c. the additional measures technically possible to further reduce the probability of a major accident to a level therein indicated;
> d. an indication of the costs of taking the measures referred to at c.
> 4. The scenarios should be chosen so as to show that the complete system of technical and procedural measures and facilities will control the hazards of major accidents to a sufficient degree.

According to the AVRIM2 methodology [2] and the report on information requirements [5], the set of scenarios can be presented in the form of a risk matrix. The scenarios should be described for those parts of an installation leading to the highest risks of a major accident.

The information required on the risk of an establishment consists of a description of a set of scenarios, including the probability and the consequences. An overview of the elements to be included in the scenario description is given in Table 1.

Table 1 Checklist to verify the elements required in the scenario description

1	Identification method for the parts of the installation with the largest risks for a major accident
2	Consideration of the direct causes: corrosion, erosion, external load, impact, overpressure, underpressure, low temperature, high temperature, vibrations, human error in use, modification or maintenance leading to a scenario

Table 1 continued

3	Qualitative estimation of the probability and the magnitude of the consequences of a scenario: A the consequences should address the harm caused to employees (see note 1); B the set of scenarios should be (semi-)quantitative, complete and with enough resolution (see note 2).
4	The lines of defence present to prevent the loss of containment and/or to limit the consequences of the loss of containment
5	Measures technically possible to reduce the probability of a major accident to a specified level and the associated costs
6	The selection of scenarios should be sufficiently representative to demonstrate that the risk of major hazards is controlled adequately (see note 3)

Notes:

1. The consequences of a scenario comprise a wide variety of effects, namely, material losses, environmental damage, harm to employees and harm to people living in the neighbourhood. The consequences of a scenario should clearly indicate the harm to employees. It is not acceptable to just describe the material damage or environmental damage.

   Table 2 gives an example of a scale of consequence, indicating the harm to employees. Risk criteria are defined with respect to major hazards. The categories of consequence to be considered in the assessment of the acceptability of the risk are the categories 3 – 6, i.e. accidents ending in employees being severely injured or one or more deaths.

Table 2 Example of the scale of consequence [2]

Consequence category*	
1	Negligible Small impact on employees
2	Small Medical treatment of employees
3	Considerable Employees severely injured
4	Serious Permanent injury/health consequences
5	Very serious One death
6	Extremely serious Multiple deaths

*The consequence is limited to effects on humans. Similar categories can be drafted for damage to the environment, material losses, etc.

An important aspect is whether the consequences presented depend on the presence of employees or not. If the consequences of an accident are shown independent of the presence of employees, the consequences are characteristic of the installation only, and a '*from what*' approach is adopted. If the presence of employees is considered in the calculation, the consequences depend on both the installation and the presence of employees, and a '*to whom*' approach is adopted. The differences between a '*from what*' and '*to whom*' approach are discussed in Section 4.2.

2. The probability of a scenario and its consequences should be expressed quantitatively. The categories should address the whole range of probabilities (down to less than 10^{-4} per year) and consequences. The ranges within one category should not be too large. The estimation of the probability of a scenario and its consequences should be made within one order of magnitude. An estimation of the probability should be made in terms of once a year, once in ten years, etc. In the case of establishment-specific estimates being given, e.g. those (never) heard of in the branch of industry or (never) heard of in the establishment, an interpretation of the estimation in terms of the frequency per year should be given. See Table 3 for an example.

Table 3 Example of the frequency scale [2]

Description	Frequency category
Very small Never heard of in industry Almost impossible in the installation.	$< 10^{-4}$ per year
Small Heard of in industry Not likely but possible in the installation	$10^{-4} – 10^{-3}$ per year.
Average Has occurred in the company Could occur in the installation.	$10^{-3} – 10^{-2}$ per year
Large Occurs several times a year in the company Possibility of isolated incidents in the installation	$10^{-2} – 10^{-1}$ per year
Very large Occurs several times a year in the installation Incidents may be repeated in the installation	$> 10^{-1}$ per year.

3. The set of scenarios selected should demonstrate that the operator of the establishment adequately controls the risks of major hazards. Evaluating whether the set of scenarios is complete and representative is done in step 5 (see Chapter 5).

4. Risk acceptance criteria (steps 3 and 4)

According to the Regulations [4], the operator of an establishment should include in the safety report the principles that form the basis of the measures to control major hazards and should show the relationship between the measures taken and the risks of major accidents:

> Article 2
> The document setting forth the policy on prevention of major accidents and the general objectives and principles of policy on managing the hazards of major accidents referred to in Article 5, paragraph two, of the Decree, shall include:
> a. an outline of the nature and severity of the hazards of major accidents;
> b. the principles underlying the organisation of the safety management system such as to give insight into the relationship between this system and policy;
> c. the criteria applied in determining the hazards of major accidents;
> d. the principles underlying the measures taken to prevent major accidents, such as to give insight into the relationship between these measures and the hazards of major accidents.

Risk acceptance criteria are applied to balance sacrifices against the risks of major accidents. Therefore the operator of an establishment is obliged to present the risk acceptance criteria in the safety report.

In this step of the judging procedure, the labour safety inspector should do a check to see if the risk acceptance criteria are included in the safety report (step 3) and do a check to see if the operator's risk acceptance criteria are not less demanding than the normative set of risk criteria adopted by the Ministry of Social Affairs and Employment (step 4). At present, there is no prescription for the type of risk acceptance criteria and various types of risk criteria are possible. A straightforward check is therefore not possible. Furthermore, a normative set of risk criteria does not exist yet. Therefore this chapter presents background information to aid the interpretation of possible risk criteria presented in a safety report and to facilitate the development of a normative set of risk criteria.

The operator of an establishment may present the risk acceptance criteria in various ways. The operator may for instance use a risk matrix, where scenarios are placed on the basis of their probability of occurrence and consequence. Risk acceptance criteria may then be indicated as areas in the risk matrix that correspond with acceptable ('green area'), risk reduction required ('grey area') and unacceptable ('red area') [2]. For instance, using the classification in Table 2 and Table 3, the operator of an establishment may consider an accident acceptable if the probability is 'very small' and the effect is 'small', whereas an accident with a 'large' probability and 'considerable' consequence may be considered unacceptable.

However, there is no obligation to have the risk acceptance criteria shown in a risk matrix. An establishment may, for instance, use risk acceptance criteria based on an individual risk and/or a group risk [6]. Similar to the division of a risk matrix, risk limits for the individual and group risk can be defined as 'acceptable', 'risk-reduction required' and 'unacceptable'. An example of a risk acceptance criterion based on individual risk is 'the individual fatality risk of an employee, which should be less than 10^{-5} per year'. An example of a risk acceptance criterion based on group risk is ‘the probability of an accident with one or more fatalities, which should be less than 10^{-4} per year’.

There are various measures to express risk and its acceptability. In order to compare the risk acceptance criteria of different establishments and to assess the acceptability of the risk, a number of issues have to be considered. This chapter provides background information to substantiate the assessment of the acceptability of the risk and gives reasonable limits to the range of tolerable risk acceptance criteria. Items discussed in this chapter are:

- Criteria based on performance indicators (Section 4.1),
- The presence of employees (Section 4.2),
- The averaging of the risk over time and employees (Section 4.3),
- The relationship between the risk per scenario and the risk of the establishment (Section 4.4),
- The risk criteria per establishment (Section 4.5),
- Definition of a minimum risk acceptance limit (Section 4.6),
- Database of risk criteria (Section 4.7).

4.1 Criteria based on performance indicators

Risk criteria, in the case of individual risk or group risk, can be expressed in terms of fatality, or (severe) injury, or in terms of (broadly based) consequence categories. Besides fatalities and severe injuries, companies record various safety performance indicators [7,8], like:

- fatal accident rate per 100 million hours,
- compensation payment following fires and explosions,
- frequency of lost-time injuries per million hours (lost time of one day or more excluding day of injury),
- lost-time severity rate (days lost due to injuries per million hours),
- hours worked since last lost-time injury,
- total recordable injuries (= lost-time injuries + restricted workday cases + medical treatment cases) per million hours worked,
- lost-time injuries per million hours worked,
- ratio of first-aid cases plus near misses to total recordable injuries,
- number of major accidents,
- number of breaches of permits.

A study [9] has investigated whether there is a correlation between the loss of containment rate and the lost-time injury rate. The loss of containment rate includes leaks, fires and explosions involving dangerous gases and liquids from pipes, vessels, pumps, compressors etc. All occupational safety incidents, such as falls and vehicle accidents were excluded. Therefore the loss of containment rate is to a certain degree representative for the major accidents with dangerous substances. The lost-time injury rate is based on incidents resulting in three or more lost working days or on the number of days lost due to injury per million hours worked, dependent on the source of information. The study showed a number of conclusions.

- There is no clear correlation between the loss of containment rate and the lost-time injury rate; and one is no good indicator for the other.
- Looking at the severity of an impact, the proportion of incidents with no significant impact was not found lower for sites with lower loss of containment rates than for sites with higher loss of containment rates or vice versa.
- The site size is an inadequate indicator of incident rates.

There is no useful correlation found between a safety performance indicator, loss of containment rate and the rate of incidents with a significant impact. Therefore, the use of risk criteria for major accidents in terms of the usual safety performance indicators is not possible.

The use of risk criteria for major accidents in terms of the usual safety performance indicators is not possible

4.2 Presence of employees: '*from what*' or '*to whom*' approach

The consequence of a scenario depends on the presence of employees near the installation involved. It is easily imagined that one particular scenario may result in a number of casualties on a site where a large number of employees are present, whereas the same scenario does not lead to any casualties if the site is unmanned. The risk of an installation can be expressed as either a '*from what*' risk or a '*to whom*' risk.

- The '*from what*' risk takes the installation as the starting point and the risk as a quality of the installation. The '*from what*' risk is calculated as if a person or a group of persons with an average density at the establishment was to be constantly present and unprotected. The '*from what*' risk is therefore comparable to the individual risk as calculated for external safety.

- The '*to whom*' risk takes the employee as the starting point and the risk as a quality of both the installation and the presence of the employees. The '*to whom*' risk is calculated using the distribution of employees over the site, e.g. based on an average number of persons in the control rooms and the presence of employees on site. The '*to whom*' risk is therefore comparable to the group risk, as calculated for external safety; it can be depicted as a FN curve. In practice, the FN curve is replaced with a set of scenarios with a single frequency and a single consequence, e.g. a few casualties.

In practice, a '*from what*' approach has elements of a '*to whom*' approach. A labour safety inspector tends to evaluate the safety of an establishment irrespective of the number of employees and consequently applies a '*from what*' approach [10]. In principle, a site without employees should be as safe as a site with numerous employees. Also the AVRIM2 inspection method is based on a '*from what*' risk determination [2]. In practice, however, elements of a '*to whom*' approach are implicitly included: if the '*from what*' risks are unacceptable and risk reduction is not possible at reasonable costs, the presence of employees is considered. For instance, if the '*from what*' risk is unacceptable, an area with restricted access may be decided on. The risk is then considered acceptable since either no persons or only those wearing personal protective equipment are present. Similarly, safety valves are required to provide relief at a safe location, i.e. a location where no persons are present.

A '*to whom*' approach can classify the presence of people into broad categories, e.g. presence probable or improbable. For instance, the Risk Graph [11,12] method determines the level of reliability of safety measures (SIL, Safety Integrity Level). The required SIL depends on the presence of employees. Two parameters are used to classify the presence of employees, namely, one parameter to account for the exposure of people in the hazard area (rare – frequent) and one to account for the possibility of avoiding the hazard, e.g. escaping (possible – impossible). The difference in exposure between rare (occasional exposure in the hazard area) and frequent (continuous exposure in the hazard area) results on average in a change in SIL of one (one order in magnitude of the probability of failure on demand of the safety system). Likewise, a difference in possibility of escape between possible (in certain circumstances it is possible to avoid the danger, for example, by escaping from the hazard zone) and impossible (it is practically impossible to avoid the danger) results, on average, in a SIL change of one.

A '*from what*' approach may use consequence zones, irrespective of the actual presence of people and the location of the installation on the site. For instance, the effect zone for toxic substances can be defined as the area around the installation extending to the 1% lethality level or to an emergency response intervention level [13]. The effect zone for flammable substances can be defined as the area extending to the lower flammable limit (LFL). Next, it can be assumed that for effect zones with a radius less than five metres, for example, no persons are present; for effect zones with a radius less than 20 metres, for example, one person is present and for effect zones with a radius larger than 20 metres several persons are present. The approach is a '*from what*' approach if the actual presence is not considered at all. However, the actual presence can be used to estimate the average density of employees on site and therefore the average area occupied by one person.

To compare the different risk criteria and to evaluate the acceptability of the risk, it should be clear if the risk will be calculated using a '*to whom*' approach or a '*from what*' approach.

How the presence of people is taken into account should be clearly indicated.

It is recommended to consider both the '*from what*' approach and the '*to whom*' approach.

- The '*from what*' risk of an installation describes its intrinsic safety. The '*from what*' risk of an installation should be reduced as far as is practically possible, balancing the risk reduction achieved and the sacrifices required. The results of the '*from what*' risk calculation can be used to define dangerous areas, i.e. areas where the risk exceeds pre-defined threshold values.
- It may not always be possible to achieve the required risk level using safety measures at the installation. A further risk reduction to employees may then be achieved by applying a zoning policy to limit the presence of employees in dangerous areas or to allow only the presence of employees wearing personal protective equipment. In this way the '*from what*' risk is not changed, but the '*to whom*' risk is reduced. It should be noted that if the same risk reduction can be achieved, measures reducing the '*from what*' risk are preferred to measures reducing the '*to whom*' risk.
- Consideration of the '*to whom*' risk is also useful to evaluate the location of buildings with relatively large numbers of people. For instance, it is not advisable to locate the office building or cafeteria close to a dangerous installation. The calculation of the '*to whom*'

risk includes the calculation of the individual risk and the calculation of the group risk (see Section 4.3).

A method to calculate the '*to whom*' risk globally, considering the presence of employees in general, follows:

- An average population density is assumed on the basis of the site area which is generally used and accessible and the average number of employees present at random places at the site.
- If access to certain areas is controlled by rules of restriction, the employee density in these areas is lower than average.
- The presence of a relatively large number of employees, e.g. in a control room, cafeteria, office building and the like should be explicitly taken into account by a higher density in this area.
- Some activities are associated with the presence of employees, e.g. loading and unloading activities and maintenance activities. The presence of employees during activities should be considered explicitly.
- Besides the risk of the installation during normal operations, the risk due to repair activities should also be calculated given the faulty situation. For instance, if the probability of failure of an installation is 1×10^{-4} per year, and the probability of a fatality during repair is 0.01, the risk of the installation would be 1×10^{-6} per year; this number may be considered acceptable. However, the mortality risk during repair given the faulty situation is 0.01; this risk of repair may be considered unacceptable.

The consequence category of a scenario can be estimated using the number of employees present in an effect zone.

4.3 Individual risk or group risk and the averaging of risk

Risk acceptance criteria may be expressed in terms of individual risk, e.g. the HSE risk acceptance criteria [14]. There are different definitions of the person to whom the individual risk is calculated. Individual risk may refer to the risk to an actual person, taking into account the personal variation in the exposure. For example, personal monitoring of the radiation dose to workers in the nuclear industry results in an estimate of the actual exposure of each individual and therefore in the assessment of a personal individual risk.

Monitoring of the risk exposure at chemical plants would be a very difficult and cumbersome task. In practice, a hypothetical person, the reference person, is defined as having some assumed pattern of life in relation to the risk involved. For example, to assess the risk of a chemical industrial plant outside the boundary of the establishment (external safety), the risk is calculated for a hypothetical person, present 24 hours a day at a fixed point near the establishment and unprotected. Occupational hazard is often assessed for a hypothetical person who is in good health and works exactly 40 hours a week. The risk of each individual person can often be derived from the risk calculated for the reference person by accounting for differences in exposure time, protection measures and the like.

When comparing risk criteria and the risk at different sites, care has to be taken to calculate the risks for the same reference person. In order to compare various risk figures, various points of special interest should be noted.

A distinction should be made between individual risk and group risk. The individual risk is the probability of a casualty of one (identifiable) person. The individual risk for an employee at a chemical plant can be compared to the annual risk of other activities, like car driving or the annual risk of death from accidents for employees for various occupational groups. For instance, the HSE document "Reducing Risks, Protecting People" [14], compares the tolerability limit of individual fatality risk of 1 per 1000 per year with the actual fatality rate for workers in the most hazardous industries. The HSE limit of tolerability of an individual risk of death for any substantial category of workers seems to be based on the maximum average risk to significant groups of workers, e.g. steel workers or deep-sea fishermen. The risk of death of an activity is calculated by dividing the number of deaths by the number of individuals exposed. For example, the risk of offshore fishing is calculated as the ratio of the number of deep-sea fishermen killed during fishing in a period of time and the number of these fishermen employed in the same period of time. Consequently, the HSE limit of tolerability seems to be based on the average risk to a group of specific workers. The HSE limit of tolerability may be applied to a group of workers in the chemical industry, e.g. operators. The individual risk criterion of death of 1 per 1000 per year would mean that on average, one out of a thousand operators would die annually due to a work-related hazard. It should be noted that this criterion for an individual employee poses a different risk criterion for the establishment as a whole: if ten persons are employed at an establishment, the limit of tolerability for this establishment results in one accident with one fatality in a hundred years. However, if hundred persons are employed at an establishment, the same limit of tolerability for the establishment as a whole would result in an accident with one fatality in every ten years.

The group risk is the probability of an accident at an establishment, resulting in one or more casualties. If, in an industrial establishment, the risk of a fatality is equal to 1 per 1000 per year, an accident with one death in a thousand years is expected, irrespective of the size of the group at risk. Unfortunately, group risk acceptance criteria may be presented as if they were individual risk criteria and be erroneously compared to the HSE tolerability limit of individual risk [15,16].

Individual risk or group risk is calculated for a group of employees. However, within the group of employees large differences may exist in exposure to the risk. For instance, at an industrial site, process operators, maintenance personnel and office staff are employed, and their exposure to risk may differ largely [17]. Contractors may also be exposed to a high risk over a limited period of time, as illustrated in Figure 2.

The risk of employees can be calculated by dividing the number of deaths by the number of individuals assumed to be exposed. If the number of individuals assumed to be exposed is equal to the group of all employees at the industrial site, including office staff, the risk to the group of employees at highest risk can be underestimated. At an establishment the (average) individual risk of employees may even be lowered without increasing safety by adding an office building on site and including the low risk of the office staff in the average site risk. Care should therefore be taken that the individual risk figure is calculated for the group at highest risk.

Similarly, different areas may be present on a site, and the risk in one area may be considerably higher than the risk in other areas. If the individual risk to an employee is calculated on the basis of presence averaged over the site as a whole, the risk of a particular installation can be covered up.

