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E.S. Kooi | M.B. Spoelstra | P.A.M. Uijt de Haag

Evaluation of the Dutch QRA directives for storage and transportation of flammable liquids

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P.A.M. Uijt de Haag

Contact:
E.S. Kooi
Centrum Externe Veiligheid
eelke.kooi@rivm.nl

This investigation has been performed by order and for the account of VROM, within the framework of Advisering en ondersteuning beleid EV

RIVM, P.O. Box 1, 3720 BA Bilthoven, the Netherlands Tel +31 30 274 91 11 www.rivm.nl

Abstract

Evaluation of the Dutch QRA directives for storage and transportation of flammable liquids

According to Dutch legislation, the possibility of incidents with human casualties has to be determined for storage and transportation of flammable petroleum products. Part of the assessment is the calculation of the size and location of the area wherein people may die. For this risk assessment a methodology is prescribed. The possibility of an explosion at a flammable liquid storage facility turns out to be sufficiently accounted for in the methodology. However, some improvements in the methodology are desired. This is established by RIVM research that was commissioned by the Dutch Ministry of VROM. The study was initiated by an unexpectedly large explosion at a flammable liquids storage facility at Hemel Hempstead, England, in 2005.

A good risk calculation methodology is desirable because safety distances for buildings in the vicinity of such companies are determined from the calculated risks. These safety distances prevent that vulnerable destinations, such as homes and schools, are built at locations where the probability of death from such accidents is high.

It is recommended to better specify in the risk assessment methodology how consequences of releases of mixtures should be calculated. Additionally, some recommendations have been done for specific parts of the consequence models.

Besides the accident in Hemel Hempstead, other incident with storage and transportation of flammable petroleum products have been taken into account as well.

Key words:
third party risk, Quantitative Risk Assessment, flammable liquids, atmospheric storage tanks, transportation

Rapport in het kort

Evaluatie van de Nederlandse QRA-voorschriften voor opslag en transport van brandbare vloeistoffen

Voor opslag en transport van brandbare aardolieproducten moet volgens de Nederlandse wetgeving worden bepaald of er ongevallen kunnen optreden waarbij dodelijke slachtoffers kunnen vallen. Als onderdeel hiervan moet ook de grootte en de ligging worden vastgesteld van het gebied waarbinnen mensen kunnen overlijden in geval van een ernstig ongeval. Voor deze risicobeoordeling is een methodiek vastgesteld. In deze methodiek blijkt de mogelijkheid van een explosie bij activiteiten met brandbare aardolieproducten voldoende te zijn verdisconteerd. Wel zijn enkele verbeteringen in de methodiek gewenst. Dit blijkt uit onderzoek van het RIVM in opdracht van het ministerie van VROM. Aanleiding voor het onderzoek was een onverwacht grote explosie bij een opslagfaciliteit van aardolieproducten in Hemel Hempstead, Engeland, in 2005.

Een goede rekenmethodiek is gewenst omdat op basis van de berekende risico's veiligheidsafstanden worden vastgesteld voor bebouwing in de omgeving van dergelijke bedrijven. Met dergelijke veiligheidsafstanden wordt voorkomen dat kwetsbare bestemmingen, zoals woningen en scholen, op locaties staan waar de kans op overlijden door dergelijke ongelukken groot is.

Aanbevolen wordt om in de rekenmethodiek beter te specificeren hoe de effecten van vrijkomende mengsels moeten worden berekend. Ook zijn verbeteringsvoorstellen gedaan voor enkele specifieke modelonderdelen.

In de evaluatie zijn naast het genoemde ongeval in Hemel Hempstead, ook andere ongevallen bij opslag en transport van brandbare aardolieproducten meegenomen.

Trefwoorden:
externe veiligheid, kwantitatieve risicoanalyse, brandbare vloeistoffen, atmosferische opslagtanks, transport

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Glossary

C3 liquids	A category of flammable liquids used for Dutch rail transportation QRAs. It concerns mostly (highly) flammable liquids with a flash point below 23 °C and is defined by a specific set of UN numbers.
Class 1 (K1) flammable liquids	Highly flammable liquids as defined in the EU Seveso II directive, Annex I, part 2, category 7a/b. Also known as 'class 1 liquids' ('klasse 1 vloeistoffen' in Dutch).
Class 2 (K2) flammable liquids	Flammable liquids as defined by the EU Seveso II Directive, Annex 1, part 2, category 6. Also known as 'class 2 liquids' ('klasse 2 vloeistoffen' in Dutch).
Free field approach	Conservative assumption that flammable clouds will always ignite if they move beyond the site boundary. Furthermore, the flammable cloud is assumed to ignite at maximum cloud size.
Individual Risk (IR)	Probability that during one year an imaginary person that resides continuously at a specific location dies as a consequence of an incident involving an activity with hazardous substances. Also referred to as Location-based Risk or Locational Risk.
LF1 liquids	Flammable liquids as defined by ADR regulations for road transportation; class 3, packing group III.
LF2 liquids	(Highly) flammable liquids as defined by ADR regulations for road transportation; class 3, packing group II.
QRA	Quantitative Risk Analysis
RBM II	Software package recommended by the Dutch Ministry of Transport, Public Works and Water Management for QRA calculations involving transportation of hazardous substances
SAFETI-NL	Software package prescribed by Dutch legislation for QRA calculations involving establishments using, storing and/or producing significant amounts of hazardous substances
Societal Risk (SR)	Probability that during one year N or more persons die in a single incident involving an activity with hazardous materials

Samenvatting

Een serie van explosies op de ‘Buncefield Oil Storage Depot’ in Hemel Hempstead, Engeland op 11 december 2005, heeft grote bezorgdheid veroorzaakt over de veiligheid van opslagfaciliteiten voor aardolieproducten. In Nederland heeft de overheid de vraag gesteld of de veiligheidsgerelateerde richtlijnen en voorschriften voor de opslag van olieproducten adequaat waren. In het huidige rapport is onderzocht hoe de Nederlandse richtlijnen ([1] en [2]) voor de kwantitatieve risicoanalyse (QRA) van opslag, verlading en transport van vloeibare aardolieproducten zich verhouden tot de incidenten die zich hebben voorgedaan. Een analyse van incidentendatabases en een literatuuronderzoek zijn uitgevoerd om te bepalen welke typen incidenten zich kunnen voordoen en welke gevolgen ze kunnen hebben. De nadruk lag op incidenten die van belang zijn voor de externe veiligheid, dat wil zeggen incidenten die dodelijke gevolgen kunnen hebben buiten de inrichting.

Een belangrijke conclusie is dat de explosie bij Hemel Hempstead niet uniek was. Soortgelijke incidenten zijn gevonden in de literatuur. Een andere belangrijke conclusie is dat de mogelijkheid van een explosie reeds is opgenomen in de vigerende Nederlandse richtlijnen voor de QRA.

Dit onderzoek heeft geen betrekking op kwantificering van frequenties voor uitstroomscenario’s. Voor de vaststelling van deze frequenties zijn gedetailleerde gegevens nodig over het aantal incidenten, het aantal tankopslagjaren en de gebruikte apparatuur. Een dergelijke gedetailleerde analyse viel buiten de doelstellingen voor het huidige onderzoek. Als gevolg daarvan kon niet worden geconcludeerd of de berekende risicoafstanden realistisch zijn, of optimistisch of pessimistisch.

De analyse heeft niet geleid tot een nauwkeurige kwantificering van effectafstanden, omdat de incidentbeschrijvingen veelal niet gedetailleerd genoeg waren om de overdrukwaarden op verschillende afstanden te bepalen. In plaats daarvan is de grootteorde van effectafstanden geraamd voor de verschillende scenario’s. De resultaten zijn als volgt:

Opslag en verlading van K1-vloeistoffen (vlampunt lager dan 21 ºC)
Het berekende risico van opslagtanks wordt voor een groot deel bepaald door het scenario instantaan vrijkomen van de volledige tankinhoud. Echter, in het incidentdatabase- en literatuuronderzoek zijn geen incidenten gevonden waarbij de volledige inhoud vrijwel instantaan vrijkwam en die aanzienlijke schade buiten het terrein tot gevolg hadden. Tankexplosies en het breken of uitscheuren van een tank treedt op, maar de optredende effecten zijn aanzienlijk kleiner dan de berekende effecten voor het scenario instantaan vrijkomen van de volledige tankinhoud. Daarom wordt voorgesteld de modellering van het instantane scenario zodanig te wijzigen dat de effecten van het instantane scenario overeenkomen met de waarnemingen.

Volgens de literatuur en incidentdatabases, zijn de grootste effectafstanden voor opslagtanks het gevolg van incidenten waarbij de tank wordt overvuld en de gaswolk met vertraging ontsteekt. De effectafstand van overvullen blijkt vergelijkbaar met de berekende gevolgen van het tien-minuten-

release scenario. Daarom wordt volgens de huidige zienswijze het scenario vrijkomen van de volledige inhoud in tien minuten representatief geacht voor overvulincidenten.

Breuk van de laadarm is het dominante scenario voor het totale risico van verlading van K1-producten van of naar schepen. Volgens de berekeningen kunnen de wolkbrand en de explosie dodelijke gevolgen hebben op afstanden tot 500 m. Voor het scenario met 3000 m^3/uur overdracht ligt de PR 10^{-6}/jaar contour op 460 m afstand. Deze afstanden worden aanzienlijk verminderd als inbloksystemen en een realistische plasomvang worden meegenomen. In het incidentdatabase- en literatuuronderzoek zijn explosies van een scheepscompartiment, overvullen van scheepscompartimenten, breuken van laadarmen en het vrijkomen van brandbare vloeistof uit open kleppen geïdentificeerd als gebeurtenissen die grote effecten kunnen hebben. Scheepsexplosies veroorzaken geen schade in een mate die relevant is voor een QRA. Breuk van de laadarm is al opgenomen als QRA-scenario. Dit scenario wordt ook geacht het vrijkomen vanuit open kleppen en het overvullen van scheepscompartimenten te representeren.

Opslag en verlading van K2-vloeistoffen (vlampunt tussen 21 en 55 ºC)
De berekende effectafstanden voor K2-vloeistoffen zijn aanzienlijk kleiner dan de effectafstanden voor K1-vloeistoffen. Bovendien is de kans op directe ontsteking beduidend lager en wordt vertraagde ontsteking niet meegenomen. Voor een enkele opslagtank wordt geen PR 10^{-6}/jaar contour berekend. Het restrisico wordt bepaald door de effectafstand van de plasbrand.

Transport van brandbare vloeistoffen (LF1, LF2, C3)
Voor het vervoer van brandbare vloeistoffen houdt de QRA-richtlijn alleen rekening met de mogelijkheid van een plasbrand. Effectberekeningen laten zien dat bij het volledig falen van een tankauto of spoorketelwagen bij atmosferische druk en temperatuur een brandbare wolk gevormd kan worden met een doorsnede van 25 m. Deze wolkomvang is vergelijkbaar met de straal van de vloeistofplas. Als een spoorketelwagen faalt in een plasbrand dan is uit casuïstiek gebleken dat er een vuurbal kan optreden, wat gepaard kan gaan met relevante overdrukeffecten. Als brandbare vloeistoffen naar een riool- of drainagesysteem lekken, dan kunnen er explosies optreden als de dampen ontsteken.

De effecten die optreden bij ongevallen in tunnels zijn in dit rapport niet beschouwd.

Modelleringsaspecten
De modeluitkomsten van het scenario instantaan vrijkomen van de volledige tankinhoud, dat volgens het voorschrift moet worden berekend op basis van de maximale hoogte van de vloeistofkolom, worden niet fysisch realistisch geacht. Daarom wordt aanbevolen om dit onderdeel van het voorschrift aan te passen en uit te gaan van een vloeistofkolom van 0 meter hoogte.

De effect- en risicoberekeningen zijn uitgevoerd met n-hexaan. Deze pure stof werd representatief geacht voor brandbare vloeistofmengsels (K1), waaronder benzine. Een oriënterende berekening met de nog in ontwikkeling zijnde ‘multi-component’ optie in SAFETI-Professional geeft aan dat de berekende effect- en de risicoafstanden van een mengsel zoals (winter-)benzine groter kunnen zijn dan die van zuiver n-hexaan. Deze ‘multi-component’ optie is op dit moment nog niet beschikbaar in SAFETI-NL.

Huidige Veiligheidsrapporten:
In de veiligheidsrapporten van de grootste Nederlandse inrichtingen met vloeibare aardolieproducten, wordt bij de installatiescenario’s het overvullen van een tank regelmatig genoemd als mogelijk uitstroomscenario. Daarbij wordt verwacht dat een overvulincident kan leiden tot een wolkbrand of een plasbrand. De meerderheid van de gerapporteerde uitstroomscenario’s betreffen lekkages zonder ontsteking. Lekkages gevolgd door een brand worden minder vaak gerapporteerd. De QRA’s toonden grote verschillen in uitkomsten, hetgeen overeenstemt met eerder uitgevoerde benchmark-studies voor de Nederlandse QRA-berekeningen (zoals [3]).

Summary and conclusions

A set of explosions at the Buncefield Oil Storage Depot in Hemel Hempstead, England on 11 December 2005, caused considerable concern about the safety of flammable liquid storage facilities. In the Netherlands public authorities wondered if the safety related guidelines for the storage of petroleum products were adequate. In the current report it was investigated how the Dutch guidelines ([1] and [2]) for quantitative risk assessment (QRA) of storage, transfer and transportation of liquid petroleum products compare to the incidents that have occurred. An incident database review and an analysis of literature were carried out to determine which types of incidents may occur and what consequences they may have. The focus was on incidents that are relevant for third party risk, that is incidents that may have lethal consequences outside the establishment.

An important conclusion is that the explosion in Hemel Hempstead was not unique, as similar incidents have been found in literature. Another important conclusion is that the possibility of an explosion is already included in the prevailing Dutch guidelines for QRA.

This study did not involve a quantification of frequencies for different release scenarios. In order to determine these frequencies, detailed data on the number of incidents, tank storage years and used equipment is needed. Such a detailed analysis was not the scope of the current project. As a result, it could not be concluded whether the calculated risk distances are realistic, pessimistic or optimistic.

The analysis did not lead to an accurate quantification of consequence distances because the incident descriptions were not detailed enough to determine the overpressure levels at different distances. Instead, the order of magnitude of the consequence distances has been estimated for different scenarios. The results are as follows:

Storage and transfer of class 1 (K1) flammable liquids (flash point below 21 ºC)
The calculated risk of storage tanks is to a large extent determined by the instantaneous release scenario. However, the databases and literature review did not reveal incidents with substantial damage off site caused by (near-)instantaneous releases. Tank explosions and ruptures and fissures of tanks occur, but the reported consequences are significantly less severe than the calculated consequences for the instantaneous release scenario. Therefore, it is proposed to alter the way in which the instantaneous scenario is modelled in such a way that the effects of the scenario will correspond to the observations.

According to literature and incident databases, the largest consequence distances dealing with storage tanks are the result of overfill incidents followed by late ignition. The consequence distance for overfilling turns out to be comparable to the calculated consequences of the ten minute release scenario. Therefore, the ten minute release scenario is considered to be representative for overfill events.

Rupture of the loading arm is the dominant scenario for the overall risks of the transfer of class 1 flammable liquids to or from ships. According to the calculations the flash fire and explosion may have lethal consequences at distances up to 500 m. For the scenario with 3000 m^3/hr transfer, the IR 10^{-6}/yr contour is located at 460 m distance. These distances are considerably reduced if blocking systems and a realistic pool size are taken into account. The accident database and literature review identified explosions of ship compartments, overfilling of ship compartments, ruptures of the loading arm and releases from open valves as events that may have large consequences. Tanker ship explosions do not cause damage to an extent that is relevant for a QRA. Rupture of the loading arm is already taken into account as a QRA scenario. This scenario is also expected to represent releases from open valves and overfilling of a ship.

Storage and transfer of class 2 (K2) flammable liquids (flash point between 21 and 55 ºC)
The calculated consequence distances for K2 liquids are considerably smaller than consequence distances for class 1 flammable liquids. Furthermore, the probability of immediate ignition is significantly lower and delayed ignition is not considered. No IR 10^{-6} contour is obtained for a single storage tank. Lower risk levels are determined by the consequences of the pool fire.

Transportation of flammable liquids (LF1, LF2, C3)
For the transportation of flammable liquids, the guideline only considers the possibility of a pool fire. Consequence calculations show that a catastrophic rupture of a road or rail tanker at atmospheric temperature and pressure may produce a flammable cloud with a diameter of 25 m. The size of this cloud is comparable to the radius of the pool. If a rail tanker ruptures in a pool fire, case history has shown that a fireball may occur, possibly coupled with relevant overpressure effects. If flammable liquids leak into a drainage- or sewer system, explosions may occur when the vapours are ignited.

Consequences of incidents in tunnels have not been considered in this study.

Modelling aspects
The model outcomes for the instantaneous release scenario, which according to the directive uses the full tank head, are not expected to be physically realistic. It is recommended to modify this part of the QRA directive by assuming a liquid head of 0 m height.

The consequence and risk calculations were carried out using n-hexane as a representative pure component for (liquid) flammable mixtures including gasoline. A first analysis with the ‘multi-component option in SAFETI-Professional showed that calculated consequence and risk distances may increase if a mixture such as (winter grade) gasoline is used instead of pure n-hexane. This ‘multi-component’ option is currently not available for risk calculations with SAFETI-NL.

Existing Safety Reports:
The installation scenarios in the safety reports of the largest Dutch oil storing companies include overfill as a possible release scenario. It was expected that an overfill may lead to a flash fire or a pool fire. The majority of the reported release scenarios involve leakages without ignition. To a lesser extend leakages followed by a fire are reported. The QRAs showed large differences in

outcomes, which is in accordance with previously performed benchmark studies for Dutch QRA calculations (for example [3]).

1 Introduction

On Sunday 11 December 2005 a number of explosions occurred at the Buncefield Oil Storage Depot in Hemel Hempstead, Hertfordshire, England. These explosions caused severe damage in the surrounding area. The explosion damage included structural damage to buildings located at 100 to 300 m distance from the site boundary of the storage depot. The explosions had the effect of a wake up call amongst the people responsible for the safety of storage facilities for liquid petroleum products. Prior to the incident the general opinion was that an explosion event following a release of gasoline from an atmospheric storage tank would be highly unlikely if not impossible.

During the months following the Buncefield incident Dutch public authorities wondered if the possibility of an explosion - and the corresponding damage effects - were sufficiently taken into account in the QRA calculations for land-use planning. This question was subsequently put in a broader context which may be summarised as follows:

Do the QRA distances for land-use planning around storage facilities for liquid petroleum products - calculated in accordance with prevailing Dutch guidelines for spatial planning - sufficiently reflect the risks that these facilities pose in reality?

This report intends to answer this question by considering the following issues:

1. *What consequences are taken into account by present day guidelines for risk calculations?*
2. *What consequences and damage effects are taken into account in existing safety reports?*
3. *What are the consequences of incidents that occur at storage facilities for liquid petroleum products?*
4. *Do the calculated consequences and damage effects match the consequences and damage effects that have occurred in reality?*

These questions are addressed in the following chapters. It is noted that the Dutch land-use planning policy concerns risk, while the current investigation deals with consequences only. The reason is that risk involves frequencies and in order to determine a frequency, quantitative information on both accidents and presence of storage tanks and equipments throughout the years is needed. It was not feasible to retrieve this information within the scope of the current investigation.

The scope of this investigation is not to determine the cause of the Buncefield incident, nor to the determine the mechanism that led to the high overpressure in the main explosion. These questions will hopefully be answered by ongoing research commissioned by the Buncefield Major Incident Investigation Board.

It is further noted that the scope of this investigation is broader than the Buncefield incident alone. Though the Buncefield incident was the direct cause of the current investigation, lessons learned from other incidents should not be disregarded.

2 Dutch QRA guidelines and corresponding outcomes

2.1 Introduction

The first step in the evaluation of the Dutch QRA directives for storage and transport of flammable liquids, is to analyse the assumptions and outcomes of risk calculations for several installation types, following the relevant guidelines [1] and [2]. The following six activities will be discussed:

1. storage installations inside SEVESO II establishments
2. loading and unloading activities inside SEVESO II establishments
3. road transport
4. rail transport
5. waterway transport (inland)
6. pipeline transport (underground)

Within the scope of this investigation oil and gasoline terminals was considered to be most relevant. Therefore, the risk is calculated for stationary installations (including loading/unloading activities) only. For the transportation of hazardous substances a qualitative study is performed.

In this chapter the following results are reported for the following reasons.

- The distance to the individual risk (IR) contour IR 10^{-6}/yr is reported because this corresponds to a limit value for spatial planning in the Dutch legislation [4]. *Note: the Dutch definition of individual risk is location dependent and is sometimes labelled location-based risk or locational risk.*
- The distance to the IR 10^{-8}/yr contour is reported because the population that is present in the area between the IR 10^{-6} and IR 10^{-8} contours usually determines the height of the societal risk (which needs to be accounted for by the responsible authorities according to [4]).
- The reported consequences follow the damage criteria of the guidelines: for a flash fire the (largest) distance to the LFL is reported, for an explosion the distance to 0.3 bar is reported and for jet- and pool fires the distance to 1% lethality is reported.

In the Netherlands, the software tool SAFETI-NL is prescribed for QRA calculations for land-use planning. Therefore, considerable attention is paid to various model aspects of SAFETI-NL.

It is further noted that the scope of this chapter is limited to the outcomes of risk calculations that follow the Dutch risk assessment requirements. These requirements show a trade off between realistic outcomes and simplicity of the instrument (for example a limited number of distinguished installation types and a limited number of scenarios per installation type). A limited set of abstract scenarios is preferred in the generic approach, as long as the outcomes are not too far off from the risks calculated with a more sophisticated method. Whether the risk outcomes for oil and gasoline terminals can be regarded as sufficiently realistic, will be discussed in chapter 5. For the sake of completeness it is also noted that the Dutch guidelines prescribe generic failure frequencies, presuming ‘current day practice’ facilities. The effect of frequency reducing measures is usually difficult to quantify and therefore it is difficult to take them into account in a QRA.

2.2 Storage installations at SEVESO II establishments

The guidelines for Dutch QRA calculations for stationary installations with hazardous substances are given by the *‘Handleiding Risicoberekeningen BEVI’* [2] (in 2009 version 3.2 of this ‘Reference Manual Bevi Risk Assessments’ was translated into English, see [43]). According to section C.3.6.3 of [2] the following Loss of Containment (LOC) events must be taken into account for a single containment atmospheric storage tank:

Table 1 Release scenarios and frequencies for a single containment atmospheric storage tank

LOC event	Frequency (yr^{-1})
Instantaneous release of the full content	5×10^{-6}
Continuous release of the full content in ten minutes	5×10^{-6}
Continuous release from a 10 mm. hole (effective diameter)	1×10^{-4}

Subsequent inputs for risk calculation, such as the consequence events to be used and the probabilities of immediate and delayed ignition, depend on the volatility of the flammable liquids. Two volatility classes are distinguished:

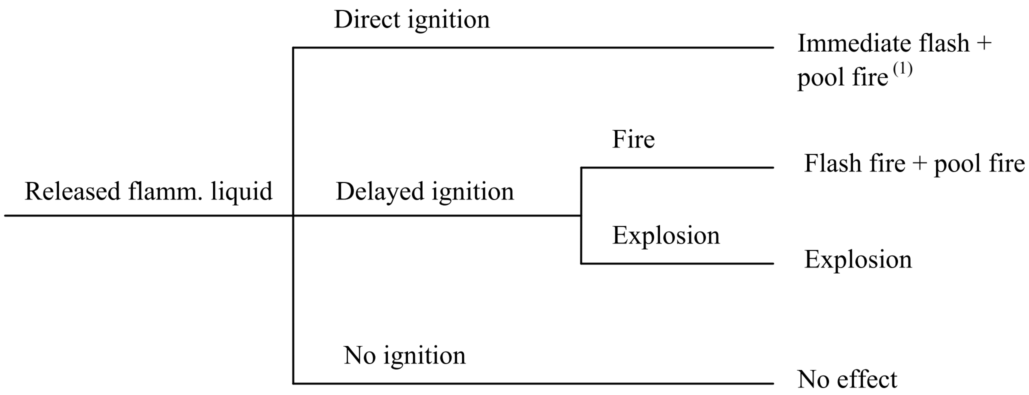
- Class 1 (K1) flammable liquids: liquids classified as highly flammable (category 7) in part 2 of Annex I of the EU Seveso II directive.
- Class 2 (K2) flammable liquids: liquids classified as flammable (category 6) in part 2 of Annex I of the EU Seveso II directive.

The risk outcomes will be discussed for these two classes separately.

Class 1 (K1) flammable liquids

Figure 1 shows the event tree for an instantaneous release of class 1 (K1) flammable liquids from an atmospheric storage tank and Figure 2 shows the event tree for a continuous release. As shown in these figures, the released flammable liquid may ignite immediately, ignite after some delay or may not ignite at all. Direct ignition leads to a pool fire in case of an instantaneous release and to a combination of a pool fire and a jet fire in case of a continuous release. Delayed ignition may either result in a vapour cloud fire (flash fire) or a vapour cloud explosion. If a continuous release is still ongoing, a delayed ignition will also give an ignited liquid jet (jet fire), but this event is not considered in the event tree (Figure 2). The reason is that the distances for the ignited liquid jet will generally be significantly smaller than the distances for the accompanying pool fire.

The probabilities corresponding to the routes in Figure 1 and Figure 2 are listed in Table 2. The probability of immediate ignition is 6.5% for class 1 flammable liquids. The probability of delayed ignition depends on the presence of ignition sources within the establishments and on the distance to the site boundary. According to the guidelines, a flammable cloud consisting of K1 vapours will always ignite if the cloud crosses the site boundary (the ‘free field approach’). If a flammable cloud of K1 vapours does not reach the site boundary, the probability of delayed ignition may be smaller than presented in Table 2 (depending on the presence of ignition sources on site).



(1) *It may be argued that during the release a small fraction of the liquid vaporises. Direct ignition will then give a small flash fire along with the pool fire. In general, the size of this immediate flash fire is negligible in comparison with the size of the pool fire. Further details are given in Appendix A.*

Figure 1 Event tree for an instantaneous release of class 1 flammable liquids from a single containment atmospheric storage tank

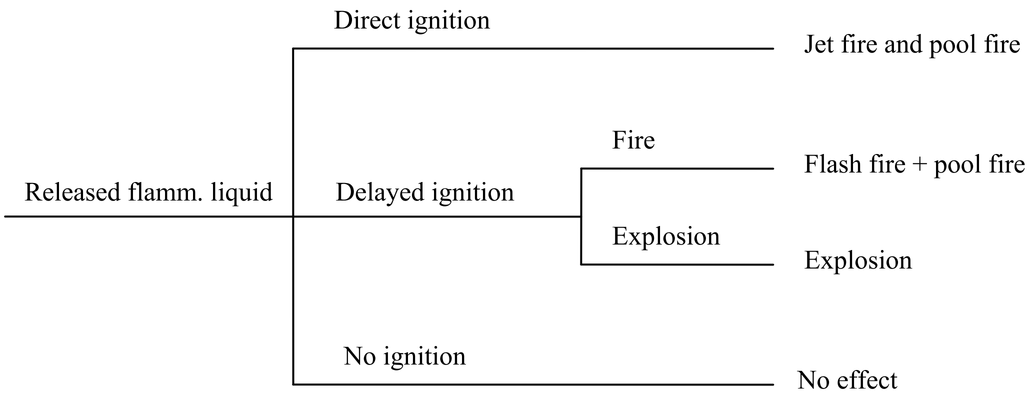


Figure 2 Event tree for a continuous release of class 1 flammable liquids from a single containment atmospheric storage tank

The parameters in Table 2 are prescribed for Dutch risk calculations. Other parameters are site specific and need to be interpreted in order to perform the risk calculations. These parameters as well as their interpretation and proposed values for risk calculations are given in Table 3.

Table 2 Ignition probabilities for a release of class 1 flammable liquids from a single containment atmospheric storage tank

Time of ignition	Event	Probability (%)
Direct ignition	Pool fire (+ flash/jet fire)	6.5
Delayed ignition (1)	Flash fire + pool fire	56.1
Delayed ignition (1)	Explosion	37.4

(1) *The listed probabilities apply when the LFL envelop crosses the site boundary. Otherwise the probability of delayed ignition (flash fire or explosion) depends on the presence of ignition sources within the site boundary (ultimately no effect).*

Table 3 Additional risk parameters (single containment atmospheric storage tank containing class 1 flammable liquids)

<table>
<tr><th>Parameter</th><th>Interpretation</th></tr>
<tr><td>Substance</td><td>The risks of class 1 (K1) flammable liquids (for example gasoline) will be calculated with SAFETI-NL 6.53 using n-hexane as a representative substance.</td></tr>
<tr><td>Contents of the tank</td><td>In this study vessels of 1000 m^3, 10,000 m^3 and 50,000 m^3 will be used (maximum liquid volume).</td></tr>
<tr><td>Storage conditions</td><td>Atmospheric storage conditions (temperature 9 °C and absolute pressure 1 bar) are presumed.</td></tr>
<tr><td>Bund size</td><td rowspan="3">Small vessel (1000 m^3):
– tank height 10.8 m (corresponding diameter 10.8 m)
– bund surface area 2500 m^2, bund height 1 m.

Medium vessel (10,000 m^3):
– tank height 14.7 m (corresponding diameter 29.4 m)
– bund surface area 15,000 m^2, bund height 2 m.

Large vessel (50,000 m^3):
– tank height 21.7 m (corresponding diameter 54.2 m)
– bund surface area 30,000 m^2, bund height 3 m.</td></tr>
<tr><td>Bund height</td></tr>
<tr><td>Tank height</td></tr>
<tr><td>Distance to site boundary</td><td>It is expected that the distance to site boundary is of great importance for the risk outcomes for class 1 (K1) flammable liquids. Therefore two values will be used: 50 m and 150 m.</td></tr>
<tr><td>Surface roughness</td><td>The Dutch default value of 300 mm is used.</td></tr>
<tr><td>Ignition sources</td><td>It is assumed that no ignition sources are present within the LFL envelope on site.</td></tr>
<tr><td>Weather</td><td>Dutch average weathers with uniform distribution over wind directions.</td></tr>
</table>

(1) *Appendix B will discuss to what extend consequence distances change if a mixture is used in the calculations.*

The risk calculation outcomes for the storage of class 1 (K1) flammable liquids are presented in Table 4.

Table 4 QRA results for single containment atmospheric storage tanks containing class 1 flammable liquids (current methodology)

Tank	1000 m^3		10,000 m^3		50,000 m^3	
Site boundary	*50 m*	*150 m*	*50 m*	*150 m*	*50 m*	*150 m*
Distance to IR 10^{-6}/yr contour (m)	90	10	270	270	580	580
- dominant scenario(s)	A	C	A	A	A	A
Distance to IR 10^{-8}/yr contour (m)	120	90	340	340	780	780
- dominant scenario for SR	A&B	B	A&B	A&B	A	A
Consequence distances (m) (1)						
- *A: instantaneous release*						
- flash fire	140	40 (2)	380	380	800	800
- explosion (0.3 barg)	115	-	300	300	640	640
- pool fire (radius)	35	35	85	85	120	120
- pool fire (1% leth.)	65	65	160	160	260	260
- *B: 10 minute release*						
- flash fire	110	0 (3)	290	290	550	550
- explosion (0.3 barg)	100	-	250	250	440	440
- jet fire (1% leth.)	110	110	210	210	380	380
- pool fire (radius)	30 (4)	30 (4)	70 (4)	70 (4)	100 (4)	100 (4)
- pool fire (1% leth.)	55 (4)	55 (4)	120 (4)	120 (4)	160 (4)	160 (4)
- *C: 10 mm leakage*						
- flash fire	0 (3)	0 (3)	0 (3)	0 (3)	0 (3)	0 (3)
- explosion (0.3 barg)	-	-	-	-	-	-
- jet fire (1% leth.)	20	20	20	20	20	20
- pool fire (radius)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
- pool fire (1% leth.)	15 (5)	15 (5)	15 (5)	15 (5)	15 (5)	15 (5)

(1) The reported values concern the maximum value for any of the day or night weathers.

(2) Results for the 'early flash fire'. Delayed ignition of the cloud does not occur in this scenario as the vapour cloud does not reach the site boundary.

(3) Immediate ignition does not give a flash fire for a continuous scenario. Delayed ignition will not occur because the cloud does not reach the site boundary and no ignition sources are assumed to be present on site.

(4) The pool radius for the ten minute release is smaller than the pool radius for the instantaneous release. An instantaneous release is supposed to give bund overtopping. Therefore the pool size is set at 150% of the bund size. For the ten minute release, the (maximum) pool size is supposed to be equal to the bund size. The distance to 1% lethality further depends on the assumed rain out location, which may be significant for the instantaneous release. Further details are given in Appendix A.

(5) Results for the early pool fire. Late ignition of the (full grown) pool does not occur as the vapour cloud does not reach the site boundary.

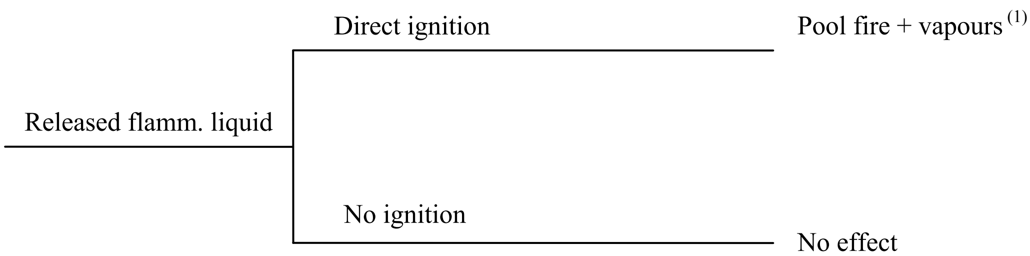
Table 4 shows that the instantaneous release scenario determines the location of the IR 10^{-6}/yr contour and the height of the risk in the area outside the IR 10^{-6}/yr contour (relevant for societal risk). Both the location of the IR 10^{-6} contour and the location of the IR 10^{-8} contour are largely determined by the delayed ignition of the cloud following an instantaneous release (giving a flash fire and an explosion, see Figure 1). For the 50,000 m^3 tank, the size of the flammable cloud (distance to LFL) is calculated to be 800 m (weather type F1.5). As will be discussed later in this report, this distance is not considered to be realistic.

Table 4 also shows jet fire results ranging from 110 m to 380 m (1% lethality) for the ten minute release. These jet fire distances are not regarded as realistic either for releases from atmospheric storage tanks. Fortunately, the jet fire outcomes turn out to be irrelevant for the location of the IR 10^{-6} to IR 10^{-8}/yr contours.

More details on various modelling aspects and their influence on consequence and risk outcomes are given in section 2.8 and Appendix A.

<u>Class 2 (K2) flammable liquids</u>
Figure 3 shows the event tree for an instantaneous release of unheated class 2 (K2) flammable liquids from an atmospheric storage tank and Figure 4 shows the event tree for a continuous release. As shown in these figures, only immediate ignition is taken into account for the QRA. This will result in a pool fire and ignition. Ignition of vapours is also considered by the model, but the amount of vapour should be limited for a release of unheated class 2 flammable liquids. The probability of immediate ignition is 1 % (see Table 5).

Figure 3 only applies when class 2 flammable liquids are stored at a temperature below their flash point. If a class 2 flammable liquid is stored above its flash point, the event trees and probabilities of class 1 flammable liquids should be used (see Figure 1, Figure 2 and Table 2).



(1) *It may be argued that during the release a small fraction of the liquid vaporises. Direct ignition will then give a small flash fire along with the pool fire. In general, the size of this immediate flash fire is negligible in comparison with the size of the pool fire. Further details are provided in Appendix A.*

Figure 3 Event tree for an instantaneous release of class 2 flammable liquids (storage temperature below the flash point) from a single containment atmospheric storage tank

Table 5 Ignition probabilities for a release of class 2 flammable liquids (storage temperature below the flash point) from a single containment atmospheric storage tank

Time of ignition	Event	Probability (%)
Direct ignition	Pool fire (+ flash/jet fire)	1
No ignition	No effect	99

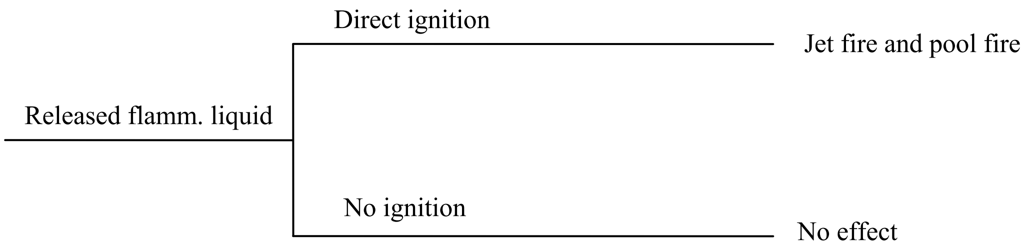


Figure 4 Event tree for a continuous release of class 2 flammable liquids (storage temperature below the flash point) from a single containment atmospheric storage tank

Table 6 Additional risk parameters (single containment atmospheric storage tank containing class 2 flammable liquids)

Parameter	Interpretation
Substance	The risks of class 2 (K2) flammable liquids (for example kerosene) will be calculated using n-nonane.[(1)] A workaround was used in SAFETI-NL for K2 liquids because a small dissimilarity between SAFETI-NL and the Reference Manual Bevi Risk Assessments was discovered [(2)].
Contents of the tank	In this study vessels of 1000 m^3, 10,000 m^3 and 50,000 m^3 will be used (maximum liquid volume).
Storage conditions	Atmospheric storage conditions (temperature 9 °C and absolute pressure 1 bar(a)) are presumed.
Bund size Bund height Tank height	Small vessel (1000 m^3): – tank height 10.8 m (corresponding diameter 10.8 m) – bund surface area 2500 m^2, bund height 1 m. Medium vessel (10,000 m^3): – tank height 14.7 m (corresponding diameter 29.4 m) – bund surface area 15,000 m^2, bund height 2 m. Large vessel (50,000 m^3): – tank height 21.7 m (corresponding diameter 54.2 m) – bund surface area 30,000 m^2, bund height 3 m.
Distance to site boundary	The distance to the site boundary is irrelevant for class 2 flammable liquids as delayed ignition is not supposed to occur (see Table 5)
Surface roughness	The Dutch default value of 300 mm is used.
Ignition sources	It is assumed that no ignition sources are present within the LFL envelope on site.
Weather	Dutch average weathers with uniform distribution over wind directions.

(1) *Appendix B will discuss to what extend consequence distances change if a mixture is used in the calculations.*

(2) *According to the Reference Manual, delayed ignition of class 2 flammable liquids with storage temperature below the flash point will not occur (see* Table 5*). In SAFETI-NL 6.53 delayed ignition is taken into account if a flammable cloud (concentration above the lower flammable limit) meets an ignition source or crosses site boundary. This dissimilarity was circumvented by reducing the probability of a release by a factor 0.01 (i.e. the probability of immediate ignition) and setting the probability of immediate ignition to 1.*

The risk calculation outcomes for the storage of class 2 (K2) flammable liquids are presented in Table 7. An IR 10^{-6}/yr contour does not occur because the probability of ignition is low (1%). The location of the IR 10^{-8}/yr contour depends on the size of the pool fire. On closer inspection, the IR 10^{-8} contour is almost identical to the 100% lethality contour of the largest pool fire. This largest pool fire occurs for the instantaneous release scenario, due to the assumption of bund overtopping (see Table 6). Significant consequence distances are found for the immediate flash fire (200 m for the 50,000 m^3 tank). As will be discussed later in this report, this effect distance is not considered to be realistic.

Table 7 QRA results for single containment atmospheric storage tanks containing class 2 flammable liquids (current methodology)

Tank	1000 m^3	10,000 m^3	50,000 m^3
Distance to IR 10^{-6}/yr contour (m)	-	-	-
- dominant scenario(s)	-	-	-
Distance to IR 10^{-8}/yr contour (m)	40	110	185
- dominant scenario for SR	A&B	A	A
Consequence distances (m) (1)			
- *A: instantaneous release*			
- flash fire	35 (2)	85 (2)	200 (2)
- explosion (0.3 barg)	-	-	-
- pool fire (radius)	35	85	120
- pool fire (1% leth.)	70	170	290
- *B: 10 minute release*			
- flash fire	0 (3)	0 (3)	0 (3)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	20	40	70
- pool fire (radius)	30 (4)	70 (4)	100 (4)
- pool fire (1% leth.)	55 (4)	100 (4)	160 (4)
- *C: 10 mm leakage*			
- flash fire	0 (3)	0 (3)	0 (3)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	5	5	5
- pool fire (radius)	10	10	10
- pool fire (1% leth.)	40	40	40

(1) *The reported values concern the maximum value for any of the day or night weathers.*

(2) *Results for the 'early flash fire'. Delayed ignition of the cloud is expected not to occur (see* Table 5*), presuming no ignition sources are present on site.*

(3) *Immediate ignition does not give a flash fire for a continuous scenario. Delayed ignition is expected not to occur (see* Table 5*), presuming no ignition sources are present on site.*

(4) *The pool radius for the ten minute release is smaller than the pool radius for the instantaneous release. An instantaneous release is supposed to give bund overtopping. Therefore the pool size is set at 150% of the bund size. For the ten minute release, the (maximum) pool size is supposed to be equal to the bund size. The distance to 1% lethality further depends on the assumed rain out location, which may be significant for the instantaneous release. Further details are given in Appendix A.*

2.3 Loading and unloading activities

The requirements for Dutch QRA calculations for loading and unloading activities are (also) given by [2]. Table 8 lists the LOC events that must be taken into account for loading activities. This table is based on the assumption that the loading/unloading activities use arms instead of hoses and that no blocking systems are present. This is a conservative approach. Table 9 lists the LOC events that apply for the corresponding presence of transport units in the loading area.