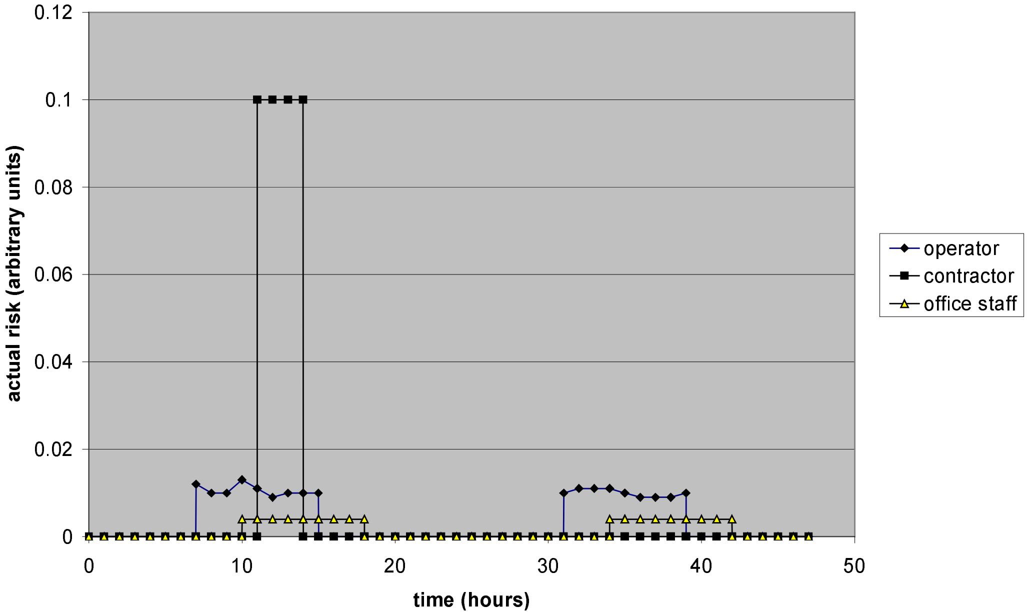

Figure 2 Example of the variation in actual risk to various types of employees in the course of two days' work.

What is meant by an 'individual risk' should be clearly described.

The individual risk figure should be calculated for the group at highest risk

4.4 Risk per scenario and per site

Risk criteria can be expressed per scenario or per site, including all scenarios and all installations.

Risk criteria per scenario applies when the operator of an establishment presents his risk criteria as areas in a risk matrix corresponding to acceptable ('green area') and unacceptable ('red area'); this may be completed with an area where risk reduction is required ('grey area'). The scenarios leading to an accident are assessed in isolation together with the lines of defence needed per scenario. Hence, information on site level, like the number of accidents expected within the establishment, is not available.

Risk criteria are usually indicated at establishment level. For instance, the individual risk of an employee should be less than a certain limit value, or the probability of an accident at the establishment with one mortality should be less than a certain limit value. In this case, the risk should be determined at the level of the establishment and all possible scenarios should be combined into one risk figure. Therefore a relationship is needed between the risk per scenario (frequency and consequence of one particular scenario) and the risk per site or installation (frequency and consequence of all possible scenarios). One way to relate the risk criteria for the overall risk of the installation to the risk per scenario is to make an assumption on the number of scenarios having the same consequence. Once all scenarios are placed in the risk matrix, the overall frequency category of the scenarios with similar consequences is determined by adding up the frequencies of the separate scenarios. In the risk matrix presenting the complete risk of an establishment, each consequence category is thus coupled to only one frequency category and the overall risk criteria can be compared with the scenarios in the risk matrix.

The process is illustrated in Figure 3. For instance, there are eleven scenarios with category of frequency ‘large’ (i.e. 10^{-2} – 10^{-1} per year) and category of consequence ‘negligible/small’. Considering the eleven scenarios together, the frequency of occurrence is 11 × 10^{-2} – 10^{-1} per year, i.e. > 10^{-1} per year and the category of frequency is ‘very large’. Therefore all eleven scenarios combined are classified in category of frequency ‘large’ (i.e. 10^{-2} – 10^{-1} per year) and category of consequence ‘negligible/small’.

Consequence → Frequency ↓	**Negligible/ small**	**Considerable**	**Serious**	**Very serious**
Very small	S-28	S-29 S-30	S-20 S-21 S-22 S-23 S-24	S-25
Small	S-26 S-27	S-6 S-8 S-11 S-13 S-16 S-17 S-18	S-19	
Average				
Large	S-1 S-2 S-3 S-4 S-5 S-7 S-9 S-10 S-12 S-14 S-15			
Very large				

Consequence → Frequency ↓	**Negligible/ small**	**Considerable**	**Serious**	**Very Serious**
Very small				SC
Small			SC	
Average		SC		
Large				
Very large	SC			

Figure 3 An example of combining scenarios. A set of scenarios (S-1 ... S–30) is placed in a risk matrix (top); next, the risk matrix of the scenarios combined (SC) is constructed (bottom).

A clue for determining whether all relevant major hazard scenarios have been considered with the correct frequency can be found in the description of the external risk calculation. For external safety, relevant standard scenarios with default frequencies are defined for a standard equipment set. In general, the failure frequency of a piece of equipment is divided over various loss-of-containment events, ranging from a small hole to an instantaneous release of the contents of the equipment. A comparison between the loss-of-containment events and their frequencies in the external safety part of the safety report, and the scenarios in the risk matrix can reveal the fairness of the presentation for the risk in the risk matrix.

An overview of loss-of-containment events and their typical failure frequencies are presented in Chapters 5 and 7.

There should be a connection between the risk criteria and the scenarios.

4.5 Risk criteria per establishment

An important aspect is whether all establishments should keep to the same safety level or whether different establishments should be allowed to have their own safety criteria. The discussion focuses on the safety criteria of establishments, applying different processes and the safety criteria of establishments applying the same processes.

Processes have their own level of safety. It is to be expected that continuous, computer-controlled processes have a higher level of safety than batch processes, requiring an operator to open vessels and to handle dangerous substances. Therefore a higher risk level for the operator in the batch process may be allowed than for the operator of the continuous process if a safer continuous process cannot realistically replace the batch process. Consequently, different processes have their own level of safety, and establishments working with different processes (storage, continuous processes, batch processes) may use different risk criteria. Even within one establishment, different installations may have different individual risk criteria and risk criteria can be defined at installation level.

The labour safety inspector considers the principle of reasonableness: the operator of an establishment should do all that is reasonable to minimise the risk of the employees [18]. This principle may lead to differences in the level of safety in different establishments. Consider, for instance, two establishments: establishment A is owned by a large international company making large profits, while establishment B is a small local establishment with small profits. A safety-promoting measure may be reasonable for establishment A, since the cost of the measure is small with respect to the profit of the establishment. However, the same measure may be too costly for the small establishment and therefore not reasonable. A small establishment with less profit is thus not required to maintain the same high level of safety as a large establishment. The question remains whether an inferior financial performance may lead to a reduced level of safety. Jurisprudence in this field [19] shows that the ALARA (as low as reasonably achievable) principle does not allow a consideration based on the *individual* economic interest of a company, but should be based on provisions that are reasonable for an average company in a particular branch. Therefore the financial situation of a company is not considered in the risk criteria.

Although differences exist between processes and establishments, allowing different risk criteria in different branches to be justified, the following should be noted:

- There should be a minimum safety level to which all establishments and all processes are subjected. If the minimum safety level is not maintained, the operation is considered

unacceptable. Guidance on the setting of a minimum risk acceptance limit is given in Section 4.6.
- An operator of an establishment may decide to keep to higher standards than the minimum risk level. The operator of the establishment should demonstrate that they do keep to these higher standards.
- The principle of ALARA can justify different risk criteria for different processes, since measures to achieve the same level of safety may be more costly for one process than for another.

The individual risk should be less than the limit of tolerability set by the labour safety inspector.

The operator of the establishment should describe his standards.

The operator of the establishment should keep to his own standards.

4.6 Definition of a minimum risk acceptance limit

The labour safety inspector should define a minimum risk acceptance limit. The limit should be defined on the basis of sound principles:

- the minimum risk acceptance limit should not be unrealistically low compared to other risk limits and the actual risks experienced in the chemical industry as accepted up to now. If the minimum risk acceptance limit is set too low, a majority of the establishments may not be able to meet the risk acceptance limits.

- the minimum risk acceptance limit should not be high compared to other risk limits and risks experienced in everyday life. The aim of a risk acceptance limit is to control the risks. If the risk acceptance limit is set too high, the limits are unsuitable for the purpose of risk control.

To give guidance on the definition of a suitable risk acceptance limit, statistics and risk acceptance limits in different countries and different fields of employment are useful. Statistics on mortality and morbidity are given in Section 4.6.1, and relevant risk acceptance limits are described in Section 4.6.2.

4.6.1 Statistics on mortality and morbidity

As a starting point, the statistics on mortality of the total workforce are considered. In the Netherlands, the average number of fatalities due to accidents at work was 84 per year in the three-year period 1996 – 1998 [20]. The labour force in the Netherlands in the same period was 6.4 million persons. On average, the individual mortality risk due to an accident at work is equal to 1.3×10^{-5} per year. The average number of fatalities due to accidents at work can be compared with transport accidents. For the population in the age category 25 – 60 years, 554 transport fatalities occurred in a population of 8.0 million persons and the mortality risk is equal to 6.9×10^{-5} per year [20].

Within the total workforce large differences may exist in risks experienced. It is therefore more useful to subdivide the statistics in the various occupational groups, like manufacturing industries, construction, service industries etc. Information on the individual mortality risk in industry for various occupational groups is found for Great Britain and is given in Table 4. The table shows that the annual risk of mortality in the manufacturing industry in Great Britain is comparable to the average annual risk of mortality in the Netherlands, i.e. $1 – 2 \times 10^{-5}$ per year. In high-risk industries, like construction and mining, the mortality risk is about a factor of 10 higher, i.e. $1 – 2 \times 10^{-4}$ per year.

Table 4 Annual risk of death from industrial accidents to employees for various occupational groups in Great Britain (source: [14])

Cause of death	Annual risk
Quarries (quarry workers)	182×10^{-6}
Construction	79×10^{-6}
Energy and water-supply industries	69×10^{-6}
Agriculture, hunting, forestry and fishing (not deep-sea fishing)	60×10^{-6}
Metal manufacturing industry	18×10^{-6}
All manufacturing industry	14×10^{-6}
Electrical and optical equipment manufacturing industry	7×10^{-6}
All service industries	4×10^{-6}

In addition to the mortality risk, the rate of major non-fatal injuries and over-3-day injuries are reported in Great Britain [21]. In the manufacturing industry, the mortality rate is equal to 1.3×10^{-5} per year, the rate of major non-fatal injuries is equal to 2.1×10^{-3} per year and the rate of over-3-day injuries is equal to 1×10^{-2} per year (1997-2000). It should be noted that although the reporting of fatalities is fairly complete, an underreporting of injury accidents exist. For the manufacturing industry, about 2/3 of the injuries due to accidents is reported [22]. It is therefore concluded that in the manufacturing industry, the rate of major non-fatal injuries is, on average, a factor 240 higher than the mortality rate and the rate of over-3-day injuries is a factor 1200 higher than the mortality rate.

It should be noted that the statistics involve all types of fatal accidents. The most important causes distinguished are falls from a height, being struck by moving vehicle or by a moving/falling object and contact with moving vehicle. Accidents with dangerous substances represent only a small percentage of the casualties in industry. Various accident causes are distinguished in the statistics, including exposure to, or contact with, a harmful substance, exposure to fire and exposure to an explosion [21,22]. Averaged over three years (1997/1998, 1998/1999 and 1999/2000), exposure to a harmful substance, exposure to fire and an explosion in manufacturing industries accounts for 14% of the reported fatalities, 5% of the reported non-fatal major injuries and 4% of the reported over-3-day injuries [21].

Since accidents due to dangerous substances represent only a small part of the accidents in industry, a lower limit for the risk due to major accidents only would seem reasonable. If the individual risk limit for an accident due to dangerous substances were set equal to the average individual mortality risk due to an accident at work in the Netherlands, the individual risk limit would be in the order of $1 – 2 \times 10^{-5}$ per year. Assuming that approximately 10% of the accidents were caused by dangerous substances, as indicated by the statistics in Great Britain [21], the individual mortality risk limit due to accidents with dangerous substances would be in the order of $1 – 2 \times 10^{-6}$ per year. The individual risk limit for major non-fatal injuries and over-3-day injuries would be about 2 and 3 orders of magnitude larger, respectively.

4.6.2 Risk acceptance limits

Appendix 1 gives an overview of a number of risk acceptance criteria in different countries and in different areas. Risk acceptance criteria are usually defined in terms of mortality risk. The results are summarised in Figure 4.

Individual risk			Group risk
Unacceptable individual risk to workers (United Kingdom); individual risk limit for radiological workers (20 mSv)	1×10^{-3} →	← 1×10^{-3}	Risk of a fatal accident or an accident with a serious health effect (company)
		← 2×10^{-4}	Risk of an accident with 50 fatalities or more (UK)
Unacceptable individual risk to members of the public (United Kingdom)	1×10^{-4} →		
Individual risk limit for members of the public re. protection against ionising radiation (1 mSv)	5×10^{-5} →		
Typical company limit of risk to workers	3×10^{-5} →		
Risk to members of the public for existing situations, chemical accidents (NL)	1×10^{-5} →	← 1×10^{-5}	Risk of a chemical accident with 10 fatalities or more off-site (NL)
Individual risk limit for members of the public offsite re protection against ionising radiation (0.1 mSv)	5×10^{-6} →		
Typical company risk limit for members of the public	3×10^{-6} →		
Risk to members of the public for new situations, chemical accidents (NL); boundary between broadly acceptable and tolerable (UK)	1×10^{-6} →		

Figure 4 Risk acceptance criteria.

It should be noted that the risk acceptance criteria are strongly connected to the method of calculation. For instance, the individual risk to members of the public in the Netherlands is the acute mortality of a person present 24 hours a day, 365 days per year, with no means of protection. In radiological protection, risk limits are based on long-term health effects and the actual exposure of an individual is taken into account. On the other hand, companies develop their acceptance limits on the basis of actual presence of an employee and the possibility of the employee to escape from the danger.

Comparison of the different risk criteria has led to a number of observations as outlined below.

- Different risk criteria are applied to the risks to which workers and members of the public are subjected. In general, the difference in risk limits is one order of magnitude. The same factor would result in an individual risk limit to employees of $1 - 10 \times 10^{-5}$ per year for major chemical accidents, ignoring differences in calculations for the employee's presence, and the possibility of mitigation and escape. The use of the same factor in the group risk would result in a group risk limit of 1×10^{-4} per year for an accident resulting in 10 fatalities or more. An extrapolation of the quadratic relationship between probability and number of fatalities results in a group risk limit of 1×10^{-3} per year for an accident with three fatalities or more and a group risk limit of 1×10^{-2} per year for an accident with one fatality or more.
- The maximum individual risk limit found for employees is in the order of 1×10^{-3} per year. This limit is the HSE boundary between unacceptable and tolerable regions. However, the HSE limit is very high with respect to the actual fatality rate and accounts for all accident causes.
- Risk acceptance criteria set internally in establishments are typically in the order of 3×10^{-5} per year and are thus comparable to the annual risk of death in the manufacturing industry (all types of accidents).

4.6.3 Discussion

The minimum risk acceptance limit should be set within a reasonable range. On one hand, the risk limit should not be too low in order to avoid that the majority of the establishments may not be able to meet the risk acceptance limits. On the other hand, the risk acceptance limit should not be too high in order to avoid that the risk limit is unsuitable for the purpose of risk control.

Risk acceptance criteria are usually defined in terms of mortality risk. The individual mortality risk due to an accident at work in the Netherlands is in the order of $1 - 2 \times 10^{-5}$ per year. This number is representative for the manufacturing industry. The fraction attributed to exposure to dangerous substances, exposure to fire and exposure to explosion is in the order of 0.1. An individual risk limit in the order of $1 - 10 \times 10^{-6}$ per year for accidents with dangerous substances would therefore constitute an acceptable range. This range would be equal to the risk limit for a member of the public. However, in the accident statistics, the use of protective equipment, the possibility of avoiding danger and the limited presence of an employee (only during working hours) is implicitly included in the mortality rate, whereas in the risk limit for a member of the public no safety measures are calculated and the limit is based on a presence of 24 hours a day, 365 days per year. If a working year equal to 1800 hours is set, and the possibility of avoiding the danger is rated with a factor of 10, the individual risk limit for employees based on a continuous presence and not accounting for the possibility of avoiding danger comes to a factor of 40 higher than the risk limit to the public.

Risk acceptance criteria for injuries are not yet common. Based on statistics, the individual risk limit for major non-fatal injuries and over-3-day injuries would be, respectively, about 2 and 3 orders of magnitude larger than the mortality risk limit.

4.7 Risk criteria database

Operators of establishments define their own risk criteria. Furthermore, the labour safety inspector often uses establishments within the same branch as a benchmark to derive standards for lines of defence. It is advised to set up a database containing the risk criteria defined in the safety reports. As the risk criteria of the various establishments become available in the course of time, the database can be used to compare the risk criteria of one establishment with (a set of) risk criteria of similar establishments. Establishments should be classified into a number of categories to facilitate the selection of similar establishments. Classifications could be, for example:

- LPG storage
- Oil refinery
- Production of (bulk) chemicals
- CPR-15 warehouses

This classification can be subdivided according to characteristics like the age and size of an establishment. The range of risk criteria in a category of comparable establishments provides the labour safety inspector with the set of mean risk criteria and a set of most stringent risk criteria. The set of most stringent risk criteria adopted by one operator of an establishment could be a guideline for improvement of safety in other establishments. Alternatively, the set of mean risk criteria may be used as a minimum risk level, thus continuously improving the average risk level of a class of establishments.

Risk acceptance criteria should be compared to the benchmark set of risk acceptance criteria.

5. Evaluation of the scenarios presented in the safety report (step 5)

5.1 Introduction

The risk of an establishment is presented using only a limited number of scenarios. If the scenarios selected do not give a good description of the risk and the lines of defence, the safety report is not acceptable and the judging procedure ends. This chapter gives background information for evaluating the scenarios presented in the safety report.

Based on the requirements of 'Hazards of Major Accidents Decree 1999'[1] and 'Hazards of Major Accidents Regulations 1999' [4] the criterion of the best selection of scenarios is met if:

- Scenarios are sufficiently representative of the hazards and how often they might be realised (Article 10.1b [1] and Article 3.1 [4]). The choice must be based on a systematic process (Article 3.1 [4]) and be sufficient to reflect all the measures (lines of defence) (Article 5.4 [4]).
- The lines of defence for the design, construction, utilisation and maintenance phase are sufficient (Article 10.1b and c [1]). This should be reflected in the location of the scenario in the risk matrix.
- The measures are present and working (verified by site inspection and audit).

> Article 10 (1b and c) [1]
> 1. A safety report shall contain the data and descriptions referred to in Annex III such that it can be demonstrated that:
> b. the major accident hazards have been identified and the necessary measures have been taken to prevent such accidents and to limit their consequences for man and the environment;
> c. adequate safety and reliability have been incorporated into the design, construction, operation and maintenance of all installations, storage facilities, equipment and infrastructure connected with the operation of the establishment which are linked to major accident hazards inside the establishment;
>
> Article 3.1 [4]
> 1. The procedures for systematically identifying undesired events and the assessment of the hazards of major accidents as referred to in Annex II, at c, to the Decree shall relate to:
> a. the systematic analysis of the major accident hazards associated with an installation during its design, construction, use and maintenance and during planned modifications thereto;
> b. the criteria for determining the methodology for the analysis referred to at a;
> c. the methods for assessing the hazards of major accidents.
>
> Article 5.4 [4]
> 4. The scenarios should be chosen so as to show that the complete system of technical and procedural measures and facilities will control the hazards of major accidents to a sufficient degree.