The events that may follow a release of flammable liquid, and their relative probabilities, are assumed to be identical to releases from storage tanks (Figure 2 and Table 2 for a continuous release of class 1 (K1) flammable liquids and Figure 4 and Table 5 for a continuous release of unheated class 2 (K2) flammable liquids). Further site specific parameters are listed in Table 10.

No calculations are carried out for transfer to or from road and rail tankers. It is assumed that this transfer will generally not be dominant for the IR 10^{-6}/yr contour or societal risk as the quantities involved are significantly lower than the transfer to/from ships.

Table 8 Release scenarios and frequencies for loading activities

LOC event	Frequency
Full bore rupture of the loading/unloading arm (1)	3×10^{-8} /hr
Leak from loading/unloading arm (2)	3×10^{-7} /hr
Additional event for atmospheric road and rail tankers:	
Instant. release due to engulfing fire (resulting in pool fire)	5.8×10^{-9} /hr

(1) It is assumed that the release rate in case of a full bore rupture is 150% of the ordinary pump flow rate.
(2) This scenario is modelled as a leak with an effective diameter of 10% of the arm diameter.

Table 9 Release scenarios and frequencies for on site transport units

LOC event	Frequency
Atmospheric road / rail tankers:	
Instantaneous release of full content	1×10^{-5}/yr (1)
Continuous release of full content from largest connection	5×10^{-7}/yr (1)
Single hull vessels:	
Continuous release of 75 m^3 in 1800 s	10% of probability of heavy damage (2)
Continuous release of 20 m^3 in 1800 s	20% of probability of heavy damage (2)
No significant release	70% of probability of heavy damage (2)

(1) To be multiplied by the time fraction of presence.
(2) The probability of heavy damage can be assessed using a formula from section 3.14.3 of [2] (also [43]).

Table 10 Additional parameters needed for risk calculations for loading activities

Parameter	Interpretation
Substance	The risks of class 1 flammable liquids (for example gasoline) will be calculated with SAFETI-NL 6.53 using n-hexane as a representative substance. The risks of class 2 flammable liquids (for example kerosene) will be calculated using n-nonane. A workaround was used in SAFETI-NL for class 2 flammable liquids because a small dissimilarity between SAFETI-NL and the Reference Manual Bevi Risk Assessments was discovered (1).
Pump flow rate Loading arm diameter Pump pressure (g)	Pump flow rates for transfer to/from vessels vary from 100 m^3/hr to 3000 m^3/hr. Loading arm diameters vary from 6” to 36”. The pump pressure may be as high as 10 bar. Low flow rate (100 m^3/hr): – the flow rate equals 19 kg/s (K1) or 22 kg/s (K2) – a loading arm diameter of 6” (15 cm) is assumed – a pump pressure of 3 bar (gauge) is assumed Average flow rate (500 m^3/hr): – the flow rate equals 97 kg/s (K1) or 111 kg/s (K2) – a loading arm diameter of 10” (25 cm) is assumed – a pump pressure of 3 bar (gauge) is assumed Higher flow rate for gasoline (1500 m^3/hr): – the flow rate equals 291 kg/s (K1) or 333 kg/s (K2) – a loading arm diameter of 12” (30 cm) is assumed – a pump pressure of 3 bar (gauge) is assumed – two loading arms are used simultaneously (the flow rate is divided between the two and the probability of a spill is doubled) High flow rate for crude oil (3000 m^3/hr): – the flow rate equals 583 kg/s (K1) – a loading arm diameter of 36” (91 cm) is assumed – a pump pressure of 10 bar (gauge) is assumed
Time fraction	In order to put the risks of loading/unloading activities in perspective with the risks of a single storage tank, it is assumed that loading or unloading activities takes place during 10% of the time (that is 876 hours per year).
Location of the jetty	It is assumed that the jetty area is separated from the main waterway in such a way that the probability of heavy damage due to a collision is negligible.
Distance to site boundary	It is expected that the distance to site boundary is of great importance for the risk outcomes. Two values will be used: 50 m and 150 m.
Ignition sources	It is assumed that no ignition sources are present within the LFL envelope on site.
Pool size	It is assumed that the size of the pool is not restricted by a bund.
Surface roughness	The Dutch default value of 300 mm is used.
Weather	Dutch average weathers with uniform distribution over wind directions.

(1) *According to the Reference Manual, delayed ignition of class 2 liquids stored at atmospheric temperature will not occur (see* Table 5*). In SAFETI-NL 6.53 delayed ignition is taken into account if a flammable cloud (concentration above the lower flammable limit) meets an ignition source or crosses the site boundary. This dissimilarity was circumvented by reducing the probability of a release by a factor 0.01 (i.e. the probability of immediate ignition) and setting the probability of immediate ignition to 1.*

Table 11 shows the results for the loading/unloading of class 1 flammable liquids to or from a ship. The distance to the IR 10^{-6}/yr contour increases from 30 m for a low flow rate to 500 m for a high flow rate. Both the location of the IR 10^{-6} contour and the location of the IR 10^{-8} contour are largely determined by the delayed ignition of the cloud following a full bore rupture of the loading arm (giving a flash fire and an explosion, see Figure 2). For the transfer of 3000 m^3 crude oil per hour, the size of the flammable cloud (distance to LFL) is calculated to be 500 m.

It needs mentioning that neither limitation of the pool size nor the presence of an automatic blocking system were considered. As a result, the maximum pool diameter was over 500 m (for a flow rate of 3000 m^3/hr). This pool size is not expected to be realistic. The effect of a limitation of the pool size is discussed in section 2.8 and Appendix A. It turns out that a reduction of the pool size leads to a considerable decrease of the distance to the IR 10^{-6} and IR 10^{-8} contours. The presence of an automatic blocking system will also reduce the size of the pool because the release duration will be limited to 120 seconds, and gives a similar decrease of risk contour distances.

For reasons of completeness, it is also mentioned that the reported jet fire effects for the leaks in the loading arm are likely to be overconservative (according to the models, the 3.6″ diameter leak in the 36″ diameter pipeline produces 1% lethality at 200 m distance). As was the case for the storage tanks, the jet fire effects are irrelevant for the location of the 10^{-6} and 10^{-8}/yr individual risk contours (the likelihood of an immediate ignition with jet fire is only 6.5%).

The consequence distances for the release of 75 m^3 and 20 m^3 from a single hull vessel are reported for reasons of completeness. As the hazard of heavy damage due to a collision is expected to be negligible (see Table 10), these two scenarios are not included in the risk calculations.

Table 12 shows the results for the loading/unloading of class 2 flammable liquids to or from a ship. The location of the IR 10^{-6}/yr contour is largely determined by the leak scenario and does not exceed 25 m. Rupture of the arm will be more important if transfer activities takes place more than 25% of the time. The IR 10^{-8}/yr contour entirely depends on the rupture scenario and has a maximum distance of 45 m in case of the transfer of 1500 m^3 K2 liquids per hour. The pool fire and thereby the size of the pool, are dominant for all risk outcomes.

Table 11 QRA results for unloading from ships or loading to ships (class 1 flammable liquids)

Flow rate	100 m^3/hr		500 m^3/hr		1500 m^3/h		3000 m^3/hr	
Distance to Site Boundary (m)	***50***	***150***	***50***	***150***	***50***	***150***	***50***	***150***
Distance to IR 10^{-6}/yr contour	30	30	220	220	320	320	460	460
- dominant scenario(s) for IR 10^{-6}/yr	B	B	A	A	A	A	A	A
Distance to IR 10^{-8}/jr contour	40	40	290	290	420	420	740	740
- dominant scenario(s) for SR	A	A	A	A	A	A	A	A
Consequence distances: (1)								
- *A: full bore rupture (un)loading arm*								
- flash fire	0 (2)	0 (2)	220	220	290	290	500	500
- explosion (0.3 barg)	-	-	250	250	320	320	540	540
- jet fire (1% leth.)	40	40	55	55	55	55	70	70
- pool fire (1% leth.)	35 (3)	35(3)	160	160	200	200	310	310
- *B: leak from (un)loading arm*								
- flash fire	0 (2)	0 (2)	55	0 (2)	110	20	320	320
- explosion (0.3 barg)	-	-	-	-	-	-	280	280
- jet fire (1% leth.)	40	40	55	55	85	85	200	200
- pool fire (1% leth.)	30 (3)	30 (3)	50	40 (3)	70	60 (3)	180	180
- *C: 75 m^3 release from vessel*								
- flash fire	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-	-	-	-	-	-
- jet fire (1% leth.)	40	40	40	40	40	40	40	40
- pool fire (1% leth.)	40 (3)	40 (3)	40 (3)	40 (3)	40 (3)	40 (3)	40 (3)	40 (3)
- *D: 20 m^3 release from vessel*								
- flash fire	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-	-	-	-	-	-
- jet fire (1% leth.)	30	30	30	30	30	30	30	30
- pool fire (1% leth.)	30 (3)	30 (3)	30 (3)	30 (3)	30 (3)	30 (3)	30 (3)	30 (3)

(1) *The reported values involve the maximum for any of the day or night weathers. Consequence distances are derived along the downwind axis. The maximum consequence distance may be larger as this can be a diagonal of a downwind and a perpendicular component. This also explains why the distance to the IR 10^{-8}/yr contour can be larger than the largest consequence distance reported in the table.*

(2) *Immediate ignition does not give a flash fire for a continuous scenario. Delayed ignition will not occur because the cloud does not reach the site boundary and no ignition sources are assumed to be present on site.*

(3) *Results for the early pool fire. Late ignition of the (full grown) pool does not occur as the vapour cloud does not reach the site boundary.*

Table 12 QRA results for unloading from ships or loading to ships (class 2 flammable liquids)

Flow rate	100 m^3/hr	500 m^3/hr	1500 m^3/h
Distance to IR 10^{-6}/yr contour	10	20	25
- dominant scenario(s) for IR 10^{-6}/yr	B	A & B	A & B
Distance to IR 10^{-8}/yr contour	30	40	45
- dominant scenario(s) for SR	A	B	A
Consequence distances: (1)			
- *A: full bore rupture (un)loading arm*			
- flash fire	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	10	10	10
- pool fire (1% leth.)	35 (3)	50 (3)	60 (3)
- *B: leak from (un)loading arm*			
- flash fire	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	10	15	15
- pool fire (1% leth.)	30 (3)	40 (3)	40 (3)
- *C: 75 m^3 release from vessel*			
- flash fire	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	10	10	10
- pool fire (1% leth.)	35 (3)	35 (3)	35 (3)
- *D: 20 m^3 release from vessel*			
- flash fire	0 (2)	0 (2)	0 (2)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	5	5	5
- pool fire (1% leth.)	30 (3)	30 (3)	30 (3)

(1) *The reported values concern the maximum value for any of the day or night weathers.*

(2) *Immediate ignition does not give a flash fire for a continuous scenario. It is assumed that delayed ignition will not occur (see* Table 5*).*

(3) *Results for the early pool fire. It is assumed that late ignition of the (full grown) pool will not occur (see* Table 5*).*

2.4 Road transportation

The risks of road transportation depend linearly on the number of road tanker movements. The requirements for Dutch QRA calculations for road transportation are given in Part 2 of the Purple Book [1] and are calculated with RBM II. The scenarios and consequences are assumed to apply to open situations, influences of objects like tunnels and noise barriers are not taken into account. Guidance on how to use RBM II for these situations is given in [5].

According to section 3.2 of Part 2 of the Purple Book, the following LOC events must be considered for road transportation with atmospheric tankers:

Table 13 Release scenarios and frequencies for a road tanker (transportation risk)

LOC event	Frequency
Release of the complete inventory (instantaneous)	15% of base frequency
Release of 5 m^3 of the inventory (instantaneous)	60% of base frequency
Release of 0.5 m^3 of the inventory (instantaneous)	25% of base frequency

The release of the total inventory of a road tanker is assumed to result in a liquid pool with a surface of 1200 m^2. The release of 5 m^3 of flammable liquid results in a pool with a surface of 300 m^2. These data are reportedly experimentally verified [6].

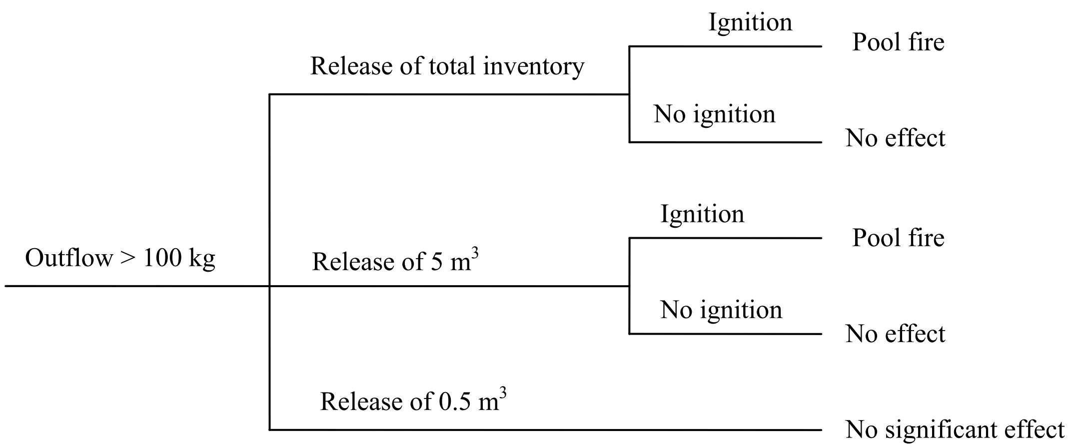


Figure 5 Event tree for a significant release of flammable liquids from a road tanker

Figure 5 shows the event tree for the release of flammable liquids (according to the guidelines). A release of more than 0.5 m^3 may ignite and give a pool fire. No other effects are considered.

Table 14 shows the probability of ignition related to Figure 5. The probability depends on the volatility of the flammable liquid. For road transportation, two classes of flammable liquids are distinguished: LF1 (flammable liquids) and LF2 (highly flammable liquids). The categorisation is derived from the international regulations for road transportation ADR [7] and rail transportation RID [8]. LF1 corresponds to ADR class 3, packing group III and is quite similar to the group of class (K2) liquids used for stationary objects. LF2 corresponds to ADR class 3, packing group II and is similar to the group of class (K1) flammable liquids. More information on the categorisation of hazardous substances for transportation related QRA is given in [9] (in Dutch).

For the highly flammable class LF2, the probability of ignition is 13% which is the sum of direct and delayed ignition. For LF1, the expected probability of immediate ignition is 1% and delayed ignition is not expected to occur.

Table 14 Ignition probabilities for a release of LF1 and LF2 flammable liquids from a road tanker

Event	Probability (%)
LF1 flammable liquids (flash point between 23 ºC and 61 ºC) (1)	
Pool fire (caused by direct ignition)	1.0
No effect	99.0
LF2 flammable liquids (flash point below 23 ºC) (1)	
Pool fire (caused by direct or delayed ignition)	13.0
No effect	87.0

The consequence distances related to the pool fires of Table 14 are reported in Table 15. The distance to 1% lethality is taken from [10] and applies to weather class D5. In RBM-II the consequences of releases of LF2 liquids (such as gasoline) are modelled with n-pentane, the consequences of releases of LF1 liquids (such as kerosene) with n-nonane. Considering that only pool fires are taken into account, the choice of substances is not very relevant for the calculation outcomes.

The consequences of the release scenarios for road tankers were studied with SAFETI-NL 6.53 in order to verify whether the assumptions of the Purple Book [1] are reasonable. The first conclusion is that the prescribed pool size (1200 m^2 for the loss of the total inventory, 300 m^2 for the loss of 5 m^3) is not based on free spreading of the liquid, but on limitations such as absorption in the ground and the presence of pot-holes, drain holes, ditches, and etcetera. The instantaneous release of the total inventory (assumed to be 25,000 kg) at ambient temperature (9 °C) gives a cloud that is flammable during 10 seconds, with a distance to LFL of 25 m. This distance is not supposed to be relevant for third party risk. The size of the flammable cloud is too small to give an explosion in a largely open environment. In other words, it is confirmed that the pool fire will be the most important effect for a release from a road tanker at ambient temperature in an open area.
Flash fire and explosion effects may be relevant for releases of LF1 or LF2 from a road tanker at elevated temperatures. Whether such a scenario is feasible will be analysed in chapter 5.

Table 15 Consequence distances for a release of LF1 and LF2 flammable liquids from a road tanker

Event	Pool size (m^2)	Pool radius (m)	Distance to 1% lethality (m)
LF1			
Pool fire (total inventory)	1200	20	68
Pool fire (5 m^3 inventory)	300	10	40
LF2			
Pool fire (total inventory)	1200	20	69
Pool fire (5 m^3 inventory)	300	10	42

2.5 Rail transportation

The risks of rail transportation depend linearly on the number of rail tanker movements. The current requirements for Dutch QRA calculations for rail transportation are given in Part 2 of the Purple Book [1] and are calculated with RBM II. The scenarios and consequences are assumed to apply to open situations, influences of objects like tunnels and noise barriers are not taken into account. Guidance on how to use RBM II for these situations is given in [5].

According to section 3.3 of Part 2 of the Purple Book, the following LOC events must be considered for rail transport:

Table 16 Release scenarios and frequencies for a rail tanker (transportation risk)

LOC event	Frequency
Rupture of a rail tanker car	40% of base frequency
Leakage from a 3” hole	60% of base frequency

The rupture of a rail tanker car is assumed to result in a liquid pool with a surface area of 600 m^2. The leakage from a 3” hole will result in a pool with a surface area of 300 m^2. These assumptions are supported by recent experiments ([11]).

Figure 6 shows the event tree for a release of flammable liquids (according to the guidelines). Table 17 lists the corresponding likelihood of each event in case a release occurs. Direct ignition and delayed ignition both lead to a pool fire (of equal size). Note as well that only one class of flammable liquids is used for the calculation of risks of rail transportation: ‘C3’. C3 mostly concerns (highly) flammable liquids with a flash point below 23 °C, and is defined by a specific set of UN numbers. See [9] (in Dutch) for more information.

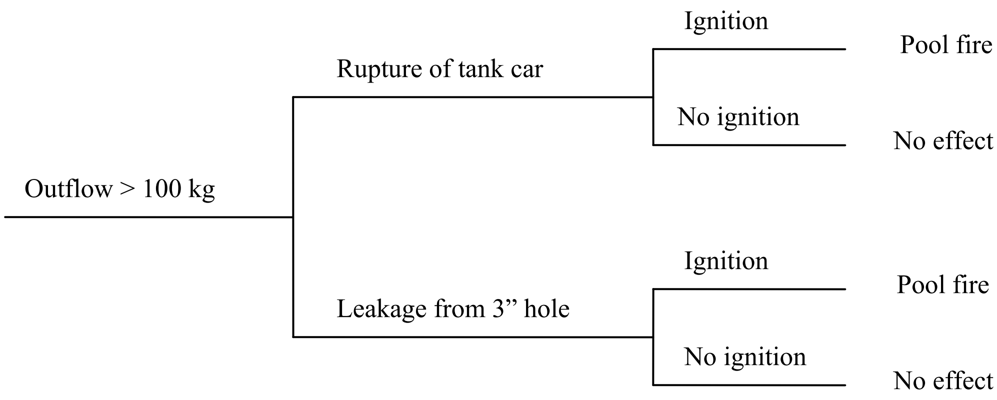


Figure 6 Event tree for a significant release of flammable liquids from a rail tanker

Table 17 Ignition probabilities for a release of C3 flammable liquids from a rail tanker

Event	Probability (%)
C3 flammable liquids (1)	
(direct or delayed) ignition resulting in pool fire	25
no ignition	75

In Table 18 the consequences of the ignition events of Table 17 are listed. The distance to 1% lethality is taken from [10] and applies to weather class D5. In RBM-II the consequences of releases of C3 flammable liquids are modelled with n-pentane.

Table 18 Consequence distances for a release of C3 flammable liquids from a rail tanker

Event	Pool size (m^2)	Pool radius (m)	Distance to 1% lethality (m)
LF1			
Pool fire (rupture of rail tanker)	600	14	49
Pool fire (leakage from a 3” hole)	300	10	41

Again, the relevant scenarios (Table 16) are put in SAFETI-NL in order to test if the assumptions of the Purple Book [1] are reasonable. The conclusions are similar to the conclusions for road tankers. The assumed pool size (600 m^2 for the rupture of the tanker, 300 m^2 for the leak from a 3” hole) is not based on free spreading of the liquid, but on limitations such as absorption in the ground, and the presence of pot-holes, drain holes, ditches, and etcetera. The rupture of the rail tanker at ambient temperature (9 °C) in an open environment does not give a flammable cloud that is relevant for third party risk and in a largely open area it will not give an explosion either.
In chapter 5 it will be analysed if releases of C3 flammable liquid from rail tankers at elevated temperatures occur.

2.6 Inland waterway transport

The risks of waterway transport depend strongly on waterway characteristics. The requirements for Dutch QRA calculations for waterway transport are given in Part 2 of the Purple Book [1] and are calculated with RBM II. According to section 3.4 of Part 2 of the Purple Book, the instant failure of a ship or tanker is not taken into account. Only one type of scenario needs to be considered, which is damage to the liquid tanker due to a collision. Table 19 and Table 20 give the probabilities for scenarios with single hull liquid tankers. Table 21 shows the consequence distances.

Table 19 Release scenarios and frequencies for a single hull liquid tanker

Continuous release	Frequency
Release of 30 m^3 in 30 min.	20% of probability of heavy damage
Release of 75 m^3 in 30 min.	10% of probability of heavy damage
No significant release	70% of probability of heavy damage

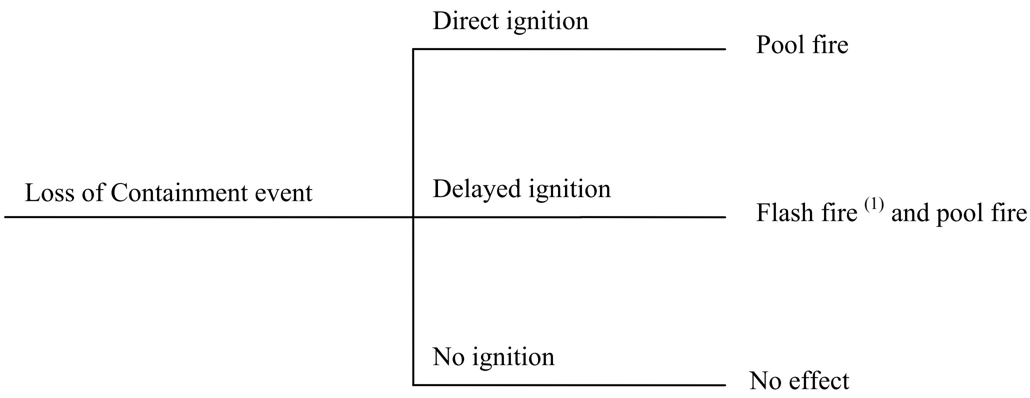
Table 20 Ignition probabilities for inland waterway transport

Substance	Ignition probability (%)		
	Direct	*Delayed*	*No ignition*
LF1	1.0	0.0	99
LF2	6.5	6.5	87

Table 21 Consequence distances for a release of LF1 and LF2 flammable liquids from a single hull vessel

Event	Distance to 1% lethality (m)
LF1	
Pool fire (release of 75 m^3 in 30 min.)	37
Pool fire (release of 30 m^3 in 30 min.)	30

The event tree for the release of flammable liquids is outlined in Figure 7. Note that an explosion is not expected as vapour clouds are supposed not to be enclosed on waterways.



(1) *As there is no flammable cloud beyond the vaporising pool, flash fire effects are irrelevant and flash fire calculations are left out in RBM II.*

Figure 7 Event tree for a release of flammable liquids from a single hull vessel

The release of flammable liquid will result in a floating pool on water. The width of the pool is generally constrained by the width of the canal. The calculated distance to 1% lethality will depend strongly on the assumed width of the canal, and is therefore not reported (nor verified).

2.7 Pipeline transport (underground)

Various substances are transported via a pipeline, most of them being fluids or liquefied gasses. The requirements for Dutch QRA calculations for pipeline transport are given in Part 2 of the Purple Book [1]. According to section 3.5, two types of scenarios are possible, rupture of the pipe and leak from the pipe (Table 22). The probabilities of these events depend on the type of pipeline.

Table 22 Release scenarios and frequencies for an underground pipeline

LOC event	Probability (/km /yr)		
	Line located in a pipe bay	*NEN 3650-line*	*All other pipelines*
Rupture of the pipeline	7×10^{-6}	1.5×10^{-4}	5×10^{-4}
Leakage from a 20 mm hole	6.3×10^{-5}	4.6×10^{-4}	1.5×10^{-3}

According to [1] an LOC event for a pipeline may in general result in a jet fire, a fireball, a pool fire, a flash fire or an explosion. The guidelines do not specify which consequences must be considered specifically for flammable liquids, nor do the guidelines specify the probability of those consequences. This information is therefore taken from a recent RIVM study on the risks of pipeline transportation of flammable liquids ([12]).

Figure 8 shows the event tree for the release of flammable liquids out of a pipeline while Table 23 lists the related probabilities. Note that a release of class 1 (L1) flammable liquids (flash point below 21 ºC) is assumed to ignite in all cases, while for the release of class 2 (K2) flammable liquids (flash point between 21 ºC and 55 ºC) only direct ignition is taken into account (with a probability of 1%).

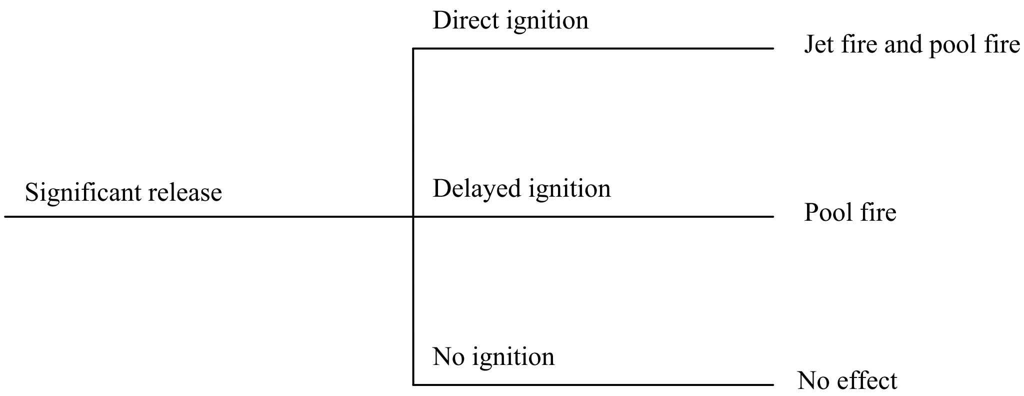


Figure 8 Event tree for a significant release of flammable liquids from a pipeline

Table 23 Ignition probabilities for an underground pipeline

Time of ignition	Event	Probability (%)
K1 flammable liquids (flash point between 0 ºC and 21 ºC)		
Direct ignition	Jet fire and pool fire	6.5
Delayed ignition	Pool fire	93.5
No ignition	No effect	0.0
K2 flammable liquids (flash point between 21 ºC and 55 ºC)		
Direct ignition	Jet fire and pool fire	1.0
No ignition	No effect	99.0

As the risks of releases from underground pipelines have recently been studied in detail in [12], they are not recalculated in the scope of the current project. Instead, the results of [12] are reproduced in Table 22. The outcomes are likely to be implemented in new (Dutch) legislation. In [12] n-octane is used as an exemplary substance for K1 flammable liquids and n-nonane for K2 flammable liquids. It is further assumed that only the initial vertical spray release (fountain) is relevant for the size of the pool. The residual liquid outflow is assumed to give underground soil contamination but no to increase the size of the aboveground pool.

Table 24 Consequence and risk data for underground pipelines

Pipe diameter (inch)	8	12	16	24	28	30	34	36
K1 flammable liquids (flash point between 0 ºC and 21 ºC)								
Maximum pool radius (m)	6	9	12	19	22	23	27	28
Distance to IR 10^{-6}/year (m)	8	11	13	19	22	24	27	29
Distance to IR 10^{-8}/year (m)	20	20	23	26	31	33	37	39
K2 flammable liquids (flash point between 21 ºC and 55 ºC)								
Maximum pool radius (m)	16	23	31	46	n.a.	n.a.	n.a.	n.a.
Distance to IR 10^{-6}/year (m)	-	-	-	-	n.a.	n.a.	n.a.	n.a.
Distance to IR 10^{-8}/year (m)	12	17	22	33	n.a.	n.a.	n.a.	n.a.

n.a. = not available (individual risk below 10^{-8}/year)

2.8 Various modelling aspects

In the SAFETI-NL calculations, many parameter values are fixed. In order to determine the sensitivity of the results to the parameter settings, several test calculations are carried out. These calculations are described in more detail in Appendix A. The conclusions from the sensitivity calculations are:

- SAFETI-NL models a jet fire in case of a ten minute release. From the sensitivity analysis, it is concluded that the jet fire is not important for the location of the IR 10^{-6} and 10^{-8}/yr contours.
- Following an instantaneous release, the location of the pool is not centred around the tank, but displaced downwind. The sensitivity analysis showed that the displacement of the pool is not important for the location of the IR 10^{-6} and 10^{-8}/yr contours.
- According to the guidelines the true tank head should be used in the risk calculations. The sensitivity analysis showed that this is a significant parameter for the location of the IR 10^{-6} and 10^{-8}/yr contours. Furthermore, the dispersion and evaporation of the product during the first 10 seconds is considered to be physically unrealistic if the true tank head is used (as required by the prevailing guidelines).
- According to the Dutch requirements for risk calculations, the size of the pool should not be restricted for releases outside bunds. Instead, free spreading on a horizontal surface is assumed, with a minimum pool depth of 10 mm. For loading activities, the calculated pool size may get unrealistically large if the release duration is 30 minutes. As shown in Appendix A, the location of the IR 10^{-6} and 10^{-8} contours is sensitive to the size of the pool.

Another important parameter is the substance that is used to calculate the risk for mixtures. In Appendix B it is investigated to what extend outcomes change if consequences are calculated with a winter grade gasoline mixture rather than with pure components n-hexane and n-pentane. Since

SAFETI-NL is not able to model mixtures correctly, the ‘multi-component’ option of SAFETI-Professional was used for this exercise.

Table B.1 gives an overview of all relevant outcomes for the mixture, and for n-hexane and n-pentane. It shows that the calculated evaporation of the winter grade gasoline mixture is significantly higher than the calculated evaporation of n-hexane. This finding applies both to evaporation prior to rainout and pool evaporation. The calculated consequence distances increase accordingly. Consequence and risk distances for n-pentane on the other hand, are significantly larger than those for the winter grade gasoline mixture. Both observations can be explained in terms of the volatility of the products (see Appendix B, Table B.2).

The comparison with real consequence distances is made in chapter 6.

2.9 Conclusions

Stationary installations – K1
For a single storage tank containing class 1 (K1) flammable liquids the distance to the IR 10^{-6}/yr contour varies from 10 to 580 m. The dominant scenario is the instantaneous release of the entire contents of the tank, in particular the late ignition of the corresponding flammable cloud (resulting in a vapour cloud fire or a vapour cloud explosion).

Transfer – K1
For transfer of class 1 (K1) flammable liquids the distance to the IR 10^{-6}/yr contour varies from 30 to 460 m. This distance is very sensitive to the size of the pool. The distance can be reduced considerably if an automatic blocking system is present and/or an upper bound is set on the size of the pool. The dominant scenario is the rupture of a loading arm. Again, late ignition of the cloud (resulting in a vapour cloud fire or a vapour cloud explosion) is most important. The consequence distances of the vapour cloud fire and the vapour cloud explosion are in the same order of magnitude.

Stationary installations – K2
For a single storage tank containing class 2 (K2) flammable liquids at a temperature below its flash point, an IR 10^{-6}/yr contour does not occur. According to the guidelines, delayed ignition of the cloud does not need to be considered. The overall risk for storage of class 2 flammable liquids is thereby dominated by the pool fire following immediate ignition.

Transfer - K2
For transfer of class 2 (K2) flammable liquids the distance to the IR 10^{-6}/yr contour varies from 10 to 25 m. Due to the low probability of immediate ignition (for K2 liquids), the dominant scenario in this case is a leak from a loading arm. An explosion is not expected to occur for incidents during the transfer of K2 products.

Transportation (LF1, LF2, C3)
The guideline [1] only considers pool fires for accidents during the transportation of flammable liquids. This assumption is valid if the released flammable liquids are at ambient temperature and pressure. It may not be valid if the temperature at the time of release is significantly higher than ambient, as can be the case for the rupture of a rail tanker in a pool fire (see section 5.5).

Modelling aspects (SAFETI-NL)
The sensitivity study of Appendix A showed that calculation outcomes were very sensitive to the value that was used for the tank head. The current guidelines prescribe that the real liquid head should be used. However, the analysis made clear that the corresponding behaviour of the product during the first ten seconds, is physically unrealistic. The modelled behaviour gets more realistic if a reduced value for the tank head is used for input (ultimately 0 m).

The comparison in Appendix B showed that the use of n-hexane leads to relatively small consequence and risk outcomes. Calculated distances increase if a winter grade gasoline mixture is used and increase further if n-pentane is used. This can be explained by the increasing volatility of these products.

Appendix A also showed that the maximum pool size is relevant for the outcomes and that the calculated maximum pool size is larger than is expected for terrains with obstacles, ridges, irregularities and drainage systems.

A comparison between calculated consequence distances and reported (real) distances is made in chapter 6.

3 Analysis of existing QRA calculations

3.1 Introduction

The second step in the evaluation of the Dutch QRA directives for storage and transport of flammable liquids is to analyse existing QRA calculations and to see to what extent they differ from the calculations presented in chapter 2 (calculations in accordance with the '*Handleiding risicoberekeningen BEVI*' [2], prescribed since January 2008). In order to obtain a good picture of existing QRA calculations, seven QRAs from different competent authorities are discussed.

The information is primarily retrieved from the QRA documentation. If a safety report was available and contained relevant additional information, this information was used as well. It has to be mentioned that the latest version of a safety report was not always available when the investigation was carried out (summer 2007).

3.2 Selected companies

The QRAs of the following oil storing companies were selected, based on the amount of flammable liquids stored, activities and competent authority.

Table 25 Selected facilities for QRA inventory

	Company	Competent Authority	Year
1	Vopak Terminal Europoort	Province of Zuid-Holland/ DCMR	2006
2	Nerefco Europoort	Province of Zuid-Holland/ DCMR	2001
3	Shell NL Raffinaderij Pernis	Province of Zuid-Holland/ DCMR	2006
4	Esso Raffinaderij Rotterdam	Province of Zuid-Holland/ DCMR	2003
5	Oiltanking Amsterdam	Province of Noord-Holland	2004
6	Rotterdam-Rijn Pijpleiding Mij.	Province of Limburg	2006
7	Van der Sluijs Tankopslag Geertruidenberg	Province of Noord-Brabant	2004

3.3 Set-up

In order to obtain a clear picture of the content of the QRAs a list of questions was formulated. The questions take notice of the type of installation, type of consequence, quantification of the consequences and some other model parameters. Class 2 (K2) flammable liquids were not considered separately because most storage tanks may contain either K1 or K2 liquids, in which case K1 is used in the QRA (worst-case calculation).

3.4 Results

The results of the inventory are listed in Table 26 and Table 27.

Table 26 General results for highly flammable liquids (class 1 and class 2)

	Total
Atmospheric tanks accounted for in QRA?	
Yes	7
No (not necessary according to 'sub selection')	
No (other reasons)	
Not clear/not reported	
Consequences for atmospheric storage tanks include:	
Pool fire only	1
Pool fire and flash fire	3
Pool fire, flash fire and explosion	
Other:	
Not clear/not reported	3
Max. consequence distances for atmospheric storage tanks:	
Less than 50 m from bund	
50 - 100 m from bund	1
100 - 200 m from bund	1
More than 200 m from bund	3
Not clear/not reported	2
Loading activities accounted for in QRA?	
Yes	5
No (not necessary according to 'sub selection')	1
No (other reasons)	1
Not clear/not reported	
Consequences for loading / unloading activities include:	
Pool fire only	1
Pool fire and flash fire	3
Pool fire, flash fire and explosion	
Other:	
Not clear/not reported	1
Max. consequence distances for loading/unloading activities	
Less than 50 m from bund	1
50 - 100 m from bund	
100 - 200 m from bund	2
More than 200 m from bund	1
Not clear/not reported	1

Discharge and dispersion calculations modelled with:	
True mixture	1
n-hexane	1
Other (mixture of octane, hexane and butane)	1
Not reported	5

Table 27 Other results from QRA survey

	Total
Individual Risk: delayed ignition modelled with:	
Realistic ignition sources	1
Free field approach	
Not reported	6
Software used for the QRA calculations (1):	
SAFETI (including SAFETI Micro)	3
SAVE II	4
Effects	1

(1) One company used two types of software for the QRA calculations.

3.5 Conclusions

- All analysed QRAs describe the use of class 1 (K1) flammable liquids while for several reasons class 2 (K2) flammable liquids are not considered separately. These reasons include the absence of K2 liquids, the incorporation of K2 liquids with K1 liquids and/or the fact that K2 liquids do not pass the subselection.
- In all cases atmospheric tanks are considered and in five out of seven cases loading activities are considered as well.
- Pool fires and/or flash fires are often not explicitly mentioned in the QRA. None of the QRAs explicitly mention or consider explosions as a possible consequence.
- The reported consequence distances for atmospheric tanks vary from 50 to more than 200 m from the bund. For loading activities roughly the same distances are found.
- The majority of the QRAs are not transparent with respect to the modelling parameters and ignition sources.
- The results are comparable with those from the benchmark studies for QRA calculations [3].

4 Analysis of reported LOC events and consequences

4.1 Introduction

According to the Dutch implementation of the SEVESO II directive, companies that store or produce certain minimum amounts of dangerous goods must write a safety report. A quantitative risk analysis (QRA) is a required part of it in which predefined scenarios are taken into account. These scenarios include the largest types of accidents possible in terms of leakage, rupture and consequence. For several reasons, other types of scenarios are described as well in safety reports besides the QRA scenarios. Installation scenarios for example, are obligatory in order to prove that a company has taken adequate precautions for preventing loss of containment. It is believed that installation scenarios are more likely to occur then QRA scenarios. The corresponding consequences are much smaller. Other scenarios which are described in safety reports are scenarios for the fire department and they are used to determine the requirements for the company's fire brigade.

In this chapter an inventory is given of the installation scenarios described in the safety reports of the seven selected oil storing companies (see Table 25). Scenarios for the fire department were not taken into account because they originate from the installation scenarios and therefore don't provide extra information.

4.2 Set-up

The survey of installation scenarios is divided in three categories: scenarios for releases from storage tanks, scenarios for releases during transshipment and scenarios for releases from pipework. Since a variety of incidents may take place, the incidents are classified in 22 types of releases (Table 28). Scenarios dealing with rail tankers and vapour recovery units were not considered.

4.3 Results

Six safety reports were available and analysed and only three of these contained installation scenarios (the remaining safety reports only give a set of preventive and repressive LODs). The analysis has resulted in a survey of 47 installation scenarios in which the occurrence of releases from storage tanks, releases during transshipment and releases from pipework, roughly is 3 : 2 : 1 (Table 29). These scenarios are condensed into a set of 22 distinct scenarios, but it has to be mentioned that the extent to which the scenarios are described varies considerably. Due to different assumptions or expert judgements similar scenarios may show different consequences.