In this chapter, background information is given in order to facilitate the evaluation of the scenarios described in the safety report (step 5 of the procedure). Guidance is given on:

- criteria for judging the selection procedure (Section 5.2)
- selection of activities and equipment failures to be described (Section 5.3)
- direct failure causes to be discussed (Section 5.4)

5.2 Criteria for judging the selection procedure

The choice of the scenarios must be based on a systematic process and be sufficient to reflect all the measures (lines of defence) [4]. The relevant scenarios could be selected according to the following system:

1. All the activities of an establishment and related components should be identified (Section 5.3).
2. The most critical parts of an activity or installation should be identified using a hazard index. The hazard index should be checked to see if it is also is suited to identifying the scenarios for substances that give only non-lethal effects. Background information on hazard indices can be found in Lees [23].
3. For each critical part of an installation scenarios are selected in such way that the direct failure causes are discussed at least once. It should be explained in the safety report why certain initiating events are not discussed. The matrix of initiating events of AVRIM2 can be used to check whether the direct failure causes are included for all the different activities. In Section 5.4 more guidance is given on the selection of the direct failure causes to be discussed.
4. Depending on the establishment, other factors that can be taken into account in the procedure are:
   - the age of an installation (which is likely to have an effect on the failure frequency),
   - random versus non-random failures,
   - destructive versus non-destructive failures,
   - the presence of ignition sources,
   - the inclusion of substances handled, especially substances forming the basis on which the establishment is obliged to prepare a safety report.

The selection of the scenarios should be done in a team of experts in the field of risk analysis and with detailed knowledge of the processes and installations under consideration. The scenarios with the largest potential hazards are determined using a '*from what*' approach. The presence of employees, especially the location of the control room is not included in the identification as the relevant-effect distances for most scenarios are not known beforehand.

Only releases of substances that give minimal effects included in the matrix are of importance. Substances classified as only hazardous to the environment will not be included as they are not relevant for internal risk. It is also of importance that scenarios resulting in less severe effects, like the number of days absent are included, scenarios and lines of defence that focus specifically on these effects should be included too. The description of scenarios and lines of defence focusing only on lethal effects will not be sufficient. The effect levels to be expected for the different hazard categories are given in Table 5.

Table 5 Effects (lethal, non-lethal) to be expected due to releases of dangerous substances

	Acute Lethal	Non-lethal
Explosive	Yes	Yes
Oxidising	Yes	Yes
Flammable	Yes	Yes
Reactive with water	Yes	Yes
Toxic	Yes	Yes
Dangerous for the environment	No	No

5.3 Selection of activities and equipment failures to be described

For the description of the overall internal risk of an installation or establishment it is important that all relevant activities are described in the safety report. As the scenarios and lines of defence depend on the failures of components of an installation, these components should be identified. The activities of an establishment are given in the notifications. For about 225 establishments the notifications were available at the RIVM in March 2001. Of these 225 establishments, about 125 have to provide a safety report to the competent authorities. The activities described in the notifications of these establishments are given in Appendix 2.

Based on the information in the notifications, the following main activities can be defined:

- storage in warehouses
- storage of fireworks or explosives
- storage of crude oil or oil products
- storage of liquids
- storage of (liquefied) gases
- loading and unloading of trucks
- loading and unloading of tank wagons
- loading and unloading of ships
- filling of gas cylinders and bottles
- (internal) transport via pipelines
- production, batch processes
- production, continuous processes
- processing of waste
- compression and mixing of natural gas

Component failures relevant for the internal risk of an installation or establishment can be derived on the basis of the activities at an establishment. Generic scenarios that should be included in a risk analysis are set for external safety and the risk for the environment. These scenarios are also based on the failures of components at an installation. The generic scenarios for external safety for the different components in an installation are given in CPR-18E [24]. Components identified are:

- Pressurised tanks and vessels. A distinction is made between storage, process (for example, distillation columns, condensers and filters) and reactor vessels (batch and continuous). A vessel consists of the vessel (tank) wall and the welded stumps, mounted plates and instrumentation pipes.
- Atmospheric tanks and vessels (different types).
- Pipelines (flanges and gaskets included).
- Pumps.
- Heat exchangers.
- Pressure relief devices.
- Warehouses for dangerous substances.
- Warehouses for explosives.
- Road tankers and the loading and unloading components like hoses and loading arms.
- Tank wagons and the loading and unloading components like hoses and loading arms.
- Ships and the loading and unloading components like (hoses and) arms.

Appendix 3 gives the generic scenarios for these components [24].

All of these component failures are also relevant for internal risk and should therefore be considered in the scenarios described in the safety report. The scenarios for external risk have a generic character, therefore no distinction is made of the sub-components (like valves on a pipeline, flanges or reflux lines in a reactor) that actually fail and the phase in which the failure occurs (utilisation or maintenance phase (start-up included)). The description of the scenarios for internal risk will be based on the failure of these sub-components. Component failures will appear in certain parts of a component, for example, the failure of the pump seal. Part of the component failures will have a random character, the location of the failure and the size of the hole or rupture can not be foreseen. An example of this is a leak in a tank wall or pipeline due to corrosion. A differentiation can also be made between destructive and non-destructive failures. For non-destructive failures, a differentiation is made between [25]:

- leakage, for instance, open valves or bad connections and
- overfilling, for instance, an operation or a process control error.

Non destructive failures occurring in installations may be related to the following:

- flow/transport
- pumping
- compression
- human action (making connections, closing/opening valves, preparing transfer lines etc.)

Also, releases of dangerous substances via flares and as a result of the use of a breaking plate can be defined as non-destructive failures.

Although the scenario description for the internal risk will be given in more detail than the generic external safety scenarios, these internal risk scenarios will result in the same types of releases. Therefore the external safety scenarios [24] can be used for describing the kinds of releases that can occur.

5.4 Direct failure causes to be discussed

Direct failure causes which should at least be considered in the safety report are:

- corrosion
- erosion
- external stress
- impact
- overpressure
- underpressure
- low temperature
- high temperature
- vibration
- human failure during use
- alterations or maintenance

The use of the wrong equipment or equipment at the wrong location in the installation is also taken into account in AVRIM2. For all these direct failure causes, generic fault trees are set up with one or more initiating events [2,5]. To be certain that all the measures are included all the initiating events of the direct failure causes [2,4] should be described for all activities and related components. However, given the number of initiating events and components present at an installation, the scenarios to be discussed in the safety report could number up to 1000 or more. For the standard systems (Section 7.1.2) the most relevant direct failure causes can be derived from data taken from the literature [26, 27] and the method given in [25]. In reference [25], insight on relevant failure phenomena is given using identification schemes. Each component of an installation is characterised by a number of factors such as process conditions, substances, materials, operation mode and location. In combination with these characterisations a scheme of failure phenomena is used for the identification of hazardous situations. The methodology can be used for various types of processes in different stages, for instance, during design or normal operation. The relevant data for pipelines and vessels are given in the following sections. For other equipment like pumps, heat exchangers, etc. no detailed data on the relative contribution of the direct failure causes are found in the literature. The relative contribution of the direct causes of equipment failure other than pipelines and vessels should be determined in a follow-up of this study.

5.4.1 Pipelines

A generic overview of the relative contribution of different known direct failure causes for on-site (process) pipeline failures is available (Table 6) [26]. This overview can be used to identify the most important failure causes for the standard pipeline. In the overview data are also incorporated for pipelines with reactive substances or failures under extreme conditions. Therefore Table 6 serves only as a guideline.

Based on the method described in reference [25], the process characterisation for the standard pipeline is defined as pumping and flow transport. Overpressure is the most relevant direct failure cause as the following failure phenomena apply:

- pressure wave
- pump head
- pressure fluctuation

Table 6 Relative contribution of different known direct failure causes for (on-site) pipeline failures (unknown failure causes–41% of all failures– are excluded) [26]

Direct failure cause	Relative contribution (%)
Operator error	30.9
Overpressure	20.5
Corrosion	15.6
Impact	8.1
Wrong equipment/location	6.7
Temperature	6.4
External Loading	5.0
Other	2.5
Vibration	2.5
Erosion	1.3

Taking the most important direct failure causes found in the literature [26] and the most important failure cause from the data in [25] the most relevant direct failure causes to be discussed in the safety report for a standard pipeline will be:

- overpressure
- operator error
- corrosion
- impact

The most important direct failure causes found in the literature are derived by taking the failure causes with the largest contribution. Combined, these causes contribute to more than 75% of all direct failure causes.

5.4.2 Storage vessels

For vessels, a generic overview is available of the relative contribution of different known direct failure causes (see Table 7 [27]). This overview can be used to identify the most important failure causes for the standard vessel. In the overview data also have to be incorporated for vessels with reactive substances or failures under extreme conditions. Therefore Table 7 serves only as a guideline.

Based on the method described in reference [25], the process characterisation for the standard storage vessel of liquefied pressurised gas is defined as storage. As overpressure, temperature and operator errors are the most relevant direct failure causes, the following failure phenomena apply:

- pressure wave
- phase transition
- pressure fluctuation
- overfilling

Table 7 Relative contribution of different known direct failure causes for vessel failures (unknown failure causes – 6.7% of the total – are excluded) [27]

Direct failure cause	Relative contribution (%)
Pressure	45.2
Operator error	24.5
Temperature	11.2
Corrosion	6.3
Impact	5.6
External loading	2.6
Other	2.6
Wrong equipment/location	1.9
Erosion	0.2
Vibration	0

Taking the most important direct failure causes found in the literature [27] and the most important failure cause from the data in [25], the most relevant direct failure causes to be discussed in the safety report for a standard storage vessel will be:

- overpressure
- operator error
- temperature

The most important direct failure causes found in the literature are derived by taking the failure causes with the largest contribution. Combined, these causes contribute to more than 75% of all direct failure causes.

6. Selection of a sample from the installations and scenarios for the judging process (step 6)

The labour safety inspector should judge the operator's evaluation of the probability and consequences of the scenarios selected, as well as the robustness of the lines of defence. Since the number of scenarios in the safety report can be very large, spot checks may have to be made. The spot check needs to provide a representative view of the establishment and the various installations. The guidelines to selecting the scenarios for a spot check are similar to the guidelines to selecting the scenarios for inclusion in the safety report (Section 5.3). In summary, the following principles should be considered in the selection of scenarios for the judging process.

- The operator of an establishment is obliged to make a safety report because of the presence of one or more substances in quantities exceeding the threshold values in the Hazards of Major Accidents Decree 1999 [1]. A number of scenarios relating to these substances should be included in the spot check.
- Dangerous substances to be considered in the safety report can either be explosive, flammable or toxic. Scenarios relating to explosive substances, to flammable substances and to toxic substances should be included in the spot check if present. The selection of scenarios should be focused on very toxic substances compared to toxic substances, and on extremely flammable substances compared to flammable substances.
- The hazard of installations can be estimated using various methods, like the selection process for external safety [24], the selection process for labour safety [28] and various hazard indices. The installations with high numbers of hazards, based on the labour safety selection process, should be included in the spot check.
- Establishments may have an organisation that is characterised as either centralised or decentralised. If the organisation is strongly centralised, a few installations may be considered representative for the safety system of the site as a whole and the spot check can be focused on a few installations. If the organisation is strongly decentralised, plants may have their own safety system, and all different plants must be included in the spot check. The consistency of the type of organisation of the establishment should be checked.
- Scenarios can be located in a risk matrix. The company's risk matrix can be used as starting point for the selection of scenarios. However, if the company does not present the set of scenarios in a risk matrix, the AVRIM2 risk matrix can be used to locate the scenarios in the risk matrix. Both scenarios located in the small effect, large probability, region as well as scenarios located in the large effect, small probability, region of the risk matrix should be included in the spot check. However, the selection of scenarios for the spot check should be focused on the scenarios with large effects.
- Scenarios, placed in step-2 and -4 approved risk matrix of the establishment (or placed in the AVRIM2 risk matrix), are classified as acceptable ('green area') or unacceptable ('red area'). It is also possible to identify an area of desired risk reduction ('grey area'). Scenarios for all areas should be included in the spot check; however, the selection of scenarios should be focused on the unacceptable scenarios and the scenarios where risk reduction needs to be considered (if applicable).
- Scenarios are associated with initiating events and direct failure causes [2]. The spot check should include various initiating events, using the matrix of initiating events to select the initiating events for the activities under consideration.

- Finally, other factors may lead to inclusion of scenarios in the spot check.
  - If installations of different ages are present at the establishment, installations of different ages should be included in the spot check.
  - If groups of people are present at a location, like the control room or cafeteria, a scenario of the nearby installation containing dangerous substances should be included.

There is as yet no general rule to decide on the number of scenarios in the spot check. The scenarios selected in the spot check are used to judge the evaluation of the operator on probability and consequences. The number of scenarios should therefore be large enough to decide on the accuracy of the evaluation of the operator.

7. Verification of the probability and consequence assessment (step 7)

For the scenarios selected, the labour safety inspector has to judge the evaluation of the operator of the probability and consequences. It should be noted that the labour safety inspector is not required to carry out consequence calculations on his own. He should judge the evaluation of the operator, using the guidelines described in this chapter. If the operator's evaluation deviates considerably from the guidelines in this chapter, the labour safety inspector should request additional information from the operator to clarify the operator's assessment.

The following steps can be distinguished in the judging procedure of the scenarios and lines of defence presented in the safety report for an activity.

1. **Determination of the loss of containment scenarios specific for the equipment under consideration**
   A standard system for the activity or equipment selected is defined, and the default loss of containment scenarios are determined along with the direct failure causes. The failure frequencies of the loss of containment scenarios are derived assuming the standard lines of defence are present.

2. **Judging additional failure causes due to the substance and judging preventive lines of defence**
   The substance present in the equipment may have properties conducive to loss of containment, e.g. corrosive, explosive and reactive properties, which will also increase the frequency of a loss of containment. Therefore additional lines of defence need to be present to reduce the extra failure frequency due to the properties of the substance. For the activity and the scenarios selected, it should be assessed whether the specific lines of defence are sufficient to compensate the increase in failure frequency.

3. **Judging additional failure causes due to the surroundings and judging preventive lines of defence**
   The surroundings of the equipment may have properties conducive to loss of containment, e.g. the possibility of external impact and flooding. The frequency of a loss of containment will be increased due to the properties of the surroundings. Therefore additional lines of defence need to be present to reduce the extra failure frequency due to the surroundings. Both for the activity and the scenarios selected, it should be judged whether the specific lines of defence are sufficient to compensate the increase in failure frequency.

   The additional causes of failure due to the substance and surroundings are reflected in the procedure by penalty factors. The factors are used so as to force the establishment to describe in detail which non-standard lines of defence due to the substance and surroundings are in place. The penalty factors are not used to describe the actual risk of an installation. Which direct failure causes are influenced by the extra hazards are described. The extra lines of defence should focus on these direct failure causes. Relevant statistical data on the influence of the substance or surroundings on the failure frequency that could be shown by the establishment can be used. The probability of occurrence can be defined on the basis of this procedure.

4. **Determining the consequences of additional preventive lines of defence**
   In addition to the standard lines of defence the establishment may have put additional lines of defence in place. Guidance is given for determining the effectiveness of these additional lines of defence.

5. **Determining the consequences of repressive lines of defence**
   Finally, lines of defence may be present to limit the consequences of the loss of containment.

The flow diagram outlining the method is given in Figure 5. The different steps in the judging procedure are explained in the following sections for pipelines and storage vessels. For other equipment a similar approach can be followed.

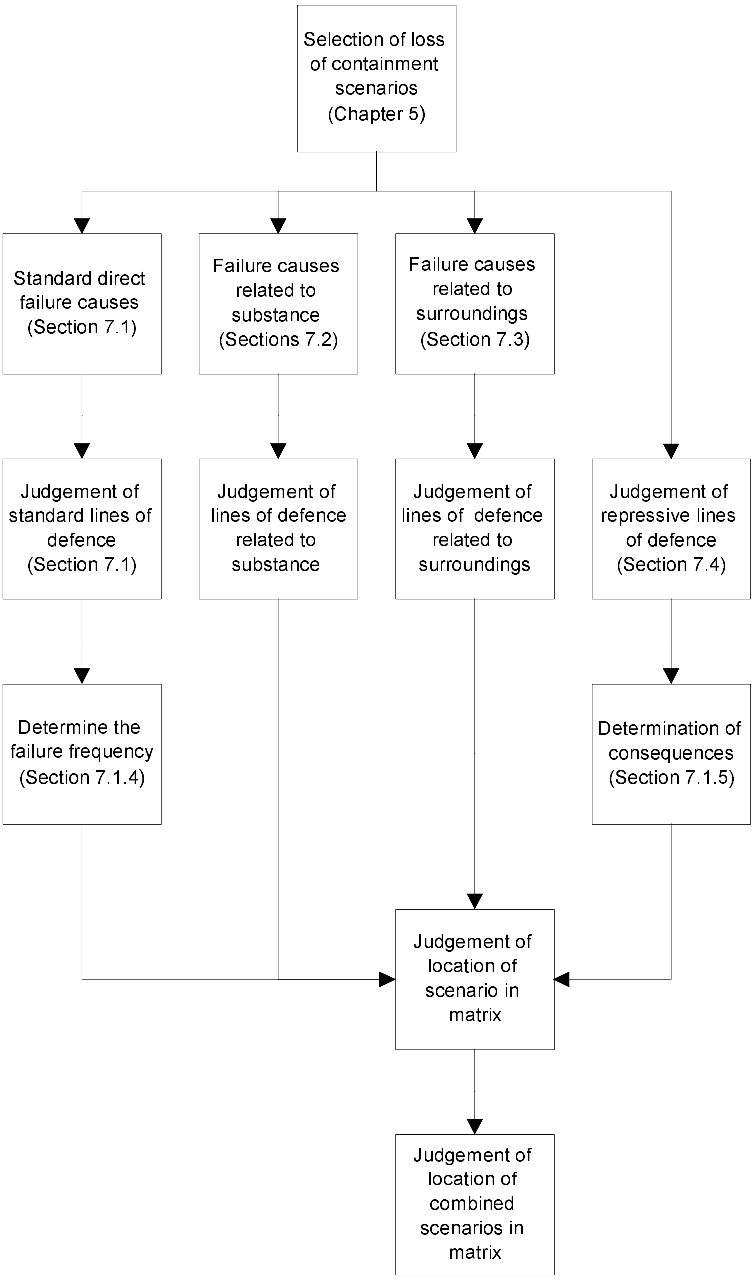

Figure 5 Flow diagram showing judging procedure for internal risk.

7.1 Loss of containment scenarios and the standard lines of defence

7.1.1 Activities and equipment

The standard activities and equipment to be described in the safety report are given in Section 5.3.

7.1.2 Definition of the standard system

A standard system is defined as a system containing an inert substance, i.e. a gas or liquid at ambient pressure and temperature, not flammable, not reactive and not corrosive or erosive. It is situated in surroundings not leading to any external causes of failure. This section describes the standard system for the selected equipment.

7.1.2.1 Pipelines

The standard pipeline has the following characteristics:

- situated above ground level
- made of a material suited for the substance transported
- has valves placed at the lower and upper ends of the pipe
- a pump is part of the pipeline
- transports substances with an inert character (no extreme corrosion, reactivity or erosive properties)
- situated in a surrounding which does not add to the probability of failure

7.1.2.2 Storage vessels

The standard storage vessel has the following characteristics:

- situated above ground level
- made of a material suited for the substance stored
- welded stumps etc. are considered part of the vessel
- valves are placed at pipelines connected to the vessel and are located directly at the vessel
- stores substances with an inert character (no extreme corrosion, reactivity or erosive character)
- situated in a surrounding which does not add to the probability of failure

7.1.3 Standard lines of defence

Lines of defence should be present for the design, construction, utilisation and maintenance phase of an installation [1,4]. A distinction can be made between preventive and repressive lines of defence. Preventive lines of defence influence the probability of occurrence of an accident. Repressive lines of defence influence the consequences of an accident and sometimes also the probability on (domino) effects. Checklists for the preventive lines of defence are given in AVRIM2. These lines of defence apply to all the phases of an installation (design, construction, utilisation and maintenance). Preventive lines of defence are, for example, corrosion protection, pressure-regulating systems and the presence of an inspection program to determine durability and required change-out frequency for the material selected. Repressive lines of defence are, for example, gas detection systems, valves, bunds and personal protection. The functioning of a line of defence can also be either preventive or repressive, depending on the procedures of an establishment; this includes, for example, vacuum and scrubber systems, flares and the shut-down of an installation.

The standard lines of defence should always be present on an establishment and should reflect the state of the art or good practice. The standard lines of defence should also be shown to be appropriate to the conditions. Standard lines of defence also include the non-technical lines of defence like instruction and training of employees, maintenance-, design and construction procedures. If they are either not, or only partly, present this will have an influence on the probability of occurrence and/or the consequences of an accident. Below several sources of authoritative indications of good practice are shown:

1. Prescriptive legislation
2. Regulatory guidance (e.g. guidelines of the Committee for Prevention of Disasters (CPR)).
3. Standards produced by standard-making organisations (e.g. NEN, Stoomwezen, ASME)
4. Guidance, which is agreed on by an organisation representing a particular industrial sector
5. Standard good practice adopted by a particular sector of industry

There is clearly an order of precedence from top to bottom and any conflicts between these sources of good practice should be resolved in favour of the one higher up in the list [43].

The standard lines are present if the following requirements are in place: prescriptive legislation, regulatory guidance and the standards produced by standard-making organisations.

It is not acceptable that the standard lines of defence are either not in place nor appropriate to the conditions.

Repressive lines of defence for external and internal risk can sometimes conflict with each other. For example, an installation situated inside is preferable for external risk, but it may have a negative effect on the internal risk. It is also possible that a line of defence is only, or more, effective for external risk. For example, a valve which closes as a result of a rupture in a pipeline transporting a toxic substance will be an effective line of defence for external risk. If employees are present at the time of the rupture (due to an external impact, for example) this line of defence will probably be less effective as the employee can be exposed to a lethal dose of the substance before the valve is closed.

7.1.4 Failure frequencies and failure causes

Failure frequencies for component failures can be found in different sources. The failure frequencies given in the literature have a generic character; the number of lines of defence included in these numbers and the age of the components at the time of failure are not known. It is therefore not certain if these frequencies can be used as absolute data. For the method described the failure frequencies are assumed to apply to standard systems. Table 8 and 9 give the standard failure frequencies of pressurised storage vessels and pipelines used for external safety [24]. Appendix 4 gives the failure frequencies for other equipment.

Table 8 Failure frequencies of a pressurised storage vessel

Equipment	Catastrophic failure Instantaneous	Large Leak 10 min. release	10 mm hole
Pressurised	5×10^{-7} per year	5×10^{-7} per year	1×10^{-5} per year

Table 9 Failure frequencies of pipelines, pumps and valves

Equipment	Full bore rupture	Leak 0.1D
Pipeline ≤ 3"	1×10^{-6} per metre per year	5×10^{-6} per metre per year
3" < Pipeline ≤ 6"	3×10^{-7} per metre per year	2×10^{-6} per metre per year
Pipeline > 6"	1×10^{-7} per metre per year	5×10^{-7} per metre per year
Pumps without additional provisions	1×10^{-4} per year	5×10^{-4} per year
Pumps with a wrought steel containment	5×10^{-5} per year	2.5×10^{-4} per year
Canned pumps	1×10^{-5} per year	5×10^{-5} per year
Valves*	1×10^{-4} per year	1×10^{-4} per year

* Data for valves are taken from [29]

The total failure frequency of a pipeline is determined by multiplying the failure frequency by the total length of the pipeline. If the exact length of the line is unknown, the length can be approximated by multiplying the distance between the vessels or other facilities by a factor of 1.4.

The generic failure frequencies defined in CPR18E [24] apply to the standard equipment (Section 7.1.2) with the standard lines of defence (Section 7.1.3) in place.

7.1.5 Consequences of a loss of containment

The consequences of a loss of containment to employees may range from negligible to acute mortality. For the control of major hazards, primary interest is in severe injuries and acute mortality. For the calculation of the number of deaths due to a release of toxic or flammable substances, so-called probit functions are available [30, 33, 24]. In a probit function the probit value is calculated as function of, for example, the toxic dose or the radiation dose. For calculating the number of severe injuries, probit functions are only available for burns [30]. Therefore at the moment it is not possible to use probit functions for calculating all effects of a release. In this study, the areas covered by emergency response intervention levels [13] are used for indicating the injuries and deaths to be expected. The area of acute mortality is assumed to be bounded by a concentration equal to the Life Threatening Value (LTV). The area of severe injury is assumed to be limited by a concentration equal to the Alert Limit Value (ALV). An exposure time of typically 600 seconds is used in the calculation of the areas corresponding to acute mortality and severe injury. Assuming that the dose is proportional to the square of the concentration and the exposure time [30], the concentration based on an exposure time of ten minutes is calculated from the concentration based on an exposure time of one hour by multiplying it by a factor 2.4. The measure best to be used in determining the number casualties should be worked out in a follow-up of the study.

Three scenarios are calculated: i.e. a 10 mm hole, representing a small leak; a 50 mm hole, representing a large leak and a 250 mm hole, representing catastrophic failure. The concentrations are calculated for weather with Pasquill stability class D and a wind velocity of 5 $m \cdot s^{-1}$. In Appendix 5, the areas covered by the Life Threatening Value and Alarm Limit Value are given for 14 categories of substances.

To estimate the consequences of a loss of containment, the following steps should be taken:

- The scenario is assigned an outflow category, i.e. small leak, large leak or catastrophic failure.
- The substance released is classified using the classification method described in reference [31].
- The consequence area is determined as corresponding with mortality (LTV) and severe injury (ALV) using Appendix 5.
- The average density of employees on site is determined.
- The number of fatalities is calculated by multiplying the average density of employees by the consequence area and a factor of 0.1. This last factor accounts for the fact that the LTV value does not correspond with 100% mortality, but a much lower number (~1%). The same factor is chosen for estimating the number of injuries.
- The number of casualties is increased by the casualties in operating rooms, cafeterias and the like. If the operating room is within the consequence area, all employees present will be affected unless (collective) measures are taken.
- The scenario is assigned to a consequence category based on the number of casualties.

7.2 Substance-specific failure causes and lines of defence

The substance involved may have properties leading to additional failure causes, like flammable, corrosive and erosive properties. This section describes the additional failure causes due to the substance and information on the lines of defence associated.

7.2.1 Description of the substance

The following substance hazards are of importance for the failure of equipment [25]:

- Flammable
- Explosive
- Reactive
- Erosive
- Corrosive

Information on the flammable and explosive properties of substances can be derived from the risk phrases [32, 33]. Information on the reactivity of a substance can be found in Bretheriks [34] or databases like BIG [35] and IUCLID [36]. The establishment should indicate whether erosion and corrosion can occur, as both depend on the substance and material properties of the equipment used.

7.2.2 Additional failure causes

As indicated, the generic failure frequencies defined in CPR18E [24] apply to the standard equipment (Section 7.1.2) with the standard lines of defence (Section 7.1.3) in place. If additional failure phenomena are present due to substance properties, the failure frequency is assumed to be higher than the generic failure frequency. The higher failure frequency is reflected in the method by a penalty factor. An additional penalty factor in the frequency of a scenario should be applied for each additional failure cause.

Failure phenomena applying to the substance properties and phase conditions are summarised in Table 10 [25]. The additional failure causes to be discussed in the safety report should be related to these phenomena. It is assumed that the standard lines of defence cover the failure phenomena associated with phase conditions, and that no extra penalty is required for this type of failure phenomena. The additional penalty factor in the frequency of a scenario applies only to the failure phenomena associated with the process material properties. As default, a factor of 10 is used for one relevant failure phenomenon, a factor 20 for two relevant failure phenomena, etc. The penalty factor is currently an arbitrary factor that should be fine-tuned.

Table 10 Failure phenomena applying to the substance properties and phase conditions [25]

Process material properties

Flammable
- explosion/fire

Chemically reactive
- runaway

Explosive
- runaway
- explosion/fire

Corrosive
- plugging
- corrosion/wrong material

Erosive
- plugging
- erosion

Other
- temperature
- adsorption
- solubility

Phase conditions

Liquid
- pressure wave
- pressure fluctuation

Liquefied gas
- pressure wave
- phase transition
- pressure fluctuation

Gas/Vapour
- compression

Solid/particle
- plugging
- erosion

7.2.3 Additional lines of defence

For each additional failure due to the substance used, additional lines of defence should be included or the safety report should argue why the standard lines of defence are sufficient. Table 11 indicates where the additional lines of defence should focus on due to the substance properties.

Table 11 Focus of additional lines of defence due to substance properties

Flammable
- explosion-safe equipment
- location of ignition sources
- pump type used
- inerting

Explosive
- explosion-safe equipment
- location of ignition sources
- pump type used
- explosive atmosphere due to phase change of material
- inerting

Exothermic reactions
- possibility of hot spots
- insulation material used
- pump type used
- polymerisation during valves closed (enclosed pipe)

Corrosive
- material used
- corrosion protection

Erosion
- material used
- presence of bends in pipelines

7.2.4 Evaluation

The establishment concerned should identify which additional lines of defence due to the substance used are included. On the basis of preferably relevant and statistical information it should be determined if the additional lines of defence will result in a system equal to the standard system. In this case, the additional lines of defence compensate the penalty factor in the scenario frequency. In Chapter 8, the use of the penalty factor is illustrated.

7.3 Failure causes and lines of defence in relation to the surroundings

The location involved may have properties leading to additional failure causes, like the possibility of fire in the surroundings, external impact. This section describes the additional failure causes due to the surroundings and the associated lines of defence.

7.3.1 Description of the surroundings
A description of the surroundings of an installation or establishment is part of the safety report.

7.3.2 Additional failure causes
External failure phenomena depend on the location and the layout of the site. External phenomena to be considered are described in Table 12 [25]. The additional failure causes to be discussed in the safety report should be related to these phenomena. For each additional failure cause an additional penalty factor in the failure frequency of a scenario should apply. As default, a factor of 10 is used for one relevant failure phenomenon, a factor 20 for two relevant failure phenomena, etc. The penalty factor is currently an arbitrary factor that should be fine-tuned.

Table 12 External failure phenomena [25]

External failure phenomenon	Source
Overloading – weather	Wind velocity distribution
Overloading – tide	Near river/canal/sea
Overloading – ground	Instability of soil
External impact	Near airport/railway/road
Fire	Near other installations with flammable/explosive substances
Explosion	Near other installations with flammable/explosive substances
Weakening – weather	Wind velocity distribution
Weakening – tide	Near river/canal/sea
Weakening – groundwater	Groundwater level
Air quality	Air quality
Water quality	Water quality

7.3.3 Additional lines of defence
For each additional failure due to the specific surroundings of an installation, additional lines of defence should be included or it should be argued in the safety report why the standard lines of defence are sufficient. In Table 13, examples are given of additional lines of defence based on the surroundings of an installation.

7.3.4 Evaluation
The establishment concerned should identify which additional lines of defence due to the surroundings are included. On the basis of preferably relevant and statistical information it should be determined if the additional lines of defence will result in a system equal to the standard system. If the system is equal to the standard system, the additional lines of defence compensate the penalty factor in the scenario frequency. In Chapter 8, the use of the penalty factor is illustrated.

Table 13 Examples of lines of defence in relation to the surroundings of an installation

Line of defence	External causes
Selection of location to guarantee internal and external safety as much as possible; Plant layout and siting	All external failure causes
Evaluation of pressure should be based on conditions of heat radiation from surroundings (content at 40°C)	Overloading – weather
Earthing according to NEN	Weakening – weather
Equipment within the horizontal projection of the reservoir and equipped with flanges; flanges close to vessel wall, block valves connected to flanges	External impact
Location safe to external impact	External impact
Location safe to heat radiation exceeding 10 $kW{\cdot}m^{-2}$	Fire
Construction 60 minutes supporting in case of fire	Fire
Reservoir, if equipped with fire-resistant covering, should prevent loss of containment following exposure to pool fire or jet fire for 60 minutes	Fire
Insulation should stay attached to reservoir during fire-extinguishing	
Area supplied with fire water deluges and/or fixed fire water monitors	
Prevention against external fire	
Protection from external fire (sprinkler)	

7.4 Valuation of the lines of defence

Lines of defence can be directed to either minimise the probability of a loss of containment (preventive lines of defence) or minimise the consequences of a loss of containment (repressive lines of defence), as shown in Figure 6. Preventive lines of defence may shift the scenario from one frequency category to another, whereas repressive lines of defence may shift the scenario from one consequence category to another.

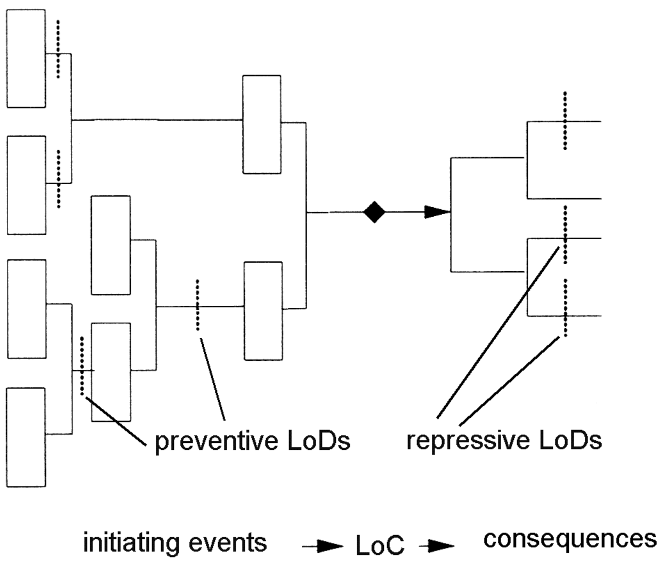

Figure 6 Preventive and repressive lines of defence

Clearly, there is a hierarchy in value of the lines of defence and guidelines, as preference for lines of defence does exist [37,38], as shown below:

1. Remove hazard altogether
2. Reduce hazard to low level
3. Contain/control hazard by physical means
4. Contain/control by systems of work
5. Protect personnel against exposure
   - Personnel not present within effect distance
   - Measures which protect a group
   - Measures which protect an individual
6. Emergency preparedness should hazard control fail

The risk to employees should preferably be removed by using an inherently safer design, e.g. non-dangerous substances, small amounts of substances and process conditions with low-level danger. Preventive lines of defence, reducing the probability of a loss of containment, shall be given priority over repressive lines of defence, reducing the consequences of containment loss (1 and 2 are preferred to 5 and 6). Technical measures shall be given priority over operational or contingency measures (3 is preferred to 4), and collective protective measures shall be given priority over individual protective measures.

In a system where there are multiple lines of defence, the reliability of each line of defence is less critical than where only one line of defence is present [38]. There is no difference in acceptability between one line of defence having a failure probability of 10^{-5} and five (independent) lines of defence having a failure probability of 10^{-1} each. Furthermore, the independence rule should apply and the lines of defence system must, as far as possible, not be common mode i.e. the failure of one line of defence should be independent of the failure of another.

For external safety, lines of defence limiting the consequences of a loss of containment by reducing the outflow or vapour generation can be valued in the calculation of the risk. However, the consequences are always calculated for an unprotected person. Applying the same approach to the valuation of repressive lines of defence, the following guidelines should be followed.

- Repressive lines of defence may limit the concentration of hazardous substances in the environment by limiting the outflow following a loss of containment, or the vapour generation or the dispersion of a substance in the environment. Examples of these types of repressive lines of defence are a gas detection system in combination with quick closing valves, a bund with the possibility of a foam blanket, an installation to apply a water-curtain and a pressure relief device connected to a flare or scrubber system. The result of these repressive lines of defence on the consequences of a loss of containment can be valued in estimating the risk of a scenario. However, the outcome of the system should be determined considering the reaction time and the effectiveness of the system. Especially when the fire brigade needs to be alerted, a considerable amount of time may pass before the line of defence becomes effective.
- Collective repressive lines of defence may limit the harm to a group of employees without limiting the concentration of hazardous substances in the environment. An example is the use of explosion-proof windows in the control room. The result of these type of repressive

lines of defence on the consequences of a loss of containment can be valued in the estimation of the number of casualties.
- Individual repressive lines of defence, i.e. personal protective equipment and escape routes, may limit the harm to a single employee without limiting the concentration of hazardous substances in the environment. Personal protective equipment and escape routes are assumed to be generally present in an establishment and are therefore not explicitly valued. However, there are situations where personal protective equipment forms the only means to prevent exposure, e.g. in the case of repairing a leak or entrance of an enclosure. In these situations where personal protective equipment are the only means to prevent exposure, their use can be valued in the risk assessment.

7.5 Effectiveness of extra lines of defence

Sections 7.2.3 and 7.3.3 discuss the lines of defence used to protect against extra failure causes due to the properties of the substance, the surroundings of the equipment and the like. However, extra lines of defence may also be present to reduce the generic failure frequencies (see Section 7.1.4). An overview of the generic contribution of design, operation and maintenance per failure cause of a piece of equipment can be used to estimate the reduction attributable to an extra line of defence (with no influence of surroundings and substance on the failure).

7.5.1 Pipelines

Table 14 [39] gives the generic contribution of design, operation and maintenance per failure cause. Combining Table 6 and Table 14 results in a generic overview of the effectiveness of an extra line of defence for one of the direct failure causes in the design, operation or maintenance phase (Table 15).

Table 14 Generic contribution (%) of design, operation and maintenance per failure cause [39].*

	Design	Operation	Maintenance	Other
Corrosion	41	2	42	15
Erosion	62	0	38	0
External Loading	38	8	12	42
Impact	11	29	12	48
Overpressure	46	11	25	18
Vibration	60	2	23	16
Temperature	46	12	21	21
Wrong equipment	22	2	29	48
Operator error	9	23	58	10
Other	65	13	23	0

* Each row adds up to 100%.

Table 15 can be used to identify the order of magnitude of the effectiveness of a line of defence. For example, 42% of all corrosion incidents occur during maintenance. Corrosion contributes about 15% to the pipe failures. So generically seen, the maximum reduction in probability of occurrence by a line of defence for preventing corrosion due to maintenance is in the order of 6%. If an establishment indicates a significantly larger reduction in occurrence, this should be explained in the safety report. The more the reduction differs from the generic values, the better the establishment should substantiate the proposed reduction with relevant data.