Table 28 List of installation scenarios per category

	Description		Description
	Atmospheric storage tanks		**Transshipment**
A	Leak from base	Q	Rupture hose/arm
B	Leak from bund	R	Leak hose/arm
C	Leak from drain	S	Overfill
D	Leak from tank	T	Hole in ship
E	Leak from weld	U	Other
F	Overfill		
I	Release in pumping station		**Pipework**
J	Release of vapour	G	Pipe failure
K	Roof collapse	H	Pipeline leak
L	Tank explosion/rupture/fire	X	Leak pipe
M	External impact	Y	Rupture pipe
N	Rimfire	Z	Other

With respect to the quantitative description of the consequences it seems that the maximum consequences with respect to heat radiation are in the same order of magnitude as those for overpressure. The word 'seems' is used because the consequences as described in the safety reports are not transparent (unknown weather conditions, the use of units deviating from the norm or consequences that could not clearly be attributed to either heat radiation or over pressure). This can be explained by the fact that detailed guidelines for the contents of safety reports were not published until December 2006.

An inventory of the consequences of the installation scenarios in terms of leakage, fire and explosion is made as well. The results are depicted in Figure 9. The majority of the consequences of the 47 installation scenarios are classified as leakage without ignition (27), whereas 18 are classified as fires and only 2 would result in an explosion. From these results it can be concluded that explosion scenarios are not considered to be plausible within oil storing facilities although the reason is not reported.

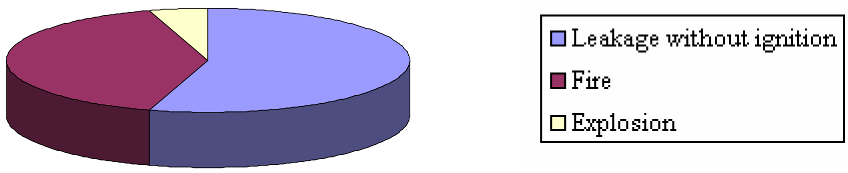


Figure 9 Occurrence of consequences in safety reports

Table 29 Reported installation scenarios and their consequences (based on three safety reports)

	Description	Amount	Maximum consequence
Storage tanks			
A	Leak from base	1	Soil contamination
B	Leak from bund	-	-
C	Leak from drain	1	Nil
D	Leak from tank	5	50 m (1)
E	Leak from weld	2	50 m (12.5 kW/m^2) (2)
F	Overfill	2	100 m (1)
I	Release in pumping station	-	-
J	Release of vapour	2	90 m (0.01 bar)
K	Roof collapse	3	100 m (12.5 kW/m^2), 100 m (0.3 bar)
L	Tank explosion/rupture/fire	5	100 m (3 kW/m^2)
M	External impact	-	-
N	Rimfire	2	Restricted to tank
	Subtotal	**23**	
Transshipment			
Q	Rupture hose/arm	5	300 m (0.1 bar)
R	Leak hose/arm	6	250 m (3 kW/m^2)
S	Overfill	1	Harbour contamination
T	Hole in ship	3	100 m (1)
U	Other	2	50 m (0.1 bar)
	Subtotal	**17**	
Pipework			
G	Pipe failure	2	65 m (3 kW/m^2)
H	Pipeline leak	1	Soil contamination
X	Leak pipe	3	60 m (1)
Y	Rupture pipe	1	None
Z	Other	-	-
	Subtotal	**7**	
	Total	**47**	

(1) *It was not clear whether the reported consequence was related to overpressure or heat radiation.*

(2) *Normally the heat radiation contour is described as 3 or 10 kW/m^2. This implies that the maximum consequences for the corresponding scenarios are in fact larger than stated.*

4.4 Conclusions

- The quantity and quality of the examined installation scenarios vary considerably.
- The selected installation scenarios show a ratio 3 : 2 : 1 for releases from tanks, releases during transshipment and releases from pipework.
- The events that are most frequently reported in the safety reports are leak from a tank, tank explosion / -rupture/ -fire and leak / rupture of a hose or arm. Overfill is mentioned three times (in a total of 47 reported events).
- The maximum reported consequence distance involving heat radiation is in the same order of magnitude as the maximum reported consequence distance for overpressure effects.

The majority of the scenarios involve leakage without ignition and to a lesser extent fire. Only two explosion scenarios were found.

5 Literature and accident database review

5.1 Introduction

In this chapter the results of a literature and incident database survey are reported. The aim of the survey was to discover which accidents may occur and at which distances they are likely to have consequences. The focus was on incidents that occurred within establishments. A distinction is made between fixed equipment (storage tanks and pipelines) and transport units (road and rail tankers and tanker ships). Accidents with flammable liquids in tunnels are not addressed in this study and the conclusions drawn in this chapter do not pertain to this type of accidents.

The survey was carried out in 2007 and 2008, with minor additional work in 2009.

5.2 Accident database analysis

5.2.1 Introduction

Three accident databases were examined. Results from the inventory of the Major Accident Reporting System (MARS) and TNOs FACTS database are reported. MARS is initiated and owned by the Major Accidents and Hazards Bureau of the EU Joint Research Centre. It exclusively handles incidents at SEVESO II sites. FACTS is owned by TNO and contains information on more than 22000 incidents worldwide.

The Hint databases from the Finnish engineering company ility Engineering was helpful to obtain a general idea of the various incidents that occur with flammable liquids. Many incidents, in particular dealing with transportation, are recorded but the overall quality of the accident descriptions was not good enough for drawing conclusions.

The French database ARIA was consulted for a few specific incidents but no detailed analysis of incidents reported in ARIA was carried out.

5.2.2 MARS database

The latest version of the MARS database (July 2004) contains 572 reported incidents, dating from the early 1980s until 2004. The majority of the reported incidents involves the period 1995-2003.

5.2.2.1 MARS incidents labelled as 'storage'

A query was carried out for substances classified as 'flammable' and/or 'explosive' and incident sources classified as 'storage'. Twenty two of these were considered relevant (large scale storage of atmospheric oil and petroleum products). Two more incidents from the analysis for transfer incidents (see hereafter) were included as their release location was in the storage area. The total number of MARS incidents related to storage of flammable liquids is therefore twenty four.

Table 30 Cause, consequences and damage for storage-related incidents (MARS data)

Cause	Primary consequence	Damage
Corrosion <Co, 3 incidents>	Minor releases were reported.	No ignitions reported. (in case of ignition pool fires are expected)
Defective equipment <DE, 3 incidents>	The defective pump gave a vapour cloud explosion. A jammed floating roof led to a tank roof fire.	Both a vapour cloud explosion and a tank explosion may have off site consequences (see M&C and OE).
Maintenance works and cleaning operations <M&C, 12 incidents>	About half of these incidents involve tank explosions. The other incidents concern releases from valves and pipes (some substantial, most minor).	Tank explosions gave heavy damage on site, and in one case damage off site [(1)]. One defect in a pumping station gave ignition of a vapour cloud with substantial damage off site [(2)]. Three fires caused limited damage and one release was not ignited.
Overfill error (defective level gauges or human error) <OE, 3 incidents>	One incident gave considerable damage off site [(3)]. Two other releases did not ignite.	The size of the flammable cloud, and the corresponding consequences can be substantial. Damage off site is possible.
Unknown <Un, 3 incidents>	At least one of these releases gave considerable damage off site [(4)].	Depending on the LOC scenario.

(1) *See incident IT/1987/001 in Appendix 5A for further details.*
(2) *See FR/1987/001.*
(3) *See IT/1985/003.*
(4) *See FR/1991/003.*

A summary of the data is given in Table 30. More detailed descriptions are shown in Table C.1 (Appendix C). The most important observations are:

- The general trend is that most reported incidents had an ignition and caused considerable damage on site, either as a result of overpressures or of rocketing tank parts. This is tightly related to the criteria for reporting incidents in MARS (incidents with injuries or considerable damage). Three incidents caused considerable damage off site (IT/1985/003, IT/1987/001 and FR/1991/001) and one caused minor damage off site (FR/1987/001). Accident reports of IT/1985/001 and FR/1991/001 were found in literature and are discussed in detail in section 5.3.
- Most incidents related to storage (twelve cases out of twenty four) involved maintenance operations (including the erroneous application of welds and blinds and errors from cleaning operations). Ignition of vapours inside the tank led to tank explosions, rocketing tank roofs and (heavy) damage on site and in the vicinity of the sites. Minor releases led to localised flash and pool fires.
- Three incidents were caused by equipment failure. A defective pump led to considerable damage on site. A roof collapse of a naphtha tank lead to a full surface roof fire, but further

escalation was prevented. A leakage from a defective hose between a pump and a pipeline had no ignition.

- Three overfill incidents were reported. One gave considerable damage off site. Two other incidents did not ignite.
- Corrosion was the cause of three incidents. Each time it resulted in a minor release that didn't ignite.
- For three incidents the cause could not be retrieved from the MARS data. A pipe failure at a Greek oil terminal in 1986 apparently caused substantial damage on site, but more details were not available. A leak from a pipeline (FR/1991/001) caused heavy damage on and off site and is discussed in more detail in section 5.3. The apparent tank farm explosion in Spain, 2003, has not yet been reported in substantial detail.

5.2.2.2 Mars incidents labelled as 'transfer'

A query was carried out for substances classified as 'flammable' and/or 'explosive' and incident sources classified as 'transfer'. Ten were considered relevant (viz leakages from pipelines or transport units involving atmospheric oil and petroleum products), of which two were reclassified as storage related incidents (see previous section). A summary of the remaining 8 incidents is given in Table 31. More detailed results are listed in Table C.2 (Appendix C).

Worth noticing is that all but one incident involved transfer to or from ships. Apparently incidents during the transfer to or from road or rail tankers usually do not lead to incidents worth reporting in the MARS database. Five out of eight incidents had ignition, four of them with local effects only (pool fire or local flash fire). For two incidents minor or major explosion effects were reported (DE/1986/003 and GR/1989/001).

Table 31 Cause, consequence and damage for incidents near transfer point (MARS data)

Cause	Primary consequence	Damage
Fire on board of ship <FoB, 2 incidents>	Both incidents led to an explosion of a ship's compartment.	In both cases the ship was destroyed. The available information is insufficient to estimate consequence distances.
Operational errors <OE, 3 incidents>	Release from open valves in transfer line and pipe manifold.	Comparable to rupture of loading arm.
Collision and impact <C&I, 3 incidents>	Rupture of (un)loading arms	Not enough data (flash fire and pool fires reported).

5.2.3 FACTS 2008 database

TNOs FACTS 2008 database (update May 2008) contained 22662 incidents. The following filters were used:

- only incidents described in substantial detail (four or five stars)
- only incidents involving common liquid hydrocarbon products, such as crude oil, gasoline, kerosene, jet fuel, gasoil, methanol, ethanol, pentane, hexane, octane, etcetera.

– only if the activity is labelled ‘storage’, ‘transshipment’, ‘road transportation’, ‘rail transportation’ or ‘marine navigation’ (marine or inland).

With the criteria above 160 incidents were selected. The reports for these incidents were analysed and - when appropriate - incorporated in the literature review (section 5.3) and Appendix C and D.

5.3 Literature review

5.3.1 Sources

The following sources have been used for the literature review:

- References in known literature about the Buncefield incident.
- A query carried out by the RIVM library. In this query journal articles have been analysed that appeared in 7000 most commonly used scientific journals between 1997 (being the first year accounted for by the database) and 2007. The journals include the Journal of Loss Prevention in the Process Industries, the Journal of Hazardous Materials, the Oil and Gas Journal, Process Safety and Environmental Protection and Process Safety Management. The title or summary should contain at least one term of each of the following categories:
  - fire / fires / explosion / explosions / accident / accidents / incident / incidents
  - oil / oils / gasoline / kerosene / diesel / flammable liquid / flammable liquids
  - refinery / storage / depot / depots / tank / tanks

  The query resulted in 282 titles, of which 15 were considered to be of considerable interest for the literature review.
- Consultation of RIVM/CEV’s ‘literature signalling profiles’, that appear once every three months. Four profiles were consulted, namely ‘transport risks’, ‘fire and flammables’, ‘explosions’ and ‘chemical accidents’.

Articles on incidents involving the release of flammable liquids resulting in an explosion of a vapour cloud were selected for further study.

Some relevant incidents found in the FACTS database [13] or Aria database [14] are also added to this paragraph.

As in the previous section, a distinction is made between incidents related to storage and pipework and incidents related to transport units (road tankers, rail tankers and ships).

5.3.2 Literature and database survey for storage tanks and pipework

5.3.2.1 Incidents involving storage tanks and pipework

Nine incidents in the literature involved explosions on industrial sites related to storage or transfer of class 1 (K1) and class 2 (K2) flammable liquids at ambient temperatures. Incidents related to process or refinery operations were excluded.

i. Houston, Texas USA, 1962; explosion after a leak from a storage tank, probably due to overfilling gasoline. Few details available. (source: [15])

ii. Philadelphia, Pennsylvania USA, 1975; explosion following overfilling of a storage tank involving crude oil. (source: [16] and [13])
iii. Shuaiba, Kuwait, 1981; explosion, probably due to a naphtha leak from a pipe rack in a bund, resulting in a 'tank farm fire'. (source: [16] and [13])
iv. Newark, New Jersey USA, 1983; heavy explosion following overfilling of a storage tank. with unleaded gasoline (source: [15] and [16])
v. Naples, Italy, 1985; heavy explosion following overfilling of a storage tank with unleaded gasoline. (source: [15] and [16])
vi. Saint Herblain, France, 1991; heavy explosion following leakage of gasoline from a pipeline. (source: [15])
vii. Jacksonville, Florida USA, 1993; heavy explosion after overfilling a storage tank with unleaded gasoline (source: [15])
viii. Leam Chabang, Thailand, 1999; heavy explosion after overfilling a gasoline storage tank (source: [15] and [16])
ix. Buncefield - Hemel Hempstead, England, 2005; heavy explosion after overfilling a gasoline storage tank (source: [15])

Seven incidents were caused by overfilling and two were caused by spills from pipelines. Eight incidents involved class 1 flammable liquids, whereas only one incident involved class 2 flammable liquids.

The analysis of the FACTS database ([13]) gave results comparable to the study of the MARS data and the literature. The most noteworthy incident found in FACTS (and not yet mentioned above) is a vapour cloud explosion following overfilling of a gasoline storage tank:

x. An overfill incident involving a 200 m^3 tank in Roosendaal, the Netherlands in 1975 reportedly led to window breakage at 900 m. (source: [13])

Of further relevance of the query in FACTS are two ruptures of crude oil storage tanks. The first (France, 2007) is described as a breach in a 13,500 m^3 storage tank. The sudden release caused a tidal wave and bund overtopping with significant environmental damage. The second rupture (Antwerp, Belgium, 2005) involved a 40,000 m^3 tank affected by corrosion at the foundation. After a short period of increasing outflow, almost 37,000 m^3 was released in about 15 minutes. A tidal wave occurred and some bund overtopping was reported. Both incidents had no ignition.

In 2009 at least two more incidents with possible relevance occurred, namely at the Caribbean Petroleum Corporation in San Juan, Puerto Rico, USA (23 October 2009) and at the IOC oil depot in Jaipur, India (29 October 2009). It was not possible to analyse these incidents within the scope of the current project.

5.3.2.2 Causes and consequences of incidents involving storage tanks and nearby pipework

Several publications in the literature were found that proved relevant for the current investigation. A summary of the most relevant publications is provided in Appendix D. Of specific interest were *A study of tank fire incidents* by Chang and Lin [17], *Tank Fires – Review of fire incidents 1951-2003* by Persson and Lönnermark [18], *Large property damage losses in the hydrocarbon* *chemical industries* by Marsh Risk Consulting [16] and *Analysis and control of major accidents from the intermediate temporary storage of dangerous substances in marshalling yards and port areas* by Christou [20].

Table 32 Causes and consequences for on site incidents with possible off site damage (excluding transport units)

Cause	Primary consequence	Damage
Vapours ignited by lightning [(1)]	Explosion within tank, rocketing tank parts, release of (burning) liquid in bund.	Tank parts may travel up to two kilometres. The likelihood of being hit is small. Off site structural damage from overpressure is exceptional. Secondary explosions may occur if other installations are affected by the fire (as in a tank farm fire).
Maintenance on tanks (including cleaning)	Explosion within tank, rocketing tank parts, release of (burning) liquid in bund.	Tank parts may travel up to two kilometres. The likelihood of being hit is small. Off site structural damage from overpressures is exceptional. Secondary explosions may occur if other installations are affected by the fire (as in a tank farm fire).
Maintenance on pipes	If the release occurs during maintenance operations, the release will either be ignited (resulting in a localised jet fire and/or pool fire) or blocked. If the release occurs after maintenance, the release duration can be significant if signalling fails. The effects will then be equal to those of pipe rupture or leakage (see below).	A release during maintenance operations will only have consequences on site. A release after maintenance operations may have off site consequences (flash fire and/or vapour cloud explosion) similar to pipe rupture.
Overfilling of tank (operator error and/or instrument failure)	Early ignition is unlikely. If signalling fails a large flammable cloud can be formed, which may ignite.	A large vapour cloud can be formed. If ignited, significant overpressures can be generated under unfortunate circumstances.
Pipe rupture or leakage	Early ignition is unlikely. If signalling fails a large flammable cloud can be formed, which may ignite.	If signalling fails a large vapour cloud can be formed. If ignited, significant overpressures can be generated under unfortunate circumstances.
Tank rupture or fissure	(2)	(2)

(1) *It is noted that lightning usually is not the primary cause of release, only an ignition source for vapours that were present prior to the lightning stroke. It is further noted that lightning incidents are less likely to occur in western Europe than in the USA and South-East Asia. Firstly, the southern states in the USA and the South-East Asia region are both notorious for the frequent and violent thunderstorms. Secondly, codes and standards differ. Open roof floating top storage tanks are applied more often in the US.*

(2) *Two tank ruptures were found in the FACTS database. Both had no ignition. It may be that probability of ignition is low in general (such that damage is usually limited to the tank and its surroundings), but this cannot be stated with sufficient certainty. According to [17] the consequences are usually limited to the bund surrounding the tank, but this conclusion is based on just a few cases. One incident description of a tank rupture incident was found through other ways ([19]). No ignition occurred.*

According to [17] the most frequent cause of incidents with oil and gasoline products involving storage tanks or pipeline transportation is lightning strokes, followed by maintenance works and operator errors. In the list from the previous section however, seven incidents were caused by overfill errors and two incidents by pipe rupture. Obviously, there is a discrepancy between the most frequent incidents and the incidents with significant damage.
(Note 1: lightning is usually not the primary cause of a release but merely the ignition source)
(Note 2: overfill errors is used as a general term and may be caused by defective equipment, by operator errors or a combination of the two. Pipe rupture may be caused by defective equipment, by errors during maintenance work or by external impacts)

None of the information sources reported the magnitude of consequence distances for the different types of incidents. Indeed consequence distances depend highly on specific incident parameters, such as tank size, orifice size, release duration, and etcetera. From [18] it may be deduced that tank explosions (ignition of vapours by lightning strokes or during maintenance works) primarily lead to rocketing tank roofs and tank accessories. After the rupture of the vessel, burning liquid flows into the bund and may cause escalations such as secondary explosions of nearby tanks and fire propagation to other bunds. Releases caused by overfilling and pipe rupture have a small probability of ignition in an early stage. However, if ignition occurs in a later stage, the consequences can be significant due to the large volume of the cloud.

Of particular interest is the fact that the majority of the 31 incidents reported in [18] had ignition prior to the (substantial) release of flammable liquid (for example ignition of a small amount of vapour leading to tank failure and subsequent loss of containment). Late ignition of a vapour cloud only occurred in overfilling incidents. It therefore appears as if for storage tanks (only) two scenarios may have consequences at large distances, namely tank explosions and overfill incidents (note that the Persson study concerns tank fires, it does not consider release scenarios such as pipe ruptures!). In the first case the flammable mass involved in the explosion is limited to the amount of vapour prior to the release. In the second case the flammable mass of the cloud depends on many factors, including release conditions, release duration and meteorological conditions.

A summary of the observations from the literature survey is given in Table 32.

5.3.3 Literature and database survey for transport units

5.3.3.1 Incidents involving transport units

No literature sources have been found that describe incidents with flammable liquids during transportation (road, rail, waterway) in substantial detail. The results obtained from the literature survey concern four explosions on or nearby vessels, and five incidents with rail tankers (explosions and/or fireballs).

xi. Baytown, Texas USA, 1977; explosion following overfilling of a ship, possibly involving a ‘congested’ area. Only limited details available. (source: [15])
xii. Bantry Bay, Ireland, 1979; a ‘massive explosion’ of a ship containing crude oil occurred 30 minutes after a small deck fire had started. (source: [16] and [20])

xiii. India, 1983; according to [20] an explosion occurred while a rail wagon was leaking kerosene at a railway station, resulting in 47 fatalities. According to [21] an explosion occurred while two tanker cars loaded with gasoline exploded at a railway station. (source: [20] and [21])

xiv. Algeciras, Spain, 1985; multiple explosions involving two ships at a jetty. At the time of the explosion the ships were transferring naphtha and gasoline. Considerable damage and a 500 m high fireball at the jetty were reported. (source: [20] and [13])

xv Hannover, Germany, 1985; a BLEVE and 200 m high column of fire following a collision of two trains. According to [22], two tank wagons carrying petrol were ruptured in the collision. The consecutive fire endangered many more tank wagons carrying petrol, one of which exploded 16 minutes after the collision. A BLEVE and a 200 m high column of fire were reported. (source: [22] and [23])

xvi Rude, Sweden, 1986; two fireballs occurred after derailment of a goods train carrying petrol wagons and diesel wagons. According to [23] spilled flammable liquids ignited, engulfing both petrol and diesel wagons. After 20 minutes, a petrol wagon ruptured giving a 100 m diameter fireball. Ten minutes later, a second petrol wagon ruptured giving a similar fireball. For the second event, a pressure wave was also reported. (source: [23])

xvii. Iran, 1989; explosion of a ship during transfer of kerosene.. (source: [20] and [13])

xviii La Voulte sur Rhône, France, 1993; multiple explosions following derailment of a goods train carrying petrol wagons. According to [14], a fire broke out after the derailment. Fifteen minutes later a petrol wagon reportedly explodes, but no overpressure damage is reported. Subsequent ignition of vapours in the sewer system did result in minor overpressure effects, such as the launching of iron plates and a car. (source: [14], [13] and [23])

xix Elsterwerda, Germany, 1997; an explosion of a rail tanker. According to [24], two petrol tank wagons started leaking after derailment. Some twenty minutes later another tank exploded, resulting in the collapse of a part of a nearby brick building and rocketing debris. (source: [24] and [23])

The article from Lautkaski ([23]) on the possibility of BLEVEs during incidents with rail tankers further mentions the rupture of rail tankers carrying gasoline and subsequent explosions in the sewer system in Brackwede, Germany, 1974. Severe fire damage was reported, but the overpressure effects seem to have been limited (i.e. lifting of sewer system manholes).

<u>Additional incidents found in the FACTS and ARIA databases (see also Appendix D):</u>

xx New York, USA, 1974; multiple explosions on two ships. A loud explosion and bright ball of fire occurred when a ship's compartment was being emptied and cleaned for repair works. Secondary explosions occurred on this ship and another ship docked next to it. According to [30], the explosion led to window breakage of homes and offices within half a mile (800 m) distance. (source: [30] and [13])

xxi Herborn, Germany, 1987; vapour cloud explosion following a release from a road tanker. A 35 m^3 road tanker turned on its side in a village and started leaking gasoline. The vapours ignited and caused an explosion resulting in the complete destruction of a nearby building, heavy damage to several nearby buildings and glass breakage further down the road. It is likely that a part of the vapours escaped to surface water drains, thereby increasing the magnitude of the explosion. (source: [13])

xxii Chavanay, France, 1990; explosions in a sewer system after derailment of a goods train. According to [14], nine rail tankers filled with gasoline start leaking after the derailment of a goods train. Fuel enters the sewer system and vapours ignite. The damage area reportedly had a size of 1 km by 400 m and 8 houses and 2 garages were destroyed. It is not reported if the collapse of these buildings was a result of fire damage or explosion damage. (source: [14])

xxiii Zürich, Switzerland, 1994; explosions in sewer system after derailment of a goods train. After the derailment of a goods train, gasoline entered the sewer system and ignited. According to [13], eighty-five building damages were reported and streets were seriously distorted over a length of 400 m. (source: [13] and [14])

xxiv New York, USA, 2003; explosion on or around a marine barge. On February 21th 2003 an explosion occurred on or near a marine barge in New York, USA. According to the accident report in FACTS one house was severely damaged (half a dozen broken windows, foundations cracked at three locations). The distance from the barge to this building was not reported. It is expected that a defective pump was the initiator of the event. (source: [13])

Most incidents with transport units involve class 1 flammable liquids. Explicit references to explosions involving class 2 flammable liquids include the explosion during transfer of kerosene in Iran, the explosion during transfer of naphtha in Spain and the rail tanker explosion in India.

5.3.3.2 Causes and consequences of incidents involving transport units

General causes of incidents with transportation units are leakages during transfer of product and leakages following external impact, collision or derailment. More severe incidents are caused by overfilling of ships (large flow rates), fires on board of a ship (possibility of escalation to the storage compartments) and fires beneath road or rail tankers. Database studies such as [25] and (especially) [26] indicate that the possibility of a vapour cloud fire, a tanker explosion or even a vapour cloud explosion in case of an incident with a road or rail tanker should not be disregarded (more information on [25] and [26] is provided in Appendix D).

It is noted that European road tankers are nowadays constructed of aluminium ([27], [29]). When an aluminium tank is exposed to heat it will be plastically deformed, resulting in a leak. It is unlikely that aluminium tanks will ‘explode’ when exposed to a pool fire. Rail tankers on the other hand are still made out of steel. Therefore, RIVM has presented a proposal to the Dutch Ministry of Transport, Public Works and Water Management on how to take into account the possibility of rail tanker explosions in risk analyses ([28]).

The most important release scenarios for road and rail tankers and their consequences are shown in Table 33. The scenarios for tanker ships are shown in Table 34. The reported consequences and damage are derived from incidents with highly flammable liquids (classification K1, LF2 or C3).

Table 33 Cause, consequence and damage for incidents with road and rail tankers (highly flammable liquids)

Cause	Primary consequence	Damage
Leakage during transfer	The amount of vapour that is formed is insufficient to give a vapour cloud explosion. Provisions at transfer stations should be such that pool fires will not escalate.	The effects of a pool fire are limited to the direct surroundings of the transfer location.
Leakage following impact or collision	Ignition will lead to a pool fire. The tanker may rupture if it is engulfed in the fire. Subsequent tank explosions are not likely to occur for road tankers (constructed from aluminium). For rail tankers, ruptures may occur and will produce a fireball and overpressure effects. Vapour cloud explosions may occur if fuel leaks into a sewage / water drainage system.	The fire effects of a pool fire are limited to the vicinity of the crash location. The explosion damage following the rupture of a rail tanker is usually limited, though exceptions exist [(1)]. Fireballs are reported for several incidents, one with a diameter of 100 m [(2)] and another with a height of 200 m [(3)]. Ignition of vapours in a sewage system gave damage at 500 m [(4)] and one kilometre [(5)].

(1) *Elsterwerda, Germany, 1997*
(2) *Rude, Sweden, 1986*
(3) *Hannover, Germany, 1985*
(4) *Zurich, Switzerland, 1994*
(5) *La Voulte sûr Rhône, France 1993*

Table 34 Cause, consequence and damage for incidents with tanker ships (highly flammable liquids)

Cause	Primary consequence	Damage
Leakage during transfer	Due to the large flow rates, large vapour clouds can be formed. Ignition is likely and will result in a vapour cloud fire or - in case of unfortunate circumstances - a vapour cloud explosion.	Depending on the release conditions, consequence distances can be comparable to overfill incidents or pipe rupture incidents. [(1)].
Leakage following impact or collision	The leakage is from the ship's compartment (unpressurised). A pool fire is most likely. Escalation of the incident (for example an explosion of a ship's compartment) is possible.	Consequence distances for pool fires will be limited, explosions may result in heavy damage nearby, debris and broken windows at 800 m [(2)].
Initiating fire on board, maintenance or cleaning operations	May result in the explosion of a ship compartment.	Explosions may result in heavy damage nearby, debris and broken windows up to 800 m [(2)] .

(1) *See Table 35 and Table 36.*
(2) *Maximum distance reported for a ship compartment explosion (New York, USA, 1975)*

5.4 Overall discussion of scenarios relevant for third party risk

In this paragraph the results from the MARS database study and the literature review are combined. Table 35 gives a summary of incidents that may occur on site, along with the maximum consequence distances found in literature or databases. Table 36 contains exemplary incident stories. The reported consequences and damage are derived from incidents with class 1 flammable liquids.

The summary for incidents with transport units was given in Table 33 and Table 34. It was argued in section 5.3.3.2 that the presence of road and rail tankers at transfer stations on site will not be very relevant for third party risk.

Table 35 Summary for on site incidents with possible off site damage (class 1 flammable liquids)

Storage / transfer	Incident	Cause(s)	Consequence	Source of information
Storage	Overfill	Defective equipment Human error	Cloud length ~50-400 [(1)] m. Blast damage (100 mbar) possible at 0-500 m [(1)]. Glass breakage possible at 2500 m [(1)].	Database Literature
	Pipe rupture	Defective equipment Maintenance operations	Cloud length ~50-250 [(2)] m. Blast damage (100 mbar) possible at 0-300 m. Glass breakage possible at 2 km [(3)].	Database Literature
	Tank explosion	Ignition of vapours by maintenance operations, lightning or static electricity	Damage from debris. Blast damage limited [(4)].	Database Literature
Transfer to/from ships	Overfill	Defective equipment Human error	Comparable to overfill	Literature
	Leak from loading arm/ transfer line	Human error Defective equipment Collision and impact	Comparable to pipe rupture	Database Literature
	Fire on board	Various causes	Heavy damage nearby. Glass breakage possible at distances up to 800 m [(1)].	Database Literature

(1) *Estimate of maximum reported effect, see Table 36.*

(2) *Expert judgment, extrapolation of the Saint Herblain incident (see Table 36).*

(3) *Distance reported for the explosion following a pump defect during transfer of gasoline from a marine tanker in New York (2003).*

(4) *Blast damage at 50 m is reported in one case (see Table 36). The case is expected to be exceptional. Dutch standards (PGS 29) require that tanks have a weak seam to avoid the generation of considerable overpressures.*

Table 36 Examples of consequences and (heavy) damage (class 1 flammable liquids)

Type of event	Examples of consequences and damage
Overfill (ignition of vapour cloud)	- A 300 m (1000 ft) long vapour cloud exploded. Heavy damage including flattened road and rail tanker cars at cloud edge, heavy damage to storage tanks at 400 - 500 m (Newark, 1983) - Destruction of terminal buildings, extensively damage of nearby industrial and residential structures, demolished rail tanker cars. Damage to window frames (estimated overpressure below 100 mbar) at 500 m, collapsed roof from a shed (estimated overpressure below 100 mbar) at 600 m, glass breakage (estimated overpressure 30 mbar) at 1 km (Naples, 1985). - Heavy structural damage and flattened cars in and around cloud envelope, 300 mbar overpressure at 120 m, 100 mbar overpressure at 270 m, glass breakage at 2 km (Buncefield, 2005). - Glass breakage at 900 m after overfilling a 200 m^3 tank (Roosendaal, 1975).
Full orifice leak from pipeline, valve or loading arm (including pipe rupture)	- A flammable cloud ignited at 50 m distance. Structural damage (100 mbarg) reported at 100 - 150 m distance and minor structural damage (50 mbarg) at 200 -300 m distance (Saint Herblain, 1991). - A high pressure escape from an open valve on a storage tank produced a vapour cloud of at least 100 m in length (GB/1994/008). - A pump defect during transfer of gasoline from a marine tanker reportedly led to severe damage to one building at unknown distance (New York, 2003).
Explosion of storage tank	- In many cases heavy damage on site is reported. This is due to rocketing tank parts, overpressure-, and fire effects. - Broken windows and slight deformation of door frames at an estimated distance of 50 m (MARS report IT/1987/001). - Rocketing debris causing broken windows and minor damage to houses at a distance of 500 to 1000 m (RIVM analysis of [18]).
Explosion of ship compartment	- Major debris after the explosion of a tanker ship compartment in Bantry Bay, Ireland was reported at 600 m (1800 ft) distance ([16]), minor debris at 10 km ([20]). - Explosion of a marine tanker in New York 1974 resulted in broken windows at 800 m ([30] and [13]).

5.5 Summary and conclusions of the literature and database survey

The following conclusions can be drawn for incidents on site (see also Table 35):

- Regarding the *storage area*, overfilling of a storage tank and rupture of adjacent pipework are most relevant for the risk off site. Under unfortunate conditions, the flammable cloud may reach a distance of 250 to 400 m from the release location. Breakage of glass can occur at two kilometres distance. Tank explosions happen more often but have less impact off-site. Damage caused by debris may occur at distances up to two kilometres, but the likelihood of being hit is small.
- Regarding the *transfer of products*, the most serious incidents involve transfers to or from ships. Rupture of a transfer arm, releases from open valves and overfilling of the ship have similar consequences as their counterpart scenarios for storage tanks. An initiating fire on board of a ship may lead to the explosion of a ship compartment with possible glass breakage at 800 m. On site incidents with road tankers or rail tankers will not have off site consequences.

The following conclusions can be drawn for incidents with transport units off site (see also Table 33 and Table 34):

- Regarding road tankers, fire damage to nearby dwellings is dominant. The event of an explosion following engulfment in a pool fire is unlikely because modern day road tankers are constructed from aluminium. Damage from a vapour cloud explosion is possible if fuel leaks into the sewage system.
- Regarding rail tankers, fire damage is usually dominant. Rupture of a tanker engulfed in a fire can produce a fireball and in some cases overpressure effects. Damage from a vapour cloud explosion is possible if fuel leaks into the sewage system.
- Regarding en route tanker ships, an explosion of a ship's compartment may occur with heavy damage nearby and damage from debris at 800 m.

Accidents in tunnels are not addressed in this study and the conclusions drawn in this section do not pertain to this type of accidents.

Most incidents involve highly flammable liquids (K1 / LF2), more specifically gasoline and crude oil). Regarding consequence distances, it was not possible to discriminate between different types of highly flammable liquids. Four major incidents with class 2 (K2 / LF1) flammable liquids were found (kerosene and naphtha). As less vapour is formed for K2 products, both the probability of ignition and the damage after ignition are lower. Again it was not possible to discriminate between different types of (K2) liquids. Moreover, three of these four incidents occurred in countries where the climate and possibly also the safety regulations deviate significantly from the Dutch situation.

6 Recommendations

The current study on incidents and QRA guidelines showed a number of differences between theory (guidelines) and reality (incidents). The following differences were found for storage tanks filled with K1 liquid:

- The way in which the instantaneous release of a large atmospheric storage tank is modelled (including the formation of a large flammable cloud that disperses downwind) is regarded as physically unrealistic.
- The calculated consequence distances for the instantaneous release are larger than those reported in literature and incident databases.
- The discharge rate for the ten minute release is regarded as unrealistic for a continuous release.
- The calculated consequences for the ten minute release are in the same order of magnitude as the reported consequences of overfill scenarios, despite the differences between these scenarios.

Further points of interest that came up in the report were:

- Calculations using the pure component n-hexane give smaller consequence distances than calculations based on a winter grade gasoline mixture. It is noted that multi-component modelling is currently not available in SAFETI-NL. The level of detail in literature is not sufficient to determine whether the actual damage of releases is in line with calculations based on n-hexane or in line with calculations based on the winter grade gasoline mixture.

Considering the above, we recommend the following:

- Storage of class 1 (K1) flammable liquids:
    - Discuss with stakeholders if it is desirable and feasible to replace the current QRA scenarios with realistic release scenarios. If realistic scenarios are used, discussion to what extent abstract QRA scenarios are appropriate is avoided. It will also enable to take additional safety measures into account in a QRA and bring about more unity between HAZOP studies, installation scenarios and QRA scenarios. The down side is that the QRA instrument will become more technical and complicated and that deriving failure frequencies for all distinguished cases will prove to be a major challenge.
    - If (or as long as) QRA scenarios are not altered, the ten minute scenario can be regarded as representative for overfill incidents. Consequences for the ten minute release should be calculated in accordance with the current guidelines, in which case the calculated distances match consequence distances of overfill incidents.
    - Use n-hexane to calculate consequences and risks of scenarios involving storage of class 1 (K1) flammable liquids, at least until a multi-component evaporation and dispersion model becomes available.
    - Evaluate the possibility to use a multi-component evaporation and dispersion model as soon as it becomes available.
    - Evaluate the possibility to specify a maximum pool size for releases outside a bund.
    - Modify the guidelines for the instantaneous release scenario by setting the tank head to 0 m. This is because the consequences of the instantaneous release, calculated in

accordance with the current guidelines, overestimate the consequences of major releases (including tank explosions, ruptures and fissures and overfills) considerably. With the proposed modifications the instantaneous scenario is supposed to represent (semi)instantaneous releases that do not give significant fire or explosion effects well outside the bund area.
  - Verify if the modelling of shape and location of the bund can be improved in SAFETI-NL.

- Storage of class 2 (K2) flammable liquids:
  - Follow the recommendations for the storage of K1 liquids with respect to release scenarios and corresponding parameter settings to be used in the QRA.
  - Use n-nonane to calculate consequences and risks of scenarios involving class 2 (K2) flammable liquids.

Table 37 and Table 38 show the results of the consequence and risk calculations for the storage tanks of Chapter 2, in case the recommendations for the short term were followed. Figure 10 and Figure 11 show the transect of individual risk for the storage of class 1 flammable liquids for 50 m and 150 distance to the site boundary respectively. Figure 12 shows the transect of individual risk for the storage of class 2 flammable liquids.

- Transportation of flammable liquids (LF1, LF2 or C3):
  - Incorporate the risk of rail tanker explosions in QRAs for the transportation of C3 flammable liquids. Recommendations for this incorporation can be found in [28].

The proposed changes for the instantaneous release scenario and the new directions for the modelling of K1 and K2 products may have serious consequences on QRA outcomes, and thus for spatial planning. Therefore we advise to investigate the consequences of the recommendations prior to implementing these recommendations.

Table 37 Consequence and risk outcomes for single containment atmospheric storage tanks containing class 1 flammable liquids (using recommendations)

Tank	1000 m^3		10,000 m^3		50,000 m^3	
Site boundary	*50 m*	*150 m*	*50 m*	*150 m*	*50 m*	*150 m*
Distance to IR 10^{-6}/yr contour (m)	40	10	110	90	170	170
- dominant scenario(s)	B	C	B	B	B	B
Distance to IR 10^{-8}/yr contour (m)	110	90	320	310	580	580
- dominant scenario for SR	B	B	B	B	B	B
Consequence distances (m) (1)						
- *A: instantaneous release*						
- flash fire	10 (2)	10 (2)	130	25 (2)	200	200
- explosion (0.3 barg)	-	-	140	-	180	180
- pool fire (radius)	35	35	85	85	120	120
- pool fire (1% leth.)	55	55	120	120	160	160
- *B: 10 minute release*						
- flash fire	110	0 (3)	290	290	550	550
- explosion (0.3 barg)	100	-	250	250	440	440
- jet fire (1% leth.)	110	110	210	210	380	380
- pool fire (radius)	30	30	70	70	100	100
- pool fire (1% leth.)	55	55	120	120	160	160
- *C: 10 mm leakage*						
- flash fire	-	-	-	-	-	-
- explosion (0.3 barg)	-	-	-	-	-	-
- jet fire (1% leth.)	20	20	20	20	20	20
- pool fire (radius)	5	5	5	5	5	5
- pool fire (1% leth.)	15	15	15	15	15	15

(1) *The reported values concern the maximum value for any of the day or night weathers.*

(2) *Results for the 'early flash fire'. Delayed ignition of the cloud is expected not to occur presuming no ignition sources are present on site.*

(3) *The flammable cloud does not reach the site boundary.*

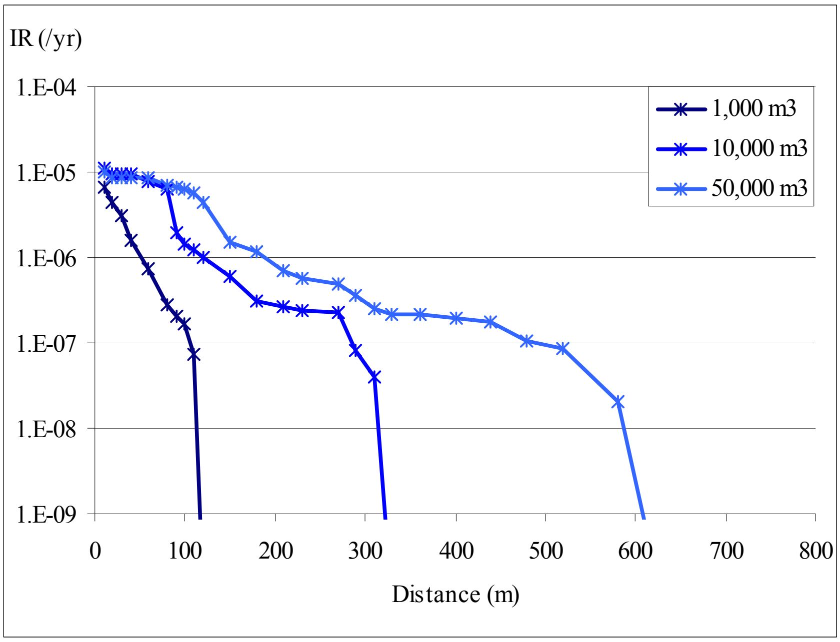


Figure 10 Transect of Individual Risk for the storage of class 1 flammable liquids (using recommendations) with site boundary at 50 m

Note: These transects were made in SAFETI-NL 6.54. Minor difference between the graphs and the tabular values (produced with SAFETI-NL 6.53) may occur.