Table 15 Effectiveness (%) of an extra Line of defence for pipelines for one of the direct failure causes in the design, operation or maintenance phase*

	Design	Operation	Maintenance	Other
Corrosion	6.5	0.3	6.6	2.3
Erosion	0.8	0.0	0.5	0.0
External Loading	1.9	0.4	0.6	2.1
Impact	0.9	2.4	1.0	3.9
Overpressure	9.4	2.3	5.1	3.7
Vibration	1.5	0.0	0.6	0.4
Temperature	3.0	0.8	1.4	1.4
Wrong equipment	1.5	0.1	1.9	3.2
Operator error	2.7	7.2	18.0	3.0
Other	1.7	0.3	0.6	0.0

* The table adds up to 100%

7.5.2 Storage vessels

Table 16 [39] gives the generic contribution of design, operation and maintenance per failure cause.

Table 16 Generic contribution (%) of design, operation and maintenance per failure cause for vessels [39]*

	Design	Operation	Maintenance	Other
Corrosion	41	0	56	4
Erosion	0	0	0	0
External Loading	27	0	18	55
Impact	0	50	0	50
Overpressure	59	25	14	2
Vibration	0	0	0	0
Temperature	17	0	7	76
Wrong equipment	0	0	38	63
Operator error	0	73	27	0
Other	73	0	27	0

* Each row adds up to 100%

Combining Table 7 and Table 16 results in a generic overview of the effectiveness of an extra line of defence for one of the direct failure causes in the design, operation or maintenance phase (Table 17). Table 17 can be used to identify the order of magnitude of the effectiveness of a line of defence. For example, 56% of all corrosion incidents occur due to maintenance. Corrosion contributes to about 6% of the vessel failures. So generically seen, the maximum reduction in probability of occurrence by a line of defence for preventing corrosion due to maintenance lies in the order of 3.5%. If an establishment indicates that the reduction in occurrence is significantly more, this should be explained in the safety report. The more the reduction differs from the generic values, the better the establishment should substantiate the proposed reduction with relevant data.

Table 17 Effectiveness (%) of an extra line of defence for vessels for one of the direct failure causes in the design, operation or maintenance phase*

	Design	Operation	Maintenance	Other
Corrosion	2.6	0	3.5	0.3
Erosion	0	0	0	0
External Loading	0.7	0	0.5	1.4
Impact	0.6	1.6	0.7	2.7
Overpressure	26.7	11.3	6.3	0.9
Vibration	0	0	0	0
Temperature	1.9	0	0.8	8.5
Wrong equipment	0	0	0.7	1.1
Operator error	0	17.9	6.6	0
Other	1.9	0	0.7	0

* The table adds up to 100%

8. Pilot study

In this chapter the various steps of the method are illustrated in a pilot study. After judging the acceptability of the presentation of the risk and the establishment's risk acceptance criteria (steps 3 and 4), the next move is to judge the selection and evaluation of the scenarios (Step 5, 6, 7). The pilot study focuses on the last three steps.

The installation chosen for the pilot study consists of an ethylene oxide storage unit (four storage vessels) connected to a production unit by an inter-unit pipeline of 200 metres and connected to a loading facility by an inter-unit pipeline of 300 metres. The pilot study is restricted to the storage unit and the internal transport via pipelines.

The establishment is situated near the coast. A control room, with an average number of five employees is situated near the storage vessels. The average density of employees on the site is one person per hectare. There are no areas with restricted access and no areas where employees are normally not present (see the discussion in Section 4.3). The diameter of the two pipelines equals 102 mm (4").

8.1 Determination of the loss of containment events

8.1.1 Pipelines

The standard loss of containment events to be discussed in the safety report are related to the equipment used. For a standard pipeline (Section 7.1.2.1), the standard equipment consists of the pipeline, a pump and valves at the lower and upper ends of the pipeline. The standard scenarios to be discussed are therefore (Table 9 [24]):

- a full bore rupture of the pipeline
- a leak in the pipeline (0.1D)
- catastrophic failure of the pump
- a leak at the pump
- catastrophic failure of the valve
- a leak at the valves

The direct failure causes to be discussed in the safety report for a standard pipeline are (Section 5.4.1):

- operator error
- overpressure
- corrosion

8.1.2 Storage vessels

The standard loss of containment scenarios to be discussed are (Section 5.3) [24]:

- instantaneous release of the inventory
- continuous release of the inventory in 10 minutes
- continuous release of the inventory, Ø 10 mm hole

The direct failure causes to be discussed in the safety report for a standard storage vessel are (Section 5.4.2):

- operator error
- overpressure
- temperature
- corrosion

8.2 Determination of the failure frequencies for the standard system

8.2.1 Pipelines

Assuming the standard lines of defence are in place, the following failure frequencies apply (see Table 9). The total length of the pipelines is 500 m.

- Pipeline, full bore rupture	$500 \times 3 \times 10^{-7} = 1.5 \times 10^{-4}$ per year
- Pipeline, leak	$500 \times 2 \times 10^{-6} = 1 \times 10^{-3}$ per year.
- Catastrophic failure of the pump	$1 \times 10^{-5} – 1 \times 10^{-4}$ per year (depending on type used)
- Leak at the pump	$5 \times 10^{-5} – 5 \times 10^{-4}$ per year (depending on type used)
- Catastrophic failure of the valve	1×10^{-4} per year
- Leak at the valve	1×10^{-4} per year

No failure frequencies for the failure of valves are given in CPR18E [24]. For this example the data given in reference [29] are used.

8.2.2 Storage vessels

Assuming the standard lines of defence are in place, the following failure frequencies apply (see Table 8).

- Instantaneous release of the inventory	$4 \times 5 \times 10^{-7} = 2 \times 10^{-6}$ per year
- Continuous release of the inventory in 10 minutes	$4 \times 5 \times 10^{-7} = 2 \times 10^{-6}$ per year
- Continuous release of the inventory, Ø 10 mm hole	$4 \times 1 \times 10^{-5} = 4 \times 10^{-5}$ per year

8.3 Determination of the consequences for the standard system

Ethylene oxide is toxic and flammable [32]. The level of severe injury, the Alert Limit Value (ALV), is equal to 100 $mg \cdot m^{-3}$ and the level of acute mortality, the Life Threatening Value (LTV), to 1000 $mg \cdot m^{-3}$ [13]. These values are based on an exposure time equal to 60 minutes. For an exposure time of 10 minutes, ALV is equal to 245 $mg \cdot m^{-3}$ (130 ppm) and LTV is 2450 $mg \cdot m^{-3}$ (1300 ppm). The results of the dispersion calculation are shown in Table 18 (see also Appendix 5).

Using the average density of one person per ha, the number of persons affected is determined (see Table 19). If the control room (five persons) is present within the consequence zone, five casualties should be added to the numbers unless adequate measures are taken.

Table 18 Area of acute mortality (LTV) and severe injury (ALV) and corresponding effect zones, with an exposure time of 10 minutes, weather class D5

Scenario	LTV (1300 ppm)		ALV (130 ppm)		Flash-fire flame envelope (LFL)	
	Area	Length	Area	Length	Area	Length
10 mm hole	600 m^2	53 m	6000 m^2	200 m	150 m^2	7 m
50 mm hole	8000 m^2	170 m	74000 m^2	640 m	4500 m^2	40 m
250 mm hole	3×10^5 m^2	700 m	3×10^6 m^2	3400 m	8×10^4 m^2	160 m

Table 19 Expected number of casualties, given the loss of containment event

Scenario	LTV (1300 ppm)	ALV (130 ppm)	Flash fire flame envelope (LFL)
10 mm hole	0	0	0
50 mm hole	0	0 – 1	0
250 mm hole	2 – 3	25	0 – 1

Where the consequence scale from Table 2 is applied, the results in Table 19 show that the consequence category for a small leak is negligible/small, while for a large leak it is considerable and for a catastrophic failure it is very serious to extremely serious.

8.4 Determination of additional failure causes due to the substance and additional lines of defence

The physical, chemical and toxic properties of ethylene oxide are described in a number of sources [33, 35]. A number of properties are important to identify hazardous situations and to determine key failure causes. The relevant properties are listed in Table 20. In principle, all these consequences are relevant for internal risk. Due the boundary condition set, only acute effects are described. For ethylene oxide the flammable and toxic effects should be described.

8.4.1 Specific failure causes

The specific failure causes are determined by combining Table 10 and Table 20. In the safety report special attention should be given to runaway (liquid phase) and explosion/fire (gaseous phase). The penalty factor to be used due to the substance properties is therefore $2 \times 10 = 20$. The establishment should identify which direct failure causes are important in these phenomena. For ethylene oxide, direct failure causes are related to temperature. The presence of contaminants may also promote runaway reactions.

8.4.2 Specific lines of defence

The establishment should indicate which additional lines of defence for the failure causes runaway and explosion (associated with temperature and contaminants) are included. On the basis of preferably relevant and statistical information it should be determined if the additional lines of defence will result in a system equal to the standard system.

Table 20 Data relevant to identifying failure causes

Property	Ethylene oxide
State of aggregation	Gas (boiling point 11 ºC)
Hazard category [32]	Extremely flammable (R12) Toxic by inhalation (R23) May cause cancer (R45) May cause heritable damage (R46) Irritating to eyes, respiratory system and skin (R36/37/38)
Explosion hazard	DIRECT EXPLOSION HAZARD Gas/vapour explosive with air within explosion limits INDIRECT EXPLOSION HAZARD Heat may cause pressure rise with explosion of tanks/drums May be ignited by sparks Reactions with explosion hazards: see "Reactivity Hazard"
Reactivity hazard	Polymerises on exposure to temperature rise on exposure to impurities on exposure to light on exposure to (some) metals and on exposure to (strong) acids/bases with heat release resulting in increased fire or explosion risk. Reacts slowly on exposure to water (moisture) Explosive decomposition on exposure to temperature rise Release of – carbon monoxide – carbon dioxide on burning Reacts violently with many compounds e.g. (strong)oxidisers: (increased) risk of fire/explosion

8.5 Determination of additional failure causes due to the surroundings and additional lines of defence

8.5.1 Specific failure causes

The specific failure causes are given in Table 12. In the safety report special attention should be given to the phenomena specific for a location near the coast. The establishment should identify which direct failure causes are important in these phenomena. Related failure causes are overloading related to weather (wind stress) and overloading related to tide (flooding). Attention should also be given to external impact. If these failure causes can not be excluded the penalty factor due to the surroundings is 3 × 10 = 30.

8.5.2 Specific lines of defence

The establishment should indicate which additional lines of defence for the failure causes of overloading – weather, overloading – tide, and external impact, are included. On the basis of preferably relevant and statistical information it should be determined if the additional lines of defence will result in a system equal to the standard system.

8.6 Determination of the consequences of repressive lines of defence

The establishment should indicate which additional repressive lines of defence are present, what their influence is on the consequences and on which analysis their influence is based.

8.7 Evaluation

8.7.1 Pipelines

For the pipeline six scenarios can be identified that should be evaluated against the evaluation of the scenarios by the establishment. Applying the frequency scale in Table 3 and the consequence scale in Table 2, the following effect combinations apply to the pipeline if the system under consideration reflects the standard system (see Table 21). It is assumed that a full bore rupture results in the consequences given for the 50 mm hole (see Table 18 and Table 19). The control room is not situated in the effect zones of the pipeline.

Table 21 Frequency and effect combinations for the pipeline

	Frequency	Effect
P1: Pipeline, full bore rupture	Small	Considerable
P2: Pipeline, leak	Average	Negligible/Small
P3: Catastrophic failure of the pump	Very small	Considerable
P4: Leak at the pump	Small	Negligible/Small
P5: Catastrophic failure of the valve	Small	Considerable
P6: Leak at the valve	Small	Negligible/Small

8.7.2 Storage vessels

Three scenarios for the storage vessels can be identified that should be evaluated against the evaluation of the scenarios by the establishment. Applying the frequency scale in Table 3 and the consequence scale in Table 2, the following effect combinations apply to the storage vessel if the system under consideration reflects the standard system, Table 22. It is assumed that an instantaneous release results in the effects given for the 250 mm hole and a continuous release results in the effects given for the 50 mm hole. The control room is situated at a distance of 100 metres and therefore in the effect zones of all scenarios.

Table 22 Frequency and effect combinations for the storage vessel

	Frequency	Effect
S1: Instantaneous release of the inventory	Very small	Very serious
S2: Continuous release of the inventory in 10 minutes	Very small	Considerable
S3: Continuous release of the inventory, Ø 10 mm hole	Very small	Negligible/Small

8.7.3 Comparison with the evaluation of the establishment

The scenarios described in Sections 8.7.1 and 8.7.2 can be placed in a risk matrix. The result is shown in Figure 7.

Freq.↓ Conseq.→	Negligible/ small	Considerable	Serious	Very serious
Very small		P3	S1	S2, S3
Small	P4, P6	P1, P5		
Average	P2			
Large				
Very large				

Figure 7 Risk matrix for the pilot study (scenarios described in Table 21 and Table 22).

The combined risk presented in Figure 8 for the evaluation of the overall risk of the establishment should be compared with the criteria set by the establishment (Section 4.4). The criteria of the establishment are already investigated and accepted in steps 2, 3 and 4 of the procedure. Out of the comparison it can be concluded whether the risk of the establishment is acceptable or not.

Freq.↓ Conseq.→	Negligible/ small	Considerable	Serious	Very serious
Very small			SC	SC
Small		SC		
Average	SC			
Large				
Very large				

Figure 8 Combined risk matrix for the pilot study.

9. Conclusions

Under the ‘Hazards of Major Accidents Decree 1999’, the labour safety inspector has to pass judgement on the acceptability of the risk to employees as presented in the safety report. In order to form an opinion on the acceptability of the risk due to major accidents, the labour safety inspector should assess the correctness of the calculation of the risk to employees and should compare the risk calculated with normative risk criteria. In the study presented here, the possibility is investigated of defining risk criteria and presenting an assessment method.

A set of normative risk criteria for internal safety due to risks of major accidents is currently lacking. However, it seems possible to develop a set of internal risk criteria based, among other aspects, on average risk figures in industry. The recommendation is therefore to further develop a set of normative risk criteria. Based on the data available, an individual mortality risk limit in the order of $1 – 10 \times 10^{-6}$ per year for accidents with dangerous substances for the group running the highest risk seems to be acceptable. Since establishments may adhere to more stringent risk acceptance criteria, it is useful to compare the risk acceptance criteria of establishments for various branches of industry. For this reason, setting up a database of the risk acceptance criteria found in the safety reports is recommended.

The study presented here shows the possibility of an assessment method for passing judgement on the calculation of an establishment’s internal risk. The assessment method is based on a standard installation with all standard lines of defence in place. The location of scenarios in the risk matrix is determined, using standard scenarios and applying penalty factors for additional failure causes due to the nature of the substance and the surroundings. The assessment method described represents an initiative for realising a complete and more rigorous method to pass judgement on the establishment’s internal risk. A number of items, including those listed below, need both to be worked out in more detail and be tested using real data:

- The method uses penalty factors applied to the frequency of occurrence of a scenario when the required lines of defence are missing. An arbitrary penalty factor of 10 is used in the report, the penalty factor will need to be fine-tuned using real data.
- The areas covered by emergency response levels are used as a measure of the number of casualties in a major accident. The best measure to be used in determining the number of casualties will have to be worked out.
- For a number of standard installations, a list of standard lines of defence will need to be compiled using such standards as CPR guidelines.
- For a number of sample substances and sample surroundings, a list of sample lines of defence needs to be compiled.
- The relative contribution of the direct causes of failure of equipment other than pipelines and vessels should be determined.

The assessment method described here will require a complete communication of the risk in the safety report. Since not all information may currently be present in the safety report, additional regulations on the information requested in the safety report may be necessary.

Appendix 1 Risk criteria

In this appendix a number of risk criteria are described to illustrate different approaches in the definition of risk criteria. Emphasis is placed on the aspects relevant to the definition of criteria for occupational safety. Risk criteria for external safety in the Netherlands are first described, followed by international criteria and in-company criteria, and then by criteria for protection of workers against the dangers of ionising radiation.

External safety criteria in the Netherlands

External safety considers the risk of the use, handling, transport and storage of dangerous substances to humans outside an establishment. In the Netherlands, two different measures have been developed to judge the acceptability of the risk, namely the individual risk and the societal risk [40].

The individual risk is the probability that in one year a person will suffer death due to an accident. The individual risk is calculated for a hypothetical person permanently (24 hours a day during the whole year) present and unprotected in a certain location. This means that the individual risk is not connected to a real person but is a characteristic of the location. The individual risk is to be calculated for all locations near an establishment and presented geographically. Criteria for the individual risk are connected to environmental planning: houses are not permitted within an individual risk level of 10^{-6} per year (10^{-5} per year for existing situations).

The societal risk is the probability that in one year an accident will kill a group of N people or more simultaneously. The societal risk is developed to protect against societal disruption caused by large accidents. The societal risk is therefore connected to real groups of people present near the establishment and able to protect themselves. The criterion for the acceptability of societal risk is:

$$F < \frac{10^{-3}}{N^2}$$

where

F is the probability that in one year an accident will kill a group of N persons or more simultaneously;
N is the number of persons dying in an accident.

The societal risk criterion runs through N = 10 and F = 1 × 10^{-5} per year. The risk criteria for external safety are related to acute mortality, i.e. persons dying directly due to the accident and within a limited time period (2 – 3 weeks [41]) after the accident. The criteria are not applicable to long-term effects of, for example, carcinogenic substances.

International criteria for external and internal safety

Safety criteria are used in many countries. To compare the various approaches, a short overview is presented of the situation in various countries, based on the work of Pikaar and Seaman [6]. A more elaborate overview is presented of the legislation in the United Kingdom and Norway.

International criteria for external safety

Pikaar and Seaman overviewed risk criteria for external safety [6]. The risk criteria are described for the Netherlands, Germany, France, Norway, Switzerland, the United Kingdom and the United States (Federal Law).

In general, a distinction is made between prescriptive legislation and goal-setting regulations. Prescriptive legislation sets technical standards which must be met; if the process equipment is designed according to the standards, the situation is considered safe. Goal-setting criteria define a safety goal that must be achieved, e.g. an individual risk level less than 10^{-6} per year. The company evaluates the organisational and technical measures needed to reach the required safety level. The use of prescriptive legislation is, in particular, in use in Germany. The legal framework in France contains prescriptive elements and applies zoning distances based on a number of scenarios representing maximum credible events. In Switzerland, the criteria address the frequency and seriousness of an accident, i.e. a societal risk, comparable to a risk matrix.

In Norway, the goal-setting criteria are set by the industry. The regulation in the United Kingdom is more-or-less comparable to the regulation in the Netherlands. The criteria in these two countries are discussed more explicitly in the following sections.

Finally, it should be noted in comparing criteria that in cases where a goal-setting regulation is applied, the method of calculation can be connected to the criteria, thus hampering a direct comparison of the criteria.