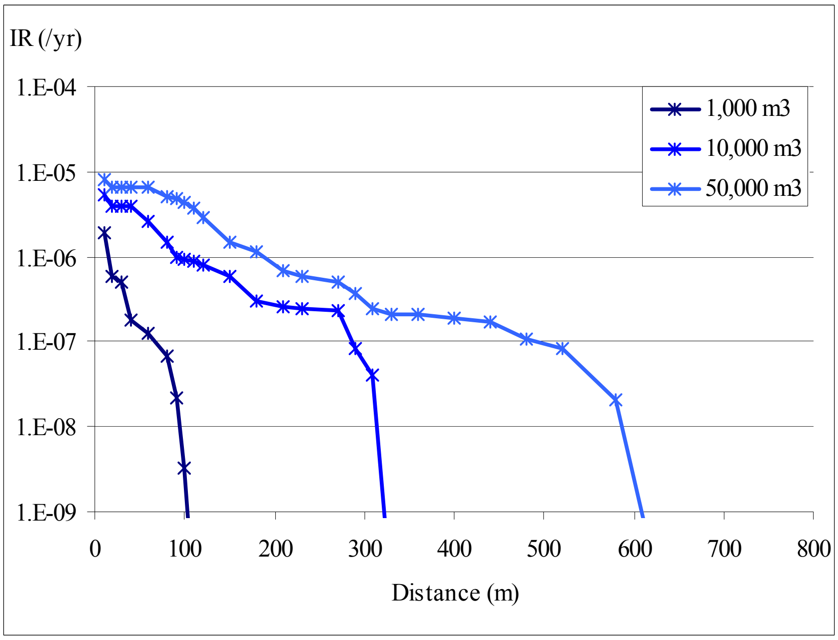


Figure 11 Transect of Individual Risk for the storage of class 1 flammable liquids (using recommendations) with site boundary at 150 m

Note: These transects were made in SAFETI-NL 6.54. Minor difference between the graphs and the tabular values (produced with SAFETI-NL 6.53) may occur.

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Table 38 Consequence and risk outcomes for single containment atmospheric storage tanks containing class 2 flammable liquids (using recommendations)

Tank	1,000 m^3	10,000 m^3	50,000 m^3
Distance to IR 10^{-6}/yr contour (m)	-	-	-
- dominant scenario(s)	-	-	-
Distance to IR 10^{-8}/yr contour (m)	40	90	130
- dominant scenario for SR	B	B	B
Consequence distances (m) (1)			
- *A: instantaneous release*			
- flash fire	10 (2)	25 (2)	40 (2)
- explosion (0.3 barg)	-	-	-
- pool fire (radius)	35	85	120
- pool fire (1% leth.)	55	120	160
- *B: 10 minute release*			
- flash fire	0 (3)	0 (3)	0 (3)
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	20	40	70
- pool fire (radius)	30	70	100
- pool fire (1% leth.)	55	100	160
- *C: 10 mm leakage*			
- flash fire	-	-	-
- explosion (0.3 barg)	-	-	-
- jet fire (1% leth.)	15	15	15
- pool fire (radius)	5	5	5
- pool fire (1% leth.)	15	15	15

(1) The reported values concern the maximum value for any of the day or night weathers.

(2) Results for the 'early flash fire'. Delayed ignition of the cloud is expected not to occur.

(3) The flammable cloud does not reach the site boundary.

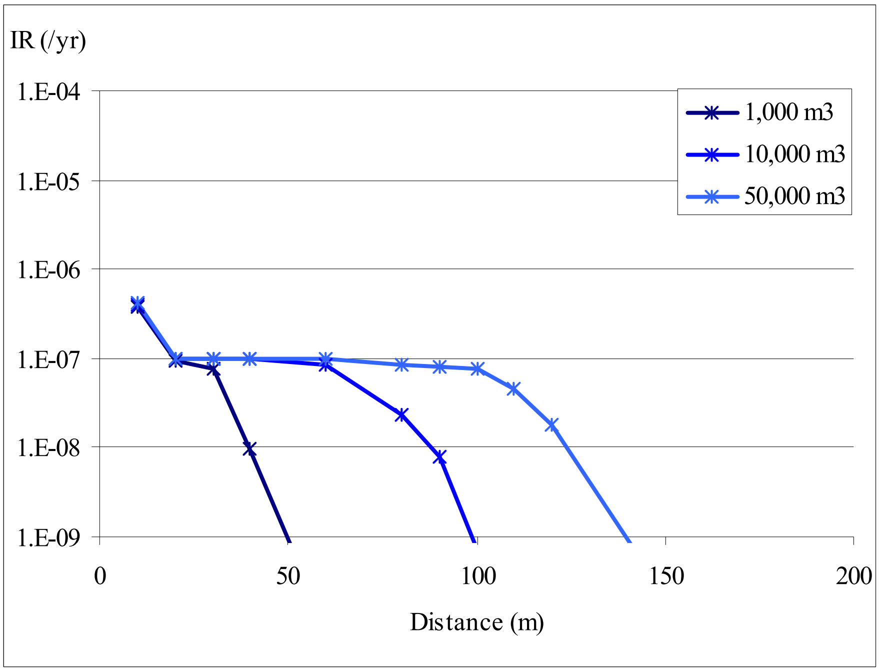

Figure 12 Transect of Individual Risk for the storage of class 2 flammable liquids (using recommendations)

Note: These transects were made in SAFETI-NL 6.54. Minor difference between the graphs and the tabular values (produced with SAFETI-NL 6.53) may occur.

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Appendix A - Sensitivity study for SAFETI-NL outcomes

As many questions arose on the way releases are modelled in SAFETI-NL, the behaviour of the outflow in the different scenarios (according to SAFETI) is explained in this appendix. A sensitivity study is performed on the influence of the height of the tank head for the intermediate tank (10,000 m^3) filled with hexane.

Instantaneous release (see Figure A.1)
Prior to the release the contents of the atmospheric tank has a hydrostatic pressure that depends on the height of the liquid (the liquid head).

1st row in Figure A1: expansion to atmospheric pressure (0 - 10 s from time of release)
In case of an instantaneous release a rapid expansion from hydrostatic pressure to atmospheric conditions is modelled. The liquid column breaks up into droplets, which are released with an initial vertical and horizontal (downwind) velocity and are subsequently moved by wind and gravity forces before falling on the ground (rainout). In the meantime a part of the liquid evaporates. In this case the expansion has a duration of 10 seconds and the distance to the rainout location is 40 m.

2nd row in figure A1: slumping and downwind dispersion (10 - 50 s from time of release)
Once rainout occurs, the cloud is repositioned around the rainout location. The fraction of the released material that has not yet evaporated rains out in a pool that is considered to be centred around the rainout location. The vapour cloud then slumps under its own gravity, is dragged by the wind and picks up vapour from the pool. Both the evaporation prior to rainout and the pool vaporisation are taken into account in the calculation of the size and location of the flammable cloud.

3rd row in figure A1: further downwind dispersion (50 - 80 s from time of release)
Passive dispersion of the cloud occurs. The pool continues to evaporate, but concentrations above the pool are below LFL and are not visible on the graphs. After 80 s the cloud has diluted below LFL and disappears. The flammable cloud reached a maximum distance of 320 m.

The displacement of vapour and liquid prior to rainout and the subsequent relocation of the vapour cloud are not considered to be realistic. A key parameter is the height of the liquid (which determines the hydrostatic pressure). If this parameter is set to 0 m, the released material immediately rains out in a pool as can be seen in Figure A.2. The amount of vapour in the cloud is considerably less than in the previous case and so is the distance to LFL.

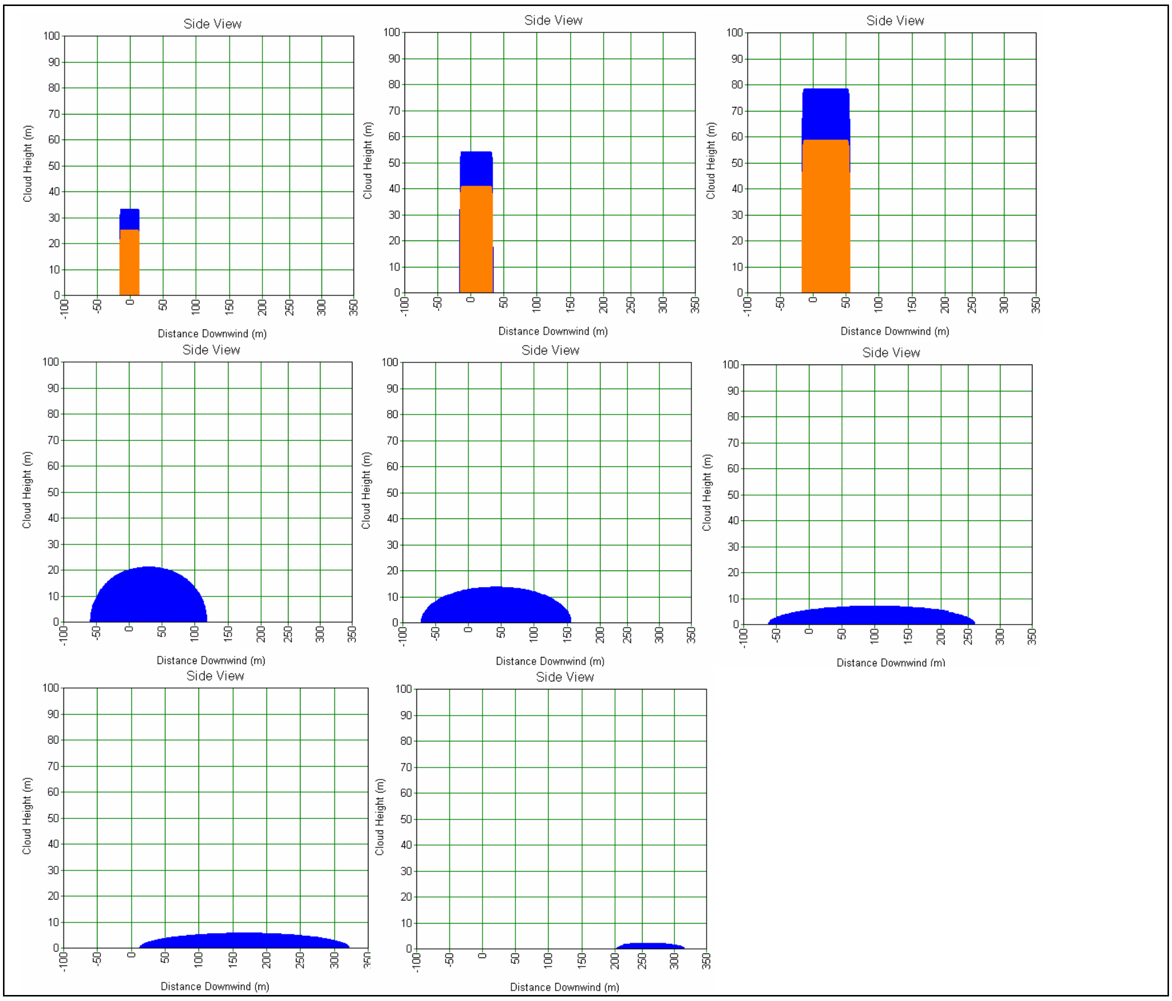


Figure A.1 Instantaneous release of 10,000 m³ hexane (UFL in orange, LFL in blue) with tank head 13.7 m. Time of frames: 1st row: 0s- 5s-10s, 2nd row: 15s-20s-50s, 3rd row: 60s-80s.

In SAFETI-NL the following consequences are modelled for an instantaneous liquid release (either liquefied gasses or atmospheric liquids):

- Early flash fire: Ignition of the vapour that flashed or evaporated during the expansion to atmospheric conditions. This event is accompanied by an early pool fire.
- Early explosion: Explosion of the vapour that flashed or evaporated during the expansion to atmospheric conditions. This event only occurs if the available heat of combustion is 5 GJ or more.
- Early pool fire: Early ignition of the pool. The burning of fuel restrains the pool diameter. Therefore, the diameter of the early pool fire will be smaller or equal to the diameter of a late pool fire (see below).
- Fireball: A rising fireball that may occur if ignition takes place immediately after an instantaneous release of compressed gasses or liquefied gasses.
- Late flash fire: Ignition of the vapour cloud at maximum cloud footprint. This event only occurs if the cloud reaches the site boundary (that is if the distance to the downwind location where the LFL concentration is reached, equals or

exceeds the distance to the site boundary). This event is accompanied by a late pool fire.

- Late explosion: Explosion of the vapour cloud at maximum cloud footprint. This event only occurs if the cloud reaches the site boundary and the available heat of combustion is 5 GJ or more.
- Late pool fire: Ignition of the pool at maximum pool radius. According to the guidelines this event also occurs if the flammable cloud does not reach the site boundary.

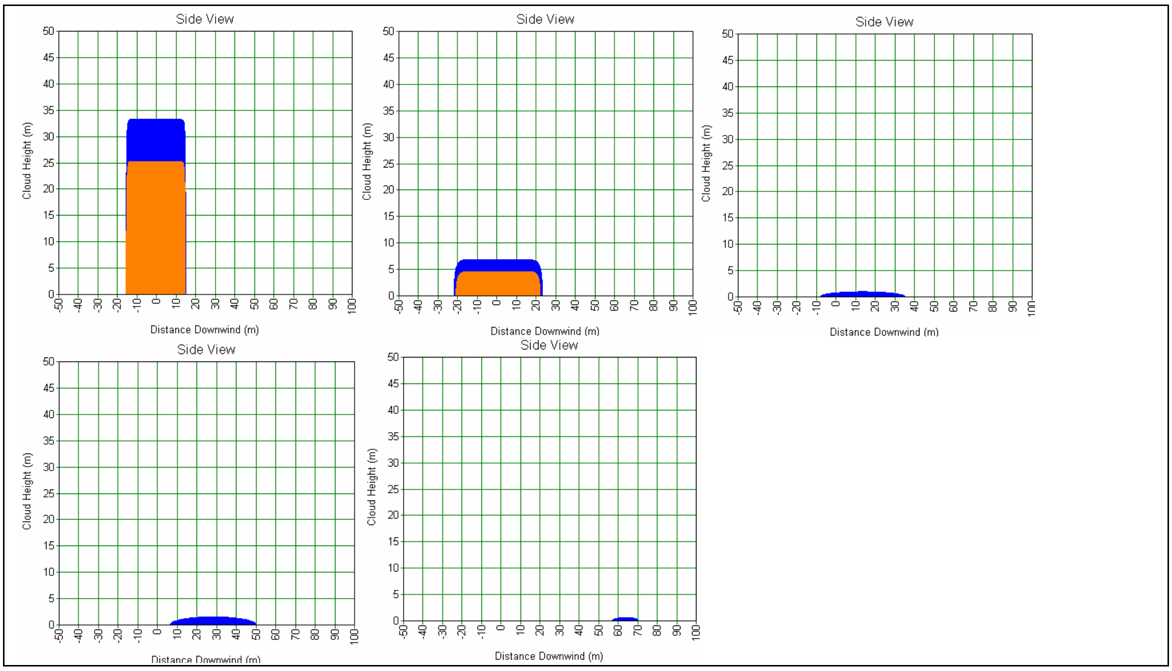


Figure A.2 Instantaneous release of 10,000 m³ hexane (UFL in orange, LFL in blue) with tank head 0 m. Time of frames: 1st row: 0s- 1s-6s, 2nd row: 10s-30.

For atmospheric liquids the vaporisation prior to rain out is usually very low and both the early explosion and the fireball will not be modelled. The results for the early flash fire will usually be negligible with respect to the results of the pool fire (for atmospheric liquids), though formally this depends on the size of the tank, the tank height and the size of the bund.

<u>Continuous release (see Figure A.3)</u>

A continuous release of n-hexane at ambient conditions leads to a liquid jet. The velocity of the jet depends on the liquid head. Part of the liquid may evaporate before the droplets hit the ground. The remaining liquid rains out in a pool. The rainout location is considered to be the centre of the pool. The vapour then disperses downwind and picks up vapour evaporating from the pool. When the release finishes after 600s, the cloud disappears in downwind direction. The pool continues to evaporate, but concentrations are below LFL.

The first three frames in Figure A.3 show the way the jet is building up during the first 20 s. In the fourth frame (30s) the jet has reached its full size. The last two frames show break-up of the jet once the release is finished (600-630s).

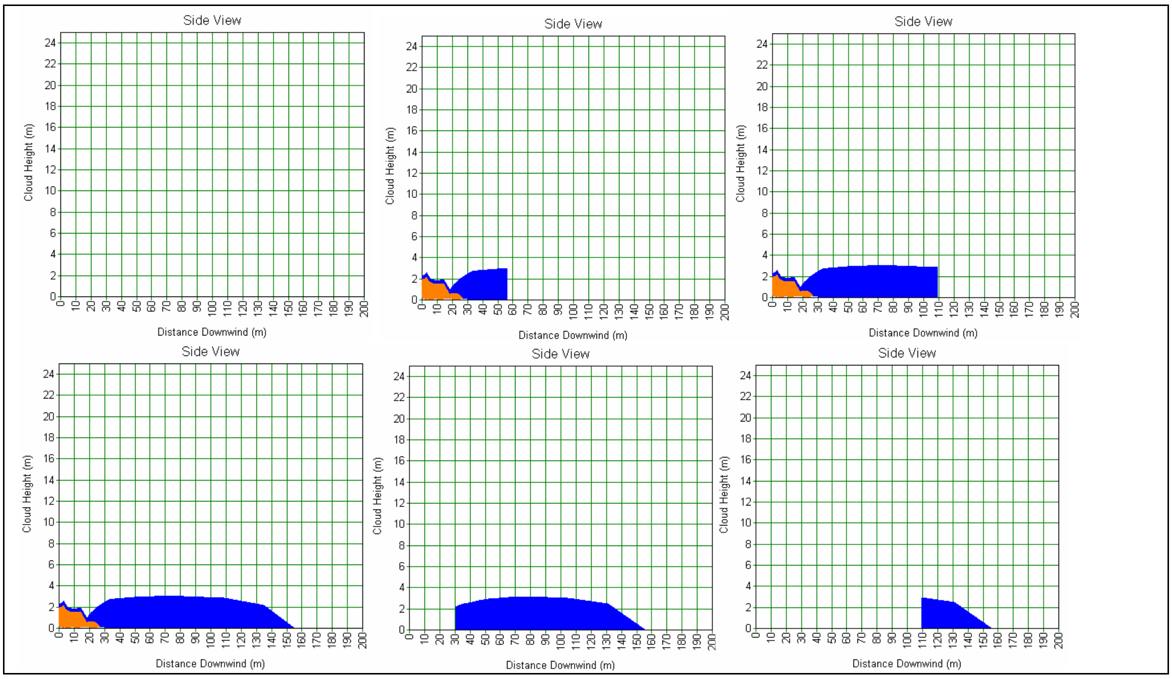


Figure A.3 Continuous release of 10,000 m³ hexane (UFL in orange, LFL in blue) with tank head 13.7 m. Time of frames: 1st row: 0s- 6s-20s, 2nd row: 30s-605s-620s.

According to [1] and [2], the following consequences are modelled for a continuous liquid release (see also Figure 1):

- Jet Fire: Ignition of the liquid/vapour jet that is being released. Following a recommendation of (global) users of PHAST / SAFETI, the mass flow rate that is used for the jet fire model is set to three times the vapour fraction after rainout. The jet fire is accompanied by an early pool fire.
- Early pool fire: Early ignition of the pool. The burning of fuel restrains the pool diameter (if not already constrained by a bund).
- Late flash fire: Ignition of the vapour cloud at maximum cloud footprint. This event only occurs if the cloud reaches the site boundary (that is: if the distance to the downwind location where the LFL concentration is reached, equals or exceeds the distance to the site boundary). This event is accompanied by a late pool fire.
- Late explosion: Explosion of the vapour cloud at maximum cloud footprint. This event only occurs if the cloud reaches the site boundary and the available heat of combustion is 5 GJ or more.
- Late pool fire: Ignition of the pool at maximum pool radius. According to the guidelines this event also occurs if the flammable cloud does not reach the site boundary.