Risk criteria in the United Kingdom

The use of risk criteria in the United Kingdom is discussed in a number of documents [42,14]. A distinction is made between three different regions:

- *Unacceptable region*: the risk cannot be justified, save in extraordinary circumstances;
- *Tolerable region*: control measures must be introduced for risk in this region to drive residual risk towards the broadly acceptable region. If residual risk remains in this region, and society desires the benefit of the activity, the residual risk is tolerable only if further risk reduction is impracticable or requires action grossly disproportionate in time, trouble and effort to the reduction in risk achieved.
- *Broadly acceptable region*: level of residual risk regarded as insignificant and further effort to reduce risk not likely to be required as resources to reduce risks are likely to be grossly disproportionate to the risk reduction achieved.

The HSE put forward criteria to determine the boundaries between the different regions. The criteria are set for risk in a limited category, namely, the risk of death either individually or in multiple. The criteria are merely guidelines to be interpreted with common sense and are not intended to be rigid benchmarks to be complied with in all circumstances.

The boundary between the *broadly acceptable region* and the *tolerable region* for risk entailing fatalities is an individual risk of death of one per million per year for both workers and the public. This risk is supposed to be extremely small when compared to the background level of risk in everyday life and many of the activities entailing such a low level of risk also bring benefits that contribute to the lowering of the background risk.

The boundary between the *unacceptable region* and the *tolerable region* for risk entailing fatalities is an individual risk of death of one per thousand per year for any substantial category of workers for any large part of one's working life. For members of the public this limit is judged to be one order of magnitude lower, one per ten thousand per year. However, this criterion for individual risk is not as widely applicable, since such high individual risk levels are also expected to give rise to societal concerns, which often play a far greater role in deciding whether a risk is acceptable or not. Furthermore, in practice, the actual fatality rate for workers in even the most hazardous industries is normally well below the criterion.

The limit of tolerability of an individual risk of death for any substantial category of workers of seems to be based on the maximum average risk of significant groups of workers, e.g. in the offshore fishing [42]. It is also the order of magnitude of the average risk of death to a worker due to all causes, natural and otherwise. The limit of tolerability to a member of the public is a (arbitrary) factor of ten lower than the limit of tolerability to a worker, and is in the same order of magnitude as the (presumably accepted) risk of death due to traffic accidents.

The limit of tolerability for the societal concerns of the risk of multiple fatalities occurring in one event from a singular major industrial activity, e.g. one chemical company in one location, is expressed as follows: the risk of an accident causing the death of fifty people or more in a single event should be less than one per five thousand per year.

The HSE issues a manual for assessing the COMAH safety report [43]. British companies do not provide their own risk criteria in the safety report. They are not required to do so, and appear not to do so voluntarily. The quantitative risk criteria of HSE (familiarly termed TOR criteria from 'tolerability of risk' and described above) are not explicitly used for the safety report assessment, although the concept of ALARA applies. What this can mean in practice is the labour safety inspector considering [44] if the best practice design standards/codes etc. are being used. This is a good baseline for the common types of installation. The ALARA arguments, which may be qualitative, focus on relevant good practice and sound engineering principles [45]. There are several sources of authoritative indications of good practice:

- Prescriptive legislation
- Regulatory Guidance
- Standards produced by standard-making organisations
- Guidance agreed by an organisation representing a particular sector of industry
- Standard good practice adopted by a particular sector of industry.

There is clearly an order of precedence downwards and any conflicts between these sources of good practice should be resolved in favour of the source higher up the list.

The HSE numerical criteria are not working in practice in a literal sense [44]. The most important criterion is whether the company has 'serious deficiencies' and the principle of ALARA [43]. The HSE assessor can ask a company to consider further risk reduction but does not specify how this should be achieved in terms of measures.

Risk criteria in Norway

The Norwegian Petroleum Directorate (NPD) issues the acts, regulations and provisions for the petroleum activities [46]. The regulation is laid down in a number of documents. Two documents in particular describe the framework of regulations concerning safety and the use of risk analyses, namely the Regulations relating to safety in the petroleum activities [47] and the Regulations relating to implementation and use of risk analyses in the petroleum activities [48].

The regulations state that the operator shall define the safety objectives.

> In order to avoid or withstand accidental events, the operator shall define safety objectives to manage the activities. [Section 10 [48]]
>
> The operator is required to define safety objectives for the total activities, cf. the scope of application of the regulations.
> These objectives express an ideal safety level. Thereby they ensure that the planning, maintaining and the further enhancement of safety in the activities becomes a dynamic and forward-looking process.
> The safety objectives are assumed to reflect the overall requirements of the applicable legislation with regard to fully satisfactory safety for people, the environment, assets and financial interests. This means that:
> a) accidental events must be avoided,
> b) the level of risk in the activities must at all times be kept as low as possible,
> c) attempt shall be made to achieve further reduction of risk over time, e.g. in view of technological development and experience.
> The operator's safety objectives applicable to the activities may be expressed as long-term and short-term objectives.
> These safety objectives shall be used actively to initiate preventive safety measures such as system audit and motivation campaigns, based on knowledge obtained through a risk analysis. This will contribute to a further enhancement of safety in the activities and will form the basis for, inter alia, revision of the operator's acceptance criteria. [Section 10 [48]]

To meet the safety objectives, the operator should define acceptance criteria for the risk of the activities.

> The operator shall define acceptance criteria for risk in the activities. The acceptance criteria shall be defined before a risk analysis is carried out.
> Requirements stipulated by or in pursuance of law or regulations, including requirements with regard to risk reducing measures, and the operator's safety objectives for the activities, shall form the basis for defining acceptance criteria.
> The operator shall document the evaluations forming the basis for the definition of the acceptance criteria.
> The operator shall update the acceptance criteria in the course of enhancing the safety level in the activities and as an effort to achieve the safety objectives defined for the activities. [Section 11[48]]
>
> The acceptance criteria must reflect the safety objectives and the distinctive characteristics of the activities, and the basis for their definition must include:
> a) the legislation applicable to safety in the petroleum activities, cf section 1 of the regulations,

> b) recognized standards for the activities,
> c) requirements with regard to risk reducing measures, cf section 16 of the regulations,
> d) knowledge of, inter alia, accidental events and their effects,
> e) experience from own and corresponding activities.
> The acceptance criteria may be defined both in quantitative and in qualitative terms, depending inter alia on the mode of expression of risk. The operator shall document the assessments which have led to the definition of the acceptance criteria.
> When quantitative acceptance criteria are used, clearly defined limits for their application must be stipulated. Basic data used in the stipulation of quantitative acceptance criteria should consequently be documented. The way these acceptance criteria are to be used should also be specified, particularly with regard to the inherent uncertainty in expressing risk in quantitative terms.
> When qualitative acceptance criteria are used, the conditions for their application should be similarly defined. [Section 11 [48]]

Acceptance criteria shall be defined with respect to risk connected to loss of human lives, to personal injury, damage to the environment and to assets and financial interests [48]. Risk analysis is to be used in the decision process to ensure that the safety aspects of the activities are in accordance with the operator's acceptance criteria.

> The results of risk analyses shall be included as part of the basis for the decision-making process in the course of ensuring that the safety aspects of the activities are in accordance with requirements laid down by or by virtue of law or regulations, with the operator's safety objectives and acceptance criteria. [Section 12 [48]]

> Identified risks shall be assessed with reference to the acceptance criteria for risk in the activities in order to identify the dimensioning accidental events[1].
> The dimensioning accidental events shall form the basis for a systematic selection of the technical, operational and/or organizational risk reducing measures to be implemented. Risk reducing measures consist of probability reducing and consequence reducing measures, including contingency measures.
> The effect of the risk reducing measures to be implemented shall be documented, assessed both individually and in a wider perspective.
> Implementation of the risk reducing measures and of the basic assumptions made in the risk analysis shall be systematically followed up in order to ensure that safety in the activities is maintained within the defined acceptance criteria for risk. [Section 14 [48]]

There is a hierarchy in the application of risk reducing measures.

> In the implementation of measures, the following shall apply to the extent it is practically feasible:
> a) Measures to reduce the probability that such failure or accidental event will occur, shall be given priority over measures to reduce the consequences of it occurring.

[1] A dimensioning accidental event is an accidental event which according to the defined acceptance criteria represents an unacceptable risk, and which consequently serves as a basis for design and operation of installations and otherwise for implementation of the activities.

> b) Technical measures shall be given priority over operational or contingency measures.
> c) Collective protective measures shall be given priority over individual protective measures.
> [Section 10 [47]]

The risk should always be as low as practically feasible, allowing for a balancing of risks and costs. The risk acceptance criteria should regularly be reconsidered to maintain a safety level in accord with technological development, thus leading to a constant improvement of the safety level.

> The level of safety shall be concurrent with the technological development in society at all times.
> Risk in petroleum activities shall be reduced as far as practically feasible. [Section 9[47]]
>
> The requirement with regard to revision of the acceptance criteria for risk applicable to the activities must be seen in connection with the purpose of the Safety Regulations with regard to enhancing the level of safety in the activities.
> The operator is expected to revise the acceptance criteria over time in order to take into account inter alia experience, new information, possible changes in the activities and technological advancement. Furthermore, the achievement of safety objectives, as mentioned in section 10 of the regulations with guidelines, may entail an actual reduction of risk in the activities, and thus provide basis for a revised definition of acceptance criteria. The revision of the acceptance criteria may consequently have the effect that accidental events which were not originally classified as dimensioning accidental events, are reclassified as dimensioning accidental events in a subsequent risk analysis. [Section 11 [48]

Technical and operational provisions for equipment are described in a number of additional regulations [49].

Risk criteria applied in industry

Companies apply risk audit methods and risk criteria to assess the risk, to evaluate the acceptability of the risk and to judge risk-reducing measures. The risk criteria applied in a number of risk audit methods and the criteria used in companies are summarised here.

Risk Audit Methods

Various risk audit methods are developed to estimate the risk and risk reduction methods in industry. Criteria on the acceptability of the risk are implicitly or explicitly incorporated in the methodology. Three methods are discussed here, namely TRAM, Risk Graph and AVRIM2.

TRAM

The Technical Risk Audit Methodology (TRAM) [15,16] is a technique for the estimation of the risk and the determination of the necessary risk-reduction measures. The method was initially set up for LPG installations. The method considers the frequency and the consequence of a fault sequence and the necessary defence systems. The essence of the method is as follows.

- Key initiating events are identified, fault tree sequences are processed and the presence of lines of defence (risk reduction measures) is considered.
- The frequency class of a fault sequence i, F_i, is determined as $F_i = -\log_{10} f_i$, with f_i the initiating event frequency. For example, an initiating event frequency $f_i = 1 \times 10^{-3}$ per year of a fault sequence i falls in frequency class 3.
- The consequence category C_i is coupled directly to criteria for the acceptability of the risk, α, by the number of fault sequences, m, leading to the consequence by the relationship:

  $$C_i = -\log_{10}\left(\frac{\alpha}{m}\right)$$

  For instance, if ten fault sequences ($m = 10$) were to lead to a worker fatality, and the limit for acceptability is 1×10^{-3} per year, the fault sequence would be assigned consequence category 4. The standard definition of the consequence category is shown in Table 23. The categories are more-or-less consistent with the HSE guidelines on the tolerability of risk.
- The acceptability of the lines of defence (LOD) present to prevent fault sequence i is now determined by considering the following relationship:

  $$F_i + \sum_{j=1}^{n} LOD_{ij} - C_i > 0$$

  where $LOD_{ij} = -\log_{10} P_{ij}$ with P_{ij} the probability of failure of defence system j to prevent fault sequence i and C_i is the consequence category for fault sequence i. As shown in the relationship, the demands on the lines of defence are more stringent if the consequence category is more severe or the frequency of occurrence of the initial event is larger.

The TRAM method can thus be used to judge the acceptability of the lines of defence present to prevent a fault sequence.

The consequence category of the TRAM method is a measure for the acceptability of the risk. For instance, accidents with one worker fatality are assigned to consequence category 4, presuming that typically ten such fault sequences are identified. A consequence category 4 combined with frequency category 4 (frequency 1×10^{-4} per year) is (just) acceptable, i.e. an accident with one worker fatality may occur once per thousand per year.

Table 23 Consequence categories for TRAM [15]

Consequence category	Descriptor
> 7	**Catastrophic Accident**: gross disruption; large numbers of dead; very newsworthy; Public Enquiry; impacts on regulatory framework &/ or law
> 6	**Major Accident**: significant off-site disruption; many dead and injured; main feature of national news; results in public enquiry &/ or prosecutions
> 5	**Significant Accident**: some off-site disruption; small numbers of dead &/ or many injured; features in national news; legal actions, investigations and compensation claims
> 4	**Small scale Accident**: disruption local to site; dead limited to workers involved in accident; few serious injuries; mentioned in local news; investigation and compensation claims
>3	**Minor Accident**: limited to a small part of the site; injuries &/or lost-time accident; not mentioned in news; site/company investigation only
>=3	**Limited Accident** of low consequence

Risk Graph

The Risk Graph [11] is applied by DSM and determines the level of reliability of safety measures. The method considers the frequency and the consequence of a fault sequence. In short, the essence of the method is as follows:

- The frequency of a scenario should be considered in the absence of safety measures. A scenario is an initial event leading to a loss of containment with specific consequences if no safety measures are present. Three different frequency classes are considered, namely
  W1 very low probability (once every 10 – 100 year)
  W2 low probability (once every 1 – 10 year)
  W3 relatively high probability (more than once a year)

- Two parameters are used to modify the frequency, namely a factor, F, to account for the exposure of people in the hazard area and a factor, P, to account for the possibility of avoiding the hazard, e.g. by escaping.
  F1 rare – sometimes exposure in the hazard area
  F2 frequent – continuous exposure in the hazard area
  P1 in certain circumstances it is possible to avoid the danger, e.g. by escaping from the hazard zone
  P2 it is practically impossible to avoid the danger

- Four different consequence classes are defined, namely
  C1 injury to be reported
  uncontrolled discharge to be reported
  C2 severe permanent injury to one or more persons or death of a person
  limited, but observable damage to the environment
  C3 several dead
  temporary severe or limited long-term damage to the environment
  C4 large number of dead
  long-term severe damage to the environment

The classification can be modified to account for public opinions. Other aspects, like economic damage can be classified in the same way.

- The reliability of a safety system is expressed as a Safety Integrity Level (SIL)
  SIL1 Probability of failure on demand (PFD) < 10^{-1}
  SIL2 Probability of failure on demand (PFD) < 10^{-2}
  SIL3 Probability of failure on demand (PFD) < 10^{-3}
  SIL4 Probability of failure on demand (PFD) < 10^{-4}

The acceptability of the risk is shown in a Risk Graph for Safety, where the required Safety Integrity Level is defined for a combination of class of consequence, class of frequency and modifying parameters. The criteria for acceptability are reproduced in tabular form in Table 24 for consequence category C2.

The numerical values of the frequency in the table are derived by setting P1 = F1 = 0.1 and P2 = F2 = 1; a frequency of once every 1 – 10 years is translated as 0.3 per year (these numerical values are not reported by Donker [11], but applied here as an indication of the order of magnitude). The result shows that a scenario with a worker fatality (scenario C2) is in general considered acceptable at a frequency of 3×10^{-3} per year.

Table 24 Acceptability of Risk for consequence category C2 using the Risk Graph

F	P	W	SIL	acceptable frequency per year
F1	P1	W3	SIL1	$0.1 \times 0.1 \times 3 \times 1 \times 0.1 = 3 \times 10^{-3}$
F1	P2	W2	SIL1	$0.1 \times 1 \times 3 \times 0.1 \times 0.1 = 3 \times 10^{-3}$
F1	P2	W3	SIL1	$0.1 \times 1 \times 3 \times 1 \times 0.1 = 3 \times 10^{-2}$
F2	P1	W1	SIL1	$1 \times 0.1 \times 3 \times 0.01 \times 0.1 = 3 \times 10^{-4}$
F2	P1	W2	SIL1	$1 \times 0.1 \times 3 \times 0.1 \times 0.1 = 3 \times 10^{-3}$
F2	P1	W3	SIL2	$1 \times 0.1 \times 3 \times 1 \times 0.01 = 3 \times 10^{-3}$
F2	P2	W1	SIL1	$1 \times 1 \times 3 \times 0.01 \times 0.1 = 3 \times 10^{-3}$
F2	P2	W2	SIL2	$1 \times 1 \times 3 \times 0.1 \times 0.01 = 3 \times 10^{-3}$
F2	P2	W3	SIL3	$1 \times 1 \times 3 \times 1 \times 0.001 = 3 \times 10^{-3}$

AVRIM2

AVRIM2 [2] is an integrated assessment and inspection methodology in use by the labour safety inspector to assess the safety report and inspect/audit the installations. To evaluate loss of containment events, scenarios are placed in a Risk Matrix with the frequency and the consequence of a loss of containment event. Five different frequency classes and five different consequence categories are defined (see Table 25). A guideline for the acceptability shown in Table 26 is based on current-day practice in two large companies.

Table25 Frequency classes and Consequence categories in AVRIM2

Frequency class	Consequence category
1 Very small Never heard of in industry Almost impossible in installation. < 10^{-4} per year	1 Negligible Small impact on employees, no loss of production time, costs < NLG 10,000.-
2 Small Heard of in industry Not likely but possible in an installation < 10^{-3} per year	2 Small Medical treatment employees, small damage, limited loss of production time, costs < NLG 100,000.-
3 Average Has occurred in a company Could occur in an installation < 10^{-2} per year	3 Considerable Employees severely injured, limited damage, partly discontinuation of production, costs < NLG 500,000.-
4 Large Occurs a few times a year in a company Possibility of isolated incidents in an installation < 10^{-1} per year	4 Serious Permanent injury/health consequences, serious damage, discontinuation of production, costs < NLG 1,000,000.-
5 Very Large Occurs a few times a year in an installation Incidents may reoccur in an installation > 10^{-1} per year	5 Very serious One or more dead, very serious damage, long-term discontinuation of production, costs > NLG 1,000,000.-

Table 26 Risk criteria defined in AVRIM2

	Consequence category				
Frequency Class	1 Negligible	2 Small	3 Considerable	4 Serious	5 Very serious
5 Very Large	▾	▼	▼	▼	▼
4 Large	▾	▾	▼	▼	▼
3 Average	—	▾	▾	▼	▼
2 Small	—	—	▾	▾	▼
1 Very small	—	—	—	▾	▾
▼ unacceptably high ▾ high, ALARA — acceptable					

To derive the acceptability of an accident with a fatality, we assume this to be in consequence category 5. The corresponding tolerable frequency is frequency class 1, i.e. < 10^{-4} per year.

Risk criteria applied in companies

Major chemical companies apply risk criteria internally to evaluate the acceptability of the risk and to judge risk-reducing measures. A distinction can be made in the use of limits to the individual risk, the societal risk and the use of risk matrices. The following sections show several risk criteria in use by major chemical companies, and on-shore and offshore oil companies.

Individual Risk criteria

Risk criteria can be defined in terms of individual risk and group risk. It should be noted that companies use different definitions of individual risk.

A number of companies define the risk targets in terms of Personal Individual Risk (PIR), i.e. the annual chance of death of an identifiable person, taking into account the fraction of time present and the possibility of mitigation and escape [6]. The value of the risk target for employees is typically in the order of $2.5 - 3.5 \times 10^{-5}$ per year and for the members of the public offsite (or an employee of a neighbouring firm) in the order of $1 - 10 \times 10^{-6}$ per year. The risk target for employees in one company is explained by postulating that the risk of a fatal accident to an employee may not be larger than the accident rate of a healthy adult at home in the United Kingdom. This fatal accident rate is equal to 3.5×10^{-5} per year. A member of the public may not be exposed to a risk of any significance compared to the total of all other risks, which leads to a PIR of 1×10^{-6} per year for a member of the public.

A company may also postulate the criteria more qualitatively.

- For the employee at greatest risk from the activity concerned, the annual risk of fatal injury from a chemicals-related accident should, wherever reasonably practicable, be no greater than the average risk of a fatal accident befalling a fit adult of working age at home in the UK.
- For the member of the public exposed to the greatest risk, the risk of fatal injury as a result of a chemicals-related accident arising from company activities should not be significant when compared with other risks to which he or she is exposed in everyday life in the UK.
- If the potential consequences in terms of injury to people as a result of a chemicals-related accident is very high, the probability that the accident might occur should be correspondingly low.

Guidance is given to translate the qualitative criteria into numerical criteria. Furthermore, the numerical criteria were set as upper limit values of risk to be taken as being indicative, not absolute. In practice, the stated aim is to achieve risk levels as far below the upper limit as is reasonably practicable. It is important to note that the limit values were used to assess major peak risks to the person(s) at greater risk, they did not indicate the overall average risk expected to be achieved.

Companies may also adhere to the HSE acceptance criteria by using the individual risk and the categories: negligible, ALARA and unacceptable. The upperbound target level for maximum individual risk of fatality is in the order of 10^{-3} per year for employees (all risks), the lowerbound level is two orders of magnitude less. The ALARA principle is applied in one company using the following principles:

- expenditure equivalent to less than GBP 0.6 million per life saved will generally be regarded as worthwhile;
- expenditure equivalent to more than GBP 6 million per life saved will generally not be regarded as ‘reasonably practicable’
- expenditure equivalent to less than GBP 6 million and more than GBP 0.6 million per life saved is, in general, reasonably practicable, and the company has to demonstrate gross disproportion. However, the decision may be influenced by uncertainties in the quantification method and other factors.

Group target risk values are also defined. Some companies define a single number for the group risk, e.g. the maximum societal risk to residents (10 or more fatalities) should be less than 10^{-5} per year. Another company applies an F-N line for N > 3 with $F = 1 \times 10^{-5}$ per year for N = 10 and $F = 1 \times 10^{-6}$ per year for N = 100.

Risk matrix criteria
Various companies use a risk matrix in which possible accidents are set against scales of severity and frequency with qualitative categories in each scale [6]. For instance, one company defines the categories of severity and probability as shown in Table 27 and Table 28.

Within the matrix three risk levels are defined, namely high (measures should be implemented to reduce the risk, if possible), medium (cost-effective measures should be implemented to reduce the risk) and low (no action required). The areas in the risk matrix relating to these levels of risk are defined on a plant level. Typically, the high-risk level corresponds to frequency category A with consequence categories I – III, frequency category B with consequence categories I – II, and frequency category C with consequence categories I.

When several risk scenarios are identified, the overall risk is calculated by adding the frequencies of all cases with the same level of severity to determine an overall frequency. The severity and the overall frequency are placed in the risk matrix to determine the risk level and the actions required.

Variations on this risk matrix are possible, e.g. using an additional severity category with multiple fatalities.

Another example of a risk matrix is the Risk Graph.

Table 27 Consequence categories used in the risk matrix

Severity[a]	Health/Safety for Personnel/Public	Public disruption	Environmental impact	Economic impact
I	Fatality or serious health effects	Significant disruption to large community	Major/Extended duration/Full scale response	Corporate approval > 10 M$
II	Serious injury or moderate health	Significant disruption to small community	Serious/Significant resources committed	Regional approval 1 – 10 M$
III	Medical treatment or minor health effects	Minor disruption	Moderate/Limited response of short duration	Site manager approval < 1 M$
IV	Minor impact	Minimal to none	Minor/Little or no response needed	Other < 0.1 M$

[a] The consequences of a scenario are assigned to the categories, and the severity of a scenario is determined by the consequence with the 'highest' score.

Table 28 Frequency categories used in the risk matrix

Level	Description[a]	Nominal frequency	Range
A	Possibility of repeated incidents	3×10^{-1} incidents per year	$1 – 10^{-1}$ per year
B	Possibility of isolated incidents	3×10^{-2} incidents per year	$10^{-1} – 10^{-2}$ per year
C	Possibility of occurring sometime	3×10^{-3} incidents per year	$10^{-2} – 10^{-3}$ per year
D	Not likely to occur, but possible	3×10^{-4} incidents per year	$10^{-3} – 10^{-4}$ per year
E	Probability near zero	3×10^{-5} incidents per year	$10^{-4} – 10^{-5}$ per year

[a] based on a plant life (approx. 30 years)

Protection against ionising radiation

The criteria for the protection against ionising radiation are currently adapted in the Netherlands as implementation of the Council Directive 96/29/Euratom [50] and 97/43/Euratom [51]. The Council Directive adapts the following dose limits as criteria:

- All new classes or types of practice resulting in exposure to ionising radiation should be justified in advance of being first adopted or first approved by their economic, social or other benefits in relation to the health detriment they may cause;
- In the context of optimisation all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account;
- The sum of the doses from all relevant practices shall not exceed the dose limits for exposed workers, apprentices and students and members of the public.
- The limit on effective dose for exposed workers shall be 100 mSv in a consecutive five-year period, subject to a maximum effective dose of 50 mSv in any single year (in the Netherlands, 20 mSv in a single year [52]). Member States may decide an annual amount.
- The limit for effective dose for members of the public shall be 1 mSv in a year. However, in special circumstances, a higher effective dose may be authorised in a single year, provided that the average over five consecutive years does not exceed 1 mSv per year.

Additional dose criteria are defined for various organs of the body and specific groups of people. In the Netherlands, dose limits are also defined for members of the public being outside the boundary of an establishment [52]: the limit for effective dose for members of the public at any location outside the establishment shall be 0.1 mSv per year. It should be noted that, similar to external safety, the dose calculation for a member of the public being outside the boundary of an establishment is related to a location and a characteristic of a geographical point. However, in contrast to the calculation of external safety, factors are used to account for the average residence time of a person on the location.

Exposed workers are defined as persons, either self-employed or working for an employer, subject to an exposure incurred at work and liable to result in doses exceeding one or other of the dose levels equal to the dose limits for members of the public. The implementation of control measures and monitoring relating to the different areas and working conditions, include, where necessary, individual monitoring and medical surveillance is required.

The dose limits are directed to protect workers and members of the public against the long-term effects of ionising radiation, i.e. mortality due to cancer induction. If a mortality risk of 5% per Sievert of exposure is assumed [53], the limit for long term mortality for members of the public outside the establishment is 5×10^{-6} per year. For members of the public in general the limit is 5×10^{-5} per year and for exposed workers is 1×10^{-3} per year.

The criteria for judging the acceptability of the exposure of (exposed) workers to ionising radiation have the following properties:

- the criterion for (long-term) mortality risk for (exposed) workers is in the order of 1×10^{-3} per year;
- the criterion is applicable to an individual worker and individual monitoring is provided to control the exposure;
- compared to an individual member of the public, the risk to an (exposed) workers is a factor 20 higher;
- compared to the ‘individual’ risk outside the establishment, the risk to an (exposed) workers is a factor 200 higher.

Appendix 2 Activities at establishments who have to provide a safety report to the competent authorities (March 2001)

1	Air Products BV, Botlek-Rt	Production of industrial gasses, storage of liquid hydrogen and oxygen, loading of carbon monoxide
2	Aircraft Fuel Supply, Haarlemmermeer	Storage and pumping of air craft fuel
3	Akzo Nobel Base Chemicals BV, Botlek-Rt	Production of (petro-) chemical products, purification, storage
4	Akzo Nobel Base Chemicals, Hengelo	Production, storage and loading of chlorine, monochloricacid and derivates
5	Akzo Nobel Car refinishes, Sassenheim	Production, storage and loading of paint
6	Akzo Nobel Chemicals BV, Farmsum	Production of salt, chlorine, hydrochlorocarbons, primary amines, hydrogen, hydrogen chloride and cholinechloride
7	Akzo Nobel Polymer Chemicals BV, Deventer	Storage of (very) toxic substances in packing and in bulk and loading, storage of explosive and oxidising substances in packing
8	Akzo Nobel Resins, Bergen op Zoom	Storage and loading of raw materials and auxiliary substances from trucks and tank cars into storage buildings and storage vessels, production (batch process) of synthetic resins, storage and loading of end products into trucks and tank cars
9	Aluminium Delfzijl BV, Delfzijl	Storage and loading of cryolite and cryolite containing substances, use of chlorine gas for the purification of liquid metal, storage, treatment and transport of cryolite containing residuals and waste products
10	ATOFINA Vlissingen BV, Vlissingen	Continuous and batch-processes
11	Avecia BV, Waalwijk	Production of semi-finished (polymerisation), storage and loading of raw materials
12	Aventis CropScience Benelux BV, Farmsum	Storage, distribution and formulation and packing of crop protecting products
13	AVR location Oude Maasweg, Botlek-Rt	Collection, treatment and storage of chemical waste, loading and unloading of ships
14	AVR-KGA Services NV, Rotterdam	Collection, sorting, storage and transport of dangerous waste
15	Baris Investment, Spijkenisse	Storage and loading of substances, pump over of flammable liquids
16	BASF Nederland BV, Arnhem	Supply of raw materials, production and transport of latex

17	Benegas BV, Putten	Loading of propane and butane into tank cars, storage of propane and butane, filling of gas cylinders
18	Borden Chemical Holland, Botlek-Rt	Production and storage of formaline
19	BP Amsterdam terminal, Amsterdam	(Un)loading of shops and tank cars and storage of motor fuels and propane/butane, additions of additives
20	Broomchemie BV, Terneuzen	Production bromine derivatives, storage of toxic and flammable substances, production of chemicals
21	Budel Zink BV, Budel-Dorplein	Production of zinc and related products
22	Caldic Europoort BV, Europoort-Rt	Production of formaldehyde and derivatives, storage and loading of flammable and toxic liquids (ships, tank wagons and road tankers)
23	Chemgas Terminal Vlissingen BV, Vlissingen	(Un)loading of ships, tank wagons and road tankers, storage in pressure and atmospheric vessels
24	Chemie-Pack Nederland BV, Moerdijk	Storage, (un)loading, mixing and packing of dangerous substances (liquids and solids)
25	Chugoku Paints BV, Heijningen	Production of paints for the shipping and container industry. Storage of products and loading of trucks. Unloading of raw materials.
26	Ciba Speciality Chemicals Maastricht BV, Maastricht	
27	Cindu BV, Uithoorn,	Tar distillation and production of synthetic resin, storage and loading of raw materials and products
28	CONDEA SERVO BV, Delden	Storage and transhipment of flammable and toxic substances, production in batch reactors
29	Corus Staal BV, IJmuiden	Production of pig iron, steel and steel products, production and transport (pipeline) of flammable gasses, distillation, storage and loading of BTX
30	Cytec Manufacturing BV, Botlek-Rt	Continuous and batch processes for the production of special chemicals. Transhipment to and from trucks, tank cars and tank wagons, storage in vessels and warehouses
31	Den Hartogh Moerdijk CV, Moerdijk	Transhipment from and to tank ships, tank cars and trucks, storage in bulk, silos and warehouses (CPR-15), filling of vessels, drums and small packages
32	Diosynth, Oss	Production and development of pharmaceutical raw materials and products, storage and internal transport, treatment in batch reactors
33	Distributiecentrum Van den Anker BV(A), Son	Storage and transhipment of chemicals

34	Distributiecentrum Van den Anker BV(B), Son	Storage and transhipment of chemicals
35	Distributiecentrum Van den Anker BV, Roosendaal	Storage and transhipment of chemicals
36	DOW Benelux NV, Terneuzen	(Un)loading of sea-going vessels of flammable liquids, chemical process plants, storage and transhipment of flammable and toxic liquids
37	Dr. W. Kolb Nederland BV, Moerdijk	Production and distribution of industrial semi-finished products, Collection of liquid raw materials using pipelines, trucks and tank wagons
38	Fuji Photo Film BV, Tilburg	Storage of raw materials and semi-finished products, production of materials for the photographic industry
39	DSM Special Products Rotterdam, Rozenburg	Production of phenol, benzene aldehyde, benzene and benzoic acid
40	DSM Agro BV, IJmuiden	Transport, storage and transhipment of ammonia and ammonium nitrate, production of nitric acid, ammonium nitrate, fertiliser granule
41	DSM Fine Chemicals, Venlo	Production of raw materials for the pharmaceutical industry
42	DSM Limburg BV, Geleen	Production processes, storage of dangerous substances, storage and transhipment to tank wagons and inland vessels
43	DSM Minera, Maarssen	Production of raw materials for the pharmaceutical industry
44	DSM Resins International, Hoek van Holland	Production of synthetic resins, (un)loading of tank cars, storage and production
45	Du Pont de Nemours (Nederland BV), Dordrecht	Production processes, (un)loading of tank wagons and tank cars
46	Elf Atochem Rotterdam BV, Vondelingenplaat-Rt	Production of crop protecting products and industrial chemicals (a.o. mercaptane and H_2S)
47	Esso Raffinaderij Rotterdam BV, Botlek-Rt	Refinery and processing oil. Storage and transhipment by pipeline, lighter, sea-going vessels, tank wagons and tank cars
48	Europoint Terminals Netherlands BV, Amsterdam	Storage, transhipment and processing of liquid hydrocarbons
49	Exxon Mobil Chemicals Holland BV, Botlek-Rt	Extraction of aromatic compounds of oil fractions. Separation of benzene, toluene and xylene. Supply and storage of raw materials
50	Ferro (Holland) BV (Industrieweg), Rotterdam	Storage and processing of dangerous substances
51	Ferro (Holland) BV (v Helmontstr.) Rotterdam	Storage and processing of dangerous substances
52	FMC Industrial Chemicals BV, Delfzijl	Production, storage and transport of hydrogen peroxide

53	Gasdepot de Kellen, Tiel	Supply of propane and butane by ship and tank car. Storage in tanks. Transport by tank car
54	GE PLASTICS BV, Bergen op Zoom	Production of thermoplastics and products based on silicons
55	General Electric Plastics ABS BV, Amsterdam	Production of polymers based on acrylnitril, polybutadien and styrenes. Storage and transhipment of toxic and flammable substances
56	Gentenaar Holding BV, Moerdijk	Inside cleaning of transport unit. Mixing of chemical products. Storage and transhipment of transport units
57	Hercules BV, Middelburg	Production of resin (various processes). Production hydrogen, Storage and transhipment
58	Hercules Zwijndrecht BV, Zwijndrecht	Production paper chemicals and water soluble cellulose derivates. Storage and transhipment. Supply ethylene oxide by pipeline (or tank car)
59	Hoek Loos BV IJmuiden, IJmuiden	Production of oxygen, nitrogen and argon (also Kr/Xe and hydrogen). Storage (cryogenic) of liquid products. Transport of products by pipeline, tank wagon and tank car.
60	Honeywell Fluorine Products Europe BV, Weert	Production, storage and transhipment of hydrogen fluoride and chlorated hydrocarbons
61	Huntsman ICI Holland BV, Botlek-Rt	Production of semi-manufactured article for polyurethane foam, MDI and polyoles. Production, storage and transhipment of dangerous substances
62	Hydro Agri Sluiskil BV, Sluiskil	Production of nitrogen containing fertilisers. Production of ammonia. Transhipment of ammonia in sea-going vessels, tank cars and tank wagons.
63	Industrial Park Vlissingen BV, Vlissingen	Production of phosphor, phosphoric acid and sodium tripolyphosphate phosphor storage and transhipment
64	Johnson Matthey BV, Maastricht	Production of glass paints and gold paints
65	Kemira Rozenburg, Rozenburg	Ammonia, storage and transhipment of liquid fertilisers, WTC and hydrogen peroxide (including supply and transport). Transhipment of flammable liquids.
66	Kuwait Petroleum Europoort BV, Europoort-Rt	Refinery of crude oil, lubricating oil and petrol factory. Storage and transhipment of liquid raw materials and products.
67	Laporte Performance Chemicals BV, Zaltbommel	Production, storage and transhipment of (fine) chemicals
68	LBC Rotterdam BV, Rotterdam	Storage and transhipment of flammable and/or toxic liquids
69	Luxan BV, Elst	Storage of raw materials, auxiliary substances and ready products. Production of crop protecting products.

70	Lyondell Chemical Nederland, Ltd., Botlek-Rt	Production of propylene oxide. Storage and transhipment of propylene oxide etc. Storage and transhipment of light hydrocarbons.
71	Lyondell Europoort, Europoort-Rt	Unloading of ships, storage of light hydrocarbons.
72	Maasvlakte Olie Terminal, Maasvlakte-Rt	Supply (ship and pipeline) and transport (pipeline and ship), storage and transhipment of crude oil.
73	Maatschap Europoort Terminal, Europoort-Rt	Supply (ship and pipeline) and transport (pipeline and ship), storage and transhipment of crude oil.
74	Messer Nederland BV, Moerdijk	Filling of gas cylinders with technical gases. Filling and production of acetylene
75	Methanor VOF, Delfzijl	Production, storage and transhipment (tank car, ship, tank wagon) of methanol. Production hydrogen and transport by pipeline
76	MoTip BV, Wolvega	Storage and transhipment (tank car, truck) of spray cans and maintenance products. Assembly of spray cans
77	Muiden Chemie International BV, Muiden	Production of explosives. Storage and transhipment (trucks) of explosive and (solid and liquid) flammable substances. Storage and transhipment of explosive substances in storage buildings
78	Nufarm, Botlek-Rt	Production of petrochemical products.
79	NV Afvalverwerking Rijnmond, Botlek-Rt	Processing of dangerous waste. Storage of ammonia. Storage in tanks
80	NV Nederlandse Gasunie, Ravenstein	Compressor and mixing station for natural gas
81	NV Nederlandse Gasunie, Maasvlakte-Rt	Storage and liquidification of methane
82	NV Nederlandse Gasunie, Vilsteren	Compressor, mixing station and air separation
83	NV Nederlandse Gasunie, Middenmeer	Compressor and mixing station for natural gas
84	Nederlandse Benzol Maatschappij BV, Botlek-Rt	Storage and transhipment of liquid petrochemical products. (Un) loading of tankers, tank cars, tank wagons. Filling of vessels and storage in tanks (above ground and underground).
85	Nerefco location Europoort, Europoort-Rt	Storage of crude oil, oil products and ballast water. (internal) Transport in pipelines. Mixing of oil fractions in ready products.
86	Neste Resins, Europoort-Rt	Production of formaldehyde and dimethylether. Storage and transhipment of formaldehyde, methanol en acetic acid
87	Netherlands Refining Company BV, Pernis	Storage and transhipment (landing-stage and tank car) of petrol and other oil fractions
88	NOVA Chemicals Netherlands BV, Breda	Production of base types of polystyrenes (batch- and continuous process). Storage in silos.

89	Novartis Agro Benelux BV, Roosendaal	Formulation, storage and distribution of crop protecting substances
90	Odfjell Terminals (Rotterdam) BV, Botlek-Rt	Storage and transhipment of chemical and mineral products in tanks. Transhipment from and to ships, tank cars and tank wagons. Distillation of products and mixing of butane in stored products.
91	Opslag en Distributiecentrum Van der Helm, Delft	Storage and transhipment of dangerous substances (drums, vessels, etc.)
92	Pechiney Nederland NV, Ritthem	Production of aluminium
93	Petroplus (Oosterhavenweg), Vlissingen	Storage and transhipment (ships and tank cars) of K1, K2 and K3 liquids
94	PVS Chemicals Holland BV, Amsterdam	Production of (fuming) sulphuric acid and liquid sulphur dioxide. Processing of polluted sulphuric acids. Processing of sulphur-containing residues
95	Recitel Nederland BV, Kesteren	Storage and transhipment from tank cars and tank wagons of flammable and toxic substances. Maintenance of installations. Process preparations.
96	Resina Chemie BV, Foxhol	Storage of propylene oxide and transhipment from tank cars. Production of polyether polyoles
97	Rohm and Haas BV, Amersfoort	Production of gluten, suspensions and dyes. Transhipment to tanks and tank cars. Mixing.
98	Rotterdam Oxo-alcohol Plant, Europoort-Rt	Production, storage and transhipment of oxo-alcohols
99	SC Johnson Europlant BV, Mijdrecht	Transhipment from tank cars and trucks to storage tanks and storage buildings of propellant and raw materials. Mixing of raw materials. Filling of cans, storage of ready product and transhipment to trucks.
100	Shell Nederland Chemie BV, Moerdijk	Manufacturing of base chemicals. Chemical processing, storage and transhipment of toxic and flammable substances.
101	Shell Nederland Chemie BV, Pernis	Production of chemical products (a.o. ethoxylates, glycolesters, propylene, PVC)
102	Shell Nederland Raffinaderij BV, Pernis	Oil refinery (distillation, conversion, purification and mixing)
103	Shell Nederland Raffinaderij BV, Europoort-Rt	Supply (ship, pipeline) and transport (pipeline, ship), storage and transhipment of crude oil and oil products. Supply (truck) of biocide. Mixing of crude oils.
104	Shin-Etsu PVC BV, Rotterdam	Production of EDC and Vinyl chloride. Production, purification and storage
105	Store-Ship BV (Merwedeweg), Europoort-Rt	Storage of packed chemical products (CPR 15-2). Transhipment, storage and internal transport of products.

106	Targor BV, Botlek Rt	Transhipment of propene from ship to storage tank. Production of propylene. Storage and transhipment
107	TCG Logistics, Veenendaal	Storage and transhipment of substances, dangerous substances and spray cans
108	TEAM Terminal BV Europoort-Rt	Supply and transport by pipeline. (Un)loading of crude oil from ships Storage and mixing of products in tanks
109	TOTAL Raffinaderij Nederland NV, Vlissingen	Refinery of oil. Transhipment of flammable liquids and liquefied gases (sea-going vessel and inland vessels, tank cars).
110	Trespa International BV, Weert	Storage and transhipment from tank cars. Production processes resins. Supply and transport of dangerous substances.
111	Twaron Products BV, Farmsum	Production of aramide polymers, PPD, TDC and hydrochloric acid
112	Unipol Holland BV, Oss	Production of expandable polystyrene
113	Uniroyal Chemical BV, Amsterdam	Production of fine chemicals; formulation, granulation and packing of semi-manufactured products and ready products
114	Van der Sluijs Holding Statendam BV, Geertruidenberg	Transhipment of flammable liquids from ships to storage and from storage to tank cars. Storage of flammable liquids.
115	Vopak Logistics Services Dordrecht BV, Dordrecht	Storage and transhipment of liquids (ships, tank wagons, tank cars and containers) board-board-transhipment. Filling, storage and transport of vessels and IBC containers
116	Vopak Terminal Botlek BV, Botlek-Rt	Storage and transhipment of liquid products (ships, tank wagons, tank cars, containers and pipelines)
117	Vopak Terminal Chemiehaven BV, Botlek-Rt	Storage of liquids. Mixing of liquids, filling and transport of vessels and IBC containers. Transhipment of liquids (ships, tank wagons, tank cars and pipelines)
118	Vopak Terminal Europoort BV, Europoort-Rt	Storage of liquids in tanks and vessels. Mixing and washing of liquids and butanising. Transhipment of liquids (ships, tank wagons, tank cars and pipelines).
119	Vopak Terminal Laurenshaven BV, Botlek-Rt	Storage of liquids in tanks and transhipment of liquids from and to ships, supply and transport by pipeline
120	Vopak Terminal TTR BV, Botlek-Rt	Storage of liquids in tanks. Mixing of liquids and filling and transport of vessels and IBC containers. Transhipment of liquids (ships, tank wagons, tank cars and pipelines).
121	Watco ecoservice Rotterdam BV, (DAPEMO), Botlek-Rt	Transhipment by third parties of ships. Processing of waste (of ships).
122	Witco BV, Amsterdam	Processing of oil products. Storage in tanks, transhipment to tank cars and use of sulphur trioxide, sulphuric acid (fuming), highly flammable and corrosive liquids
123	Zuid-Chemie BV Sas van Gent	Storage and transhipment of liquid ammonia from tank cars and tank wagons. Storage and transhipment of liquid ammonium nitrate melt from tank cars. Storage A2-fertilisers.

Appendix 3 Loss of containment events for external safety

In CPR-18E [24] the following generic scenarios are given for component failures:

Pipelines:
- Full bore rupture
- Leak

Vessels:
- Instantaneous release of the complete inventory
- Continuous release of the complete inventory in 10 min
- Continuous release from a hole with an effective diameter of 10 mm
- (Runaway reactions)

Pumps:
- Catastrophic failure

Heat Exchangers:
- Instantaneous release of the complete inventory
- Continuous release of the complete inventory in 10 min
- Continuous release from a hole with an effective diameter of 10 mm
- Full bore rupture of ten pipes simultaneously
- Leak

Pressure relief devices:
- Discharge of a pressure relief device with maximum discharge rate

Storage in warehouses:
- Handling solids: dispersion of a fraction of the packaging unit inventory as respirable powder
- Handling liquids: spill of the complete packaging unit inventory
- Emission of unburned toxics and toxics produced in the fire

Storage of explosives:
- Mass detonation in a storage unit
- Fire in a storage unit

Road tankers and tank wagons:
- Instantaneous release of the complete inventory
- Continuous release from a hole the size of the largest connection
- Full bore rupture of the loading/unloading hose
- Leak of the loading/unloading hose
- Full bore rupture of the loading/unloading arm
- Leak of the loading/unloading arm
- External impact
- Fire under tank

Ships:
- Full bore rupture of the loading/unloading arm
- Leak of the loading/unloading arm
- External impact, large and small spill

Appendix 4 Failure frequencies of equipment

In CPR-18E [24] standard frequencies for equipment failures are given. The data are summarised in this appendix.

Stationary pressurised vessels

Table 29 Frequencies (per year) of loss of containment events for stationary vessels

	Instantaneous	Continuous, 10 min	Continuous, Ø10 mm
pressure vessel	5×10^{-7}	5×10^{-7}	1×10^{-5}
process vessel	5×10^{-6}	5×10^{-6}	1×10^{-4}
reactor vessel	5×10^{-6}	5×10^{-6}	1×10^{-4}

Stationary atmospheric vessels

Table 30 Frequencies (per year) of loss of containment events for atmospheric tanks

	Instantaneous, release to atmosphere	Instant., release to secondary container	Continuous 10 min, release to atmosphere	Continuous 10 min, release to secondary container	Continuous Ø10 mm, release to atmosphere	Continuous Ø10 mm, release to secondary container
single-containment tank	5×10^{-6}		5×10^{-6}		1×10^{-4}	
tank with a protective outer shell	5×10^{-7}	5×10^{-7}	5×10^{-7}	5×10^{-7}		1×10^{-4}
double containment tank	1.25×10^{-8}	5×10^{-8}	1.25×10^{-8}	5×10^{-8}		1×10^{-4}
full containment tank	1×10^{-8}					
membrane tank	see note 1					
in-ground tank		1×10^{-8}				
mounded tank	1×10^{-8}					

Note:

1. The failure frequency of a membrane tank, determined by the strength of the secondary container, should be estimated case by case using the data on the other types of atmospheric tanks.

Pipes

Table 31 Frequencies of loss of containment events for pipes

	Full bore rupture	Leak
nominal diameter ≤ 75 mm	1×10^{-6} m^{-1} y^{-1}	5×10^{-6} m^{-1} y^{-1}
75 mm < nominal diameter ≤ 150 mm	3×10^{-7} m^{-1} y^{-1}	2×10^{-6} m^{-1} y^{-1}
nominal diameter > 150 mm	1×10^{-7} m^{-1} y^{-1}	5×10^{-7} m^{-1} y^{-1}

Pumps

Table 32 Frequencies (per year) of loss of containment events for pumps

	Catastrophic failure	Leak
pumps without additional provisions	1×10^{-4}	5×10^{-4}
pumps with a wrought steel containment	5×10^{-5}	2.5×10^{-4}
canned pumps	1×10^{-5}	5×10^{-5}

Heat exchangers

Table 33A Frequencies (per year) of loss of containment events for heat exchangers

	Instantaneous	Continuous, 10 min	Continuous, Ø10 mm
dangerous substance outside pipes	5×10^{-5}	5×10^{-5}	1×10^{-3}

Table33B Frequencies (per year) of loss of containment events for heat exchangers

	Rupture, 10 pipes	Rupture, 1 pipe	Leak
dangerous substance inside pipes, design pressure outer shell less than pressure of dangerous substance	1×10^{-5}	1×10^{-3}	1×10^{-2}
dangerous substance inside pipes, design pressure outer shell more than pressure of dangerous substance	1×10^{-6}		

Pressure relief devices

Table 34 Frequencies (per year) of loss of containment events for pressure relief devices

	discharge
pressure relief device	2×10^{-5}

Storage of substances in warehouses

Table 35 Frequencies of loss of containment events for storage of substances in warehouses

	Dispersion of respirable powder	Liquid spill	Fire
storage in warehouses with protection levels 1 and 2	1×10^{-5} per handling of packaging unit	1×10^{-5} per handling of packaging unit	8.8×10^{-4} y^{-1}
storage in warehouses with protection level 3	1×10^{-5} per handling of packaging unit	1×10^{-5} per handling of packaging unit	1.8×10^{-4} y^{-1}

Storage of explosives

Table 36 Frequencies (per year) of loss of containment events for storage of explosives

	Mass detonation	Fire
storage of explosives	1×10^{-5}	see note 1

Note:

1. If a detonation occurs in a storage unit, the loss of containment event should be modelled as mass detonation in a storage unit. If detonation is excluded, the loss of containment event should be modelled as fire in a storage

Road tankers and tank wagons in an establishment

Table 37 Frequencies of loss of containment events for road tankers and tank wagons in an establishment

	Instantant. (y^{-1})	Cont, large conn.(y^{-1})	Full bore hose (h^{-1})	Leak hose (h^{-1})	Full bore arm (h^{-1})	Leak arm (h^{-1})	Extern. impact	Fire
tank, pressurised	5×10^{-7}	5×10^{-7}	4×10^{-6}	4×10^{-5}	3×10^{-8}	3×10^{-7}	see note 1	see note 2
tank, atmospheric	1×10^{-5}	5×10^{-7}	4×10^{-6}	4×10^{-5}	3×10^{-8}	3×10^{-7}	see note 1	see note 2

Notes:

1. The external impact LOCs for road tanker or tank wagon accidents in an establishment are determined by the local situation. A calculation method is described elsewhere in this report. In general, the LOCs for road tanker accidents do not have to be considered in an establishment if measures have been taken to reduce road accidents, like speed limits.

2. Fire under a tank may lead to the instantaneous release of the complete inventory of the tank. Various causes of failure may lead to a fire under a tank:
   - leakage of the connections under the tank followed by ignition. This event only occurs for tanks loaded with flammable substances. The frequency is equal to 1×10^{-6} per year for pressurised tanks and 1×10^{-5} per year for atmospheric tanks.

- fire in the surroundings of the tank. The failure frequency is determined by the local situation. Important aspects are the presence of tanks with flammable substances nearby and failure during loading and unloading of flammable substances. A calculation method to determine the failure frequency due to the presence of tanks with flammable substances nearby is described elsewhere in this report.

Ships in an establishment

Table 38 Frequencies of loss of containment events for ships in an establishment

	Full bore arm	Leak arm	External large spill	External small spill
single-walled liquid tanker	6×10^{-5} per transhipment	6×10^{-4} per transhipment	$0.1 \times f_0$	$0.2 \times f_0$
double-walled liquid tanker	6×10^{-5} per transhipment	6×10^{-4} per transhipment	$0.0015 \times f_0$	$0.006 \times f_0$
gas tanker, semi-gas tanker	6×10^{-5} per transhipment	6×10^{-4} per transhipment	$0.00012 \times f_0$	$0.025 \times f_0$

Note:

1. The base accident failure rate, f_0, is equal to $6.7 \times 10^{-11} \times T \times t \times N$, where T is the total number of ships per year on the transport route or in the harbour, t the average duration of loading/unloading per ship (in hours) and N, the number of transhipments per year.

Appendix 5 Areas covered by the Life Threatening Value and Alarm Limit Value for different substance categories

Substances can be classified in categories based on their physical and toxic characteristics. A classification method used in risk analyses of the transport of dangerous substances is described in [31].

The areas covered by the Life Threatening Value and the Alarm Limit Value are calculated with the model PHAST V6.0 [DNV. PHAST6.0, Londen, 2000] with the following method:

1. For each substance category a sample substance is selected.
2. For the sample substance, the concentrations of the Life Threatening Value and the Alarm Limit Value, based on one hour exposure time, are looked up in [13].
3. The concentrations of the Life Threatening Value (one hour exposure time) and the Alarm Limit Value (one hour exposure time) are converted to the values based on 10 minutes exposure time. For flammable substances, the distance to the lower flammable limit (LFL) and the area in the flash fire flame envelope is reported.
4. The model PHAST V6.0 is used to calculate the distance to the Life Threatening Value (10 minutes exposure time) and the Alarm Limit Value (10 minutes exposure time). Three different scenarios are calculated, namely a hole of 10 mm diameter, a hole of 50 mm diameter and a hole of 250 mm diameter. The outflow scenarios are calculated for a tank with a volume of 500 tonnes and a bund area equal to 500 m^2. The substances are stored at 10 ºC as saturated liquid, as padded liquids (ethylene oxide) or under atmospheric pressure (liquid head 5 metres). The weather conditions are stability class D and wind velocity 5 $m \cdot s^{-1}$.

The results of the calculations are given in the following tables for flammable substances and for toxic substances. In addition to the sample substances, the substances ammonia and ethylene oxide (toxic) are also given.

Table 39 Distance to the lower flammable limit (LFL) and the area in the flash fire flame envelope

Substance category	scenario	distance to LFL	area within flame envelope
GF1 – ethylene oxide	10 mm hole	7 m	150 m^2
	50 mm hole	40 m	4500 m^2
	250 mm hole	160 m	8×10^4 m^2
GF2 – butane	10 mm hole	6 m	110 m^2
	50 mm hole	60 m	1.1×10^4 m^2
	250 mm hole	300 m	2×10^5 m^2
GF3 – propane	10 mm hole	9 m	200 m^2
	50 mm hole	100 m	3×10^4 m^2
	250 mm hole	600 m	1.1×10^6 m^2
LF1 – octane	10 mm hole	4 m	50 m^2
	50 mm hole	6 m	110 m^2
	250 mm hole	8 m	200 m^2
LF2 – pentane	10 mm hole	6 m	110 m^2
	50 mm hole	30 m	4000 m^2
	250 mm hole	100 m	3×10^4 m^2

Table 40 Distance to the LTV and ATV and the corresponding area

Substance category	scenario	distance to LTV (10 min)	area within LTV (10 min)	distance to ATV (10 min)	area within ATV (10 min)
GT2 – ethyl chloride	10 mm hole	4 m	1 m^2	10 m	9 m^2
	50 mm hole	6 m	2 m^2	60 m	800 m^2
	250 mm hole	70 m	900 m^2	160 m	8000 m^2
GT3 – methyl chloride	10 mm hole	60 m	500 m^2	80 m	1000 m^2
	50 mm hole	300 m	2×10^4 m^2	400 m	4×10^4 m^2
	250 mm hole	1200 m	5×10^5 m^2	1400 m	9×10^5 m^2
GT4 – sulphur dioxide	10 mm hole	140 m	4000 m^2	800 m	8×10^4 m^2
	50 mm hole	600 m	1×10^5 m^2	4000 m	2×10^6 m^2
	250 mm hole	3000 m	2×10^6 m^2	30000 m	5×10^7 m^2
GT5 – chlorine	10 mm hole	500 m	3×10^4 m^2	1100 m	1.5×10^5 m^2
	50 mm hole	2000 m	1×10^6 m^2	7000 m	5×10^8 m^2
	250 mm hole	15000 m	4×10^7 m^2	50000 m	2×10^8 m^2
LT1 – acrylonitril	10 mm hole	70 m	600 m^2	150 m	3000 m^2
	50 mm hole	300 m	1.6×10^4 m^2	600 m	6×10^4 m^2
	250 mm hole	700 m	3×10^5 m^2	2000 m	1×10^6 m^2
LT2 – nitric acid*	10 mm hole	60 m	400 m^2	300 m	8000 m^2
	50 mm hole	150 m	3000 m^2	800 m	6×10^5 m^2
	250 mm hole	200 m	2000 m^2	900 m	6×10^5 m^2
LT3 – acrolein	10 mm hole	700 m	5×10^4 m^2	1700 m	3×10^5 m^2
	50 mm hole	2000 m	4×10^5 m^2	5000 m	2×10^6 m^2
	250 mm hole	5000 m	1.8×10^6 m^2	12000 m	1×10^7 m^2
LT4 – methylisocyanate	10 mm hole	500 m	3×10^4 m^2	1200 m	1.4×10^5 m^2
	50 mm hole	1600 m	3×10^5 m^2	4000 m	1.5×10^6 m^2
	250 mm hole	4000 m	1.5×10^6 m^2	10000 m	9×10^6 m^2
ammonia	10 mm hole	120 m	2000 m^2	300 m	1.2×10^4 m^2
	50 mm hole	500 m	7×10^4 m^2	1300 m	4×10^5 m^2
	250 mm hole	2000 m	1.8×10^6 m^2	6000 m	9×10^6 m^2
ethylene oxide (toxic)	10 mm hole	50 m	600 m^2	200 m	6000 m^2
	50 mm hole	170 m	8000 m^2	600 m	7×10^4 m^2
	250 mm hole	700 m	3×10^5 m^2	3400 m	3×10^6 m^2

* This substance is probably not suited as sample substance

Appendix 6 Mailing list

1 - 15	Ministerie van Sociale Zaken en Werkgelegenheid
16	Depot Nederlandse Publikaties en Nederlandse Bibliografie
17	Directeur Milieu
18	Directeur Sector Risico's, Milieu en Gezondheid
19	Hoofd van het Laboratorium voor Stralingsonderzoek
20 – 24	Auteurs
25	SBD/Voorlichting & Publications
26	Bureau Rapportenregistratie
27	Bibliotheek RIVM
28	Bibliotheek LSO
29	Bureau Rapportenbeheer
30 – 40	Reserve-exemplaren LSO

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