Sensitivity study for storage tanks (class 1 and class 2 flammable liquids)

Important risk modelling parameters are the tank content and storage conditions, the height of the liquid (the liquid head) and the size of the bund. The influence of the tank head on risk and consequence distances is illustrated for the 10,000 m^3 tank in Table A.1 (class 1 flammable liquids) and Table A2 (class 2 flammable liquids). The most conservative results are reported.

Table A.1 Influence of the tank head for the 10000 m³ tank filled with class 1 flammable liquids (site boundary at 50 m)

Scenario	i	ii	iii
Tank head for instantaneous release	**13.7 m (1)**	**0 m**	**(as ii)**
Tank head for ten minute release	**13.7 m**	**(as i)**	**1 m**
Distance to IR 10^{-6}/yr contour (m)	270	110	75
- dominant scenario(s)	A	B	A&B
Distance to IR 10^{-8}/yr contour (m)	340	320	160
- dominant scenario for SR	A&B	B	B
Scenario results:			
- *A: instantaneous release*			
- vapour fraction after initial expansion	0.007	0.000002	(see ii)
- vapour mass after initial expansion (kg)	49000	13	(see ii)
- pool (radius, m)	85	85	(see ii)
- pool vapour flow rate (kg/s)	60	60	(see ii)
- flash fire (distance to LFL, m)	380	130	(see ii)
- explosion (distance to 0.3 barg, m)	300	-	(see ii)
- distance to rainout location (m)	40	0	(see ii)
- pool fire (distance to 1% lethality, m)	160	120	(see ii)
- *B: 10 minute release*			
- vapour fraction	0.004	(see i)	0.0009
- release vapour flow rate (kg/s)	45	(see i)	10
- pool (radius, m)	70	(see i)	70
- pool vapour flow rate (kg/s)	45	(see i)	45
- flash fire (distance to LFL, m)	290	(see i)	140
- explosion (distance to 0.3 barg, m)	250	(see i)	-
- distance to rainout position (m)	19	(see i)	
- jet fire (distance to 1% lethality, m)	210	(see i)	100
- pool fire (distance to 1% lethality, m)	120	(see i)	105

(1) *The instantaneous scenario gave convergence errors when the true tank head was used. For these cases the Droplet Evaporation Thermo Model was changed from 'Rainout - Non-Equilibrium' to 'Rainout - Equilibrium'.*

Table A.2 Influence of the tank head for the 10,000 m³ tank filled with class 2 flammable liquids (site boundary at 50 m)

Scenario	i	ii	iii
Tank head for instantaneous release	**13.7 m [(1)]**	**0 m**	**0 m**
Tank head for ten minute release	**13.7 m**	**13.7 m**	**1 m**
Distance to IR 10^{-6}/yr contour (m)	-	-	0
- dominant scenario(s)	-	-	-
Distance to IR 10^{-8}/yr contour (m)	110	90	75
- dominant scenario for SR	A	B	A&B
Scenario results:			
- *A: instantaneous release*			
- vapour fraction after initial expansion	0.0003	0	(see ii)
- vapour mass after initial expansion (kg)	2300	0	(see ii)
- pool (radius, m)	85	85	(see ii)
- pool vapour flow rate (kg/s)	2	2	(see ii)
- flash fire (distance to LFL, m)	100 [(2)]	25 [(3)]	(see ii)
- explosion (distance to 0.3 barg, m)	95	-	(see ii)
- distance to rainout location (m)	50	0	(see ii)
- pool fire (distance to 1% lethality, m)	170	120	(see ii)
- *B: 10 minute release*			
- vapour fraction	0.00001	(see i)	0.00002
- release vapour flow rate (kg/s)	1	(see i)	0.3
- pool (radius, m)	70	(see i)	70
- pool vapour flow rate (kg/s)	1	(see i)	1
- flash fire (distance to LFL, m)	20 [(4)]	(see i)	5
- explosion (distance to 0.3 barg, m)	-	(see i)	-
- distance to rainout position (m)		(see i)	0
- jet fire (distance to 1% lethality, m)	40	(see i)	20
- pool fire (distance to 1% lethality, m)	100	(see i)	100

(1) As the instantaneous scenario gave convergence errors, the Droplet Evaporation Thermo Model was set to 'Rainout - Equilibrium'.

(2) Result for the late flash fire. This value is not used in the risk calculation because delayed ignition is not expected to occur. The maximum distance for the early flash fire is 85 m.

(3) The outcomes for the early flash fire and the late flash fire are both 25 m.

(4) Result for the late flash fire. This value is not used in the risk calculation because delayed ignition is not expected to occur. Immediate ignition will not give a flash fire for this case.

Tables A.1 and A.2 show that a higher tank head leads to a higher amount of vapour being formed, and, subsequently, larger consequence distances for flash fires and explosions. Consequently, the liquid head also has a large impact on the location of the IR 10^{-6}/yr and 10^{-8}/yr risk contours.

The calculations reveal that a higher tank head also gives a larger downwind displacement of the vapour and liquid cloud prior to rainout (see explaining text at the start of the Appendix), which explains the larger distances for the pool fire (the rainout location is considered to be the centre of the pool). The maximum displacement for the 10,000 m^3 tank filled with n-hexane is 40 m (weather type D9). As this downwind displacement is not considered to be realistic, it can be concluded that the flash fire and pool fire effects are overestimated. This overestimation does not influence the location of the IR 10^{-6} contour. The location of the IR 10^{-6} contour mainly depends on the maximum footprint of the flammable cloud (relevant for the delayed ignition). By varying the bund size, it was shown that the vapour formation prior to rainout (opposed to the pool vapour flow) is dominant for the location of the LFL contour and thus for the derived consequence and risk results as well.

Individual risk results for six combinations of tank size and distance to site boundary are shown in Table A.3 for three different ways of modelling:

A Option A is the option that follows the guidelines and was used for chapter 2. The dispersion parameter in SAFETI-NL had to be modified in order to circumvent a convergence error.

B In option B the value of the tank head is set to 0 m for the instantaneous scenario. This option is available for all users, and has already been communicated by the SAFETI-NL helpdesk in 2006 and 2007. It turns out to bring about a significant reduction of the risk distances. With this option the risks are no longer determined by the instantaneous release scenario but by the ten minute release scenario.

C Option C is to disregard the instantaneous scenario altogether. The distances are equal to those of option 2, thus showing that the instantaneous scenario is no longer relevant if the second option is used.

Table A.3 Impact of different proposals on distances for storage tanks with class 1 flammable liquids

Calculation option (see text)	**A**		**B**		**C**	
Site boundary	***50 m***	***150 m***	***50 m***	***150 m***	***50 m***	***150 m***
1000 m^3 storage tank						
Distance to IR 10^{-6}/yr contour (m)	90	10	40	10	40	10
Distance to IR 10^{-8}/yr contour (m)	120	90	110	90	110	90
10,000 m^3 storage tank						
Distance to IR 10^{-6}/yr contour (m)	270	270	110	90	110	85
Distance to IR 10^{-8}/yr contour (m)	340	330	320	310	320	310
50,000 m^3 storage tank						
Distance to IR 10^{-6}/yr contour (m)	580	580	170	170	160	160
Distance to IR 10^{-8}/yr contour (m)	780	780	580	580	580	580

Sensitivity study for transfer to ships (class 1 flammable liquids only)

Important risk modelling parameters are the flow rate, the diameter of the loading arm and the size of the pool.

Table A.4 shows the details for the transfer of class 1 flammable liquids to or from ships. For a flow rate of 500 m^3/hr, the flammable cloud reaches a distance of 220 m in case of a rupture of the loading arm, which in this case is further than the site boundary. The risk therefore mainly depends on the vapour cloud fire and explosion that follow delayed ignition of the cloud.

In the calculations of section 2.3, the release duration was not limited by repression systems. Furthermore, the used model assumes free spreading of the pool until the minimum pool depth of 10 mm is reached. The resulting pool size is very large (over 50,000 m^2 for a flow rate of 500 m^3/hr). In reality, the size of the pool will often be limited due to drain systems, the presence of rims at the site and general uneven terrain. Tables A.4 and A.5 show that the pool surface area is a sensitive parameter for consequence and risk distances. These distances are considerably reduced if the pool surface area is limited to 25,000 m^2. It is hereby noted that limitation of the pool diameter is currently only foreseen if a bund is present.

Table A.4 Detailed results for loading/unloading class 1 flammable liquids to ships (500 m^3/hr, site boundary at 50 m)

Pool size	unconstrained pool	pool size 25,000 m^2
Distance to IR 10^{-6}/yr contour (m)	220	130
- dominant scenario(s)	A	A
Distance to IR 10^{-8}/yr contour (m)	290	170
- dominant scenario for SR	A	A
Scenario results:		
- *A: full bore rupture of loading arm*		
- vapour fraction	0.18	0.18
- release vapour flow rate (kg/s)	2.6	2.6
- pool (radius, m)	130	90
- pool vapour flow rate (kg/s)	83	45
- flash fire (distance to LFL, m)	220	150
- explosion (distance to 0.3 barg, m)	250	170
- distance to rainout position (m)	2	2
- jet fire (distance to 1% lethality, m)	55	55
- pool fire (distance to 1% lethality, m)	160	120
- *B: leak from loading arm*		
- vapour fraction	0.45	0.45
- release vapour flow rate (kg/s)	2.9	2.9
- pool (radius, m)	25	25
- pool vapour flow rate (kg/s)	26	26
- flash fire (distance to LFL, m)	55	55
- explosion (distance to 0.3 barg, m)	-	-
- distance to rainout position (m)	14	14
- jet fire (distance to 1% lethality, m)	55	55
- pool fire (distance to 1% lethality, m)	50	50

According to Table A.5, a pool size of 45,000 m^2 is obtained for the release of 500 m^3/hr class 1 flammable liquids during 30 minutes. A pool size of 230,000 m^2 is calculated for a transfer of 3000 m^3/hr during 30 minutes. These values are considerably larger than values reported in the literature for the release of flammable liquids on land:

- According to Part 2 of the Purple Book ([1]), the maximum pool size after rupture of a pipeline is 3000 m^2. This value applies both to rupture of underground pipelines and aboveground pipelines.
- In a study for gasoline pipelines in the UK ([31]), commissioned by HSE, it is argued that pools may theoretically spread for many hours. 'However, the formation of such large pools would require a very extensive area of either totally flator basin shaped terrain, with no cracks, fissures or drainage (...). The formation of such large pools is therefore extremely unlikely and pool sizes have been limited to 100 m diameter throughout the study to account for these features in a generic way". The surface area corresponding to a diameter of 100 m is 7850 m^2.
- In a report presented by CONCAWE ([32]) consequences of 379 incidents with oil pipelines in the period between 1971 and 2000 are reported. The list includes 8 spills of aboveground pipelines. The 'ground area affected' is reported for 3 of these incidents. The maximum reported value is 10,000 m^2.

The reported dimensions of the pool are considerably smaller than the size that is calculated for free spreading of a pool. Considering that the size of the pool is relevant for the calculated consequence distances, it is recommended to provide further guidance on the pool size to be used in QRA calculations.

Table A.5 Impact of the pool size on distances for transfer of class 1 flammable liquids (site boundary at 50 m)

	unconstrained pool	pool size 25,000 m^2
Transfer 100 m^3/hr		
Pool size (m^2) [(1)]	9500	9500
Distance to IR 10^{-6}/yr contour (m)	30	30
Distance to IR 10^{-8}/yr contour (m)	40	40
Transfer 500 m^3/hr		
Pool size (m^2) [(1)]	45.000	25,000
Distance to IR 10^{-6}/yr contour (m)	220	130
Distance to IR 10^{-8}/yr contour (m)	290	170
Transfer 1500 m^3/hr [(2)]		
Pool size (m^2) [(1)]	80.000	25,000
Distance to IR 10^{-6}/yr contour (m)	320	150
Distance to IR 10^{-8}/yr contour (m)	420	190
Transfer 3000 m^3/hr		
Pool size (m^2) [(1)]	230.000	25,000
Distance to IR 10^{-6}/yr contour (m)	460	290
Distance to IR 10^{-8}/yr contour (m)	740	310

(1) *Maximum pool size in 1800 s.*
(2) *It is assumed that two pipelines are used for transfer. In case of rupture of a pipeline, the pump rate is 375 m^3/hr.*

Appendix B - Pure components versus mixtures

The current version of SAFETI-NL cannot adequately calculate evaporation of components of a mixture (neither evaporation prior to rainout nor evaporation from the pool). Instead, the evaporation of mixtures is based on a pseudo-component that is considered to be representative for the mixture. This type of modelling is referred to as the PC-method. An alternative approach is to use a pure component that is expected to be sufficiently representative for the mixture.

In chapter 2 and Appendix A, n-hexane was used as an exemplary substance to calculate the consequences of gasoline releases. This method was proposed by RIVM in spring 2007 [1]. The proposal was criticised by representatives from the industry who feared that risks would be underestimated with this assumption.
In the summer of 2007, a software extension became available that could adequately calculate the evaporation of a mixture prior to rainout, but not yet evaporation from the pool. Evaporation from the pool still uses the “pseudo-component” assumption. This method is thus a hybrid of multi-component (MC) modelling prior to rainout and pseudo-component (PC) modelling after rainout.

Table B.1 shows the results of consequence calculations for n-hexane and n-pentane (both pure components). The table also show consequence outcomes for a mixture that is expected to be representative for winter grade gasoline (using the hybrid MC/PC calculation described above). The mixture consists of 2-methylheptane (14 mole%), 2-methylpentane (15%), 4-ethyl-m-xylene (3%), toluene (17%), n-butane (12%), isopentane (21%), m-xylene (10%) and 1,2,4-trimethylbenzene (8%).

Table B.1 shows that the release vapour rate of the gasoline winter grade mixture is significantly higher than the release rate of n-hexane. As a result, the distance to LFL increases from 330 m to 470 m for the instantaneous release scenario and from 150 m to 220 m in the ten minute release scenario. The consequence outcomes for n-pentane are again noticeably higher than those of the mixture. The distance to LFL increases to 550 m (instantaneous release) and 310 m (continuous release). It is expected that the explosion distances and risk distances will increase likewise.

Table B.2 gives an overview of the vapour pressures of various hydrocarbon products. An industrial norm exists (EN 228) that defines the quality criteria for gasoline on the European customer market. According to this norm, the vapour pressure of gasoline at 37.8 °C has to be between 450 mbar and 600 mbar in summer and between 650 mbar and 900 mbar in winter. Storage facilities may store gasoline of a higher volatility; a vapour pressure of 1172 mbar at 37.8°C is believed to be the maximum value in practice.
If these values are compared to the volatility of n-pentane and n-hexane, it can be concluded that pentane is more volatile than ‘European gasoline’, and hexane is less volatile. The table also shows

1 The choice was based on the following arguments: (i) a unified approach for all gasoline mixtures is desired; (ii) SAFETI-NL cannot model the behaviour of mixtures adequately if the components have a wide range in volatility (as is the case for gasoline). RIVM prefered the use of a pure component instead of a (pseudo-component) mixture and n-hexane was considered to be the best candidate for gasoline mixtures.

that the volatility of Arabian Light crude oil is comparable with the volatility of the gasolines considered.

The conclusion of this study is that the evaporation of winter grade gasoline mixtures is underestimated if n-hexane is used as an exemplary substance. If n-pentane would be used as an exemplary substance, the consequences and risks would be overestimated. Whether the consequences and risks are underestimated in the QRA calculation depends on the realism in the scenario definition and frequency attribution.

A fully adequate evaporation model for mixtures is not yet implemented in SAFETI. DNV intends to implement such a model in PHAST Risk (formally known as SAFETI) in the near future.

Table B.1 Consequence results for the mixture in PC and Hybrid approach and pure components n-hexane and n-pentane (weather = D5)

	n-hexane	mixture	n-pentane
A: instantaneous release			
- vapour fraction after initial expansion	0.0073	0.018	0.024
- vapour mass after initial expansion (kg)	49000	118000	150000
- pool vapour flow rate (kg/s)	37	n/a	120
- flash fire (distance to LFL, m)	330	470	550
- explosion (distance to 0,3 barg, m)	n/a	n/a	n/a
- distance to rainout location (m)	23	n/a	22
- pool fire (radius, m)	70	n/a	70
- pool fire (distance to 1% lethality, m)	110	n/a	110
B: 10 minute release			
- vapour fraction	0.004	0.008	0.02
- release vapour flow rate (kg/s)	40	85	195
- pool vapour flow rate (kg/s)	16	n/a	125
- jet fire (distance to 1% lethality, m)	190	200	390
- flash fire (distance to LFL, m)	150	220	310
- explosion (distance to 0,3 barg, m)	n/a	n/a	n/a
- pool fire (radius, m)	70	n/a	70
- pool fire (distance to 1% lethality, m)	110	n/a	110

Differences in reported distances between Table B.1 and Table A.1 occur. In Table A.1 maximum distances for any weather are reported. The distances in Table B.1 apply specifically for neutral weather (Pasquill class D, wind speed 5 m/s).

Table B.2 Saturated vapour pressure of various hydrocarbon products

	Sat. vap. press. (9 ºC, 1 atm)	Sat. vap. press. (20 ºC, 1 atm).	Sat. vap. press. (37.8 ºC, 1 atm)
Gasoline according to EN 228 (summer)			450-600 mbar
Gasoline according to EN 228 (winter)			650-900 mbar
Gasoline (1), (2)	303 mbar	454 mbar	816 mbar
Crude oil (1), (3)	324 mbar	444 mbar	704 mbar
Naphtha (1)	18 mbar	34 mbar	82 mbar
Kerosene (1)	0.4 mbar	0.8 mbar	2.4 mbar
Diesel (1)	0.1 mbar	0.3 mbar	0.9 mbar
n-pentane (4)	363 mbar	566 mbar	1075 mbar
n-hexane (4)	96 mbar	162 mbar	344 mbar
n-heptane (4)	26 mbar	47 mbar	111 mbar
n-octane (4)	7 mbar	14 mbar	37 mbar
n-nonane (4)	2 mbar	4 mbar	12 mbar
n-decane (4)	0.6 mbar	1.3 mbar	4 mbar
n-undecane (4)	0.1 mbar	0.4 mbar	1.4 mbar
n-dodecane (4)	0.04 mbar	0.1 mbar	0.5 mbar

(1) Typical composition, provided to RIVM by an international petrochemical company.
(2) Reportedly a ‘winter grade’ gasoline composition.
(3) Reportedly the composition of an ‘Arabian light’ crude oil.
(4) Vapour pressure calculated with PHAST 6.53.

Appendix C - Detailed results from MARS database analysis

Table C.1 Details for incidents with storage tanks or on site pipework (selection of 24 cases sorted by cause)

Incident	Substance	Installation type	LOC scenario	Cause [1]	Consequence	Blast damage (if any)
Corrosion (3 cases):						
DE/1998/002	Diesel oil	Pipeline	Leak	Corrosion (Co)	No ignition	
GB/1999/001	Crude petroleum	Storage tank (100,000 m^3)	Leak from base	Corrosion (Co)	No ignition	
GB/1999/005	Crude oil	Storage tank (23,000 m^3)	Leak from base (20 cm^2 hole)	Corrosion (Co)	Spill to bund, no ignition	
Defective equipment (3 cases):						
GB/1991/002	Naphtha	Storage tank (floating roof 7000 m^3)	Jammed/sunken floating roof	Jammed floating roof (DE)	Tank roof fire	
ES/1992/002	Gasoline	Pump	Release from pump while filling a tank	Defective pump (DE)	Late explosion and subsequent fire	Unspecified material damage inside establishment, 4 kills and 2 injuries on site
DE/2000/001	MTBE	Fixed hose	Leak from hose	Defective hose (DE)	No ignition	
Maintenance works and cleaning operations (12 cases):						
GR/1986/001	Fuel oil	Storage depot (multiple tanks, biggest tank 62,000 m^3)	Pipe failure	Maintenance work involving flame cutting (M&C) [2]	Fire spread and affected multiple tanks, explosion of multiple oil tanks and BLEVE of a 70 m^3 water tank.	Not clear whether damage was result from fire or from explosion. No damage reported off site.

Incident	Substance	Installation type	LOC scenario	Cause [1]	Consequence	Blast damage (if any)
IT/1987/001	Methanol	Storage depot (initial explosion in 2500 m^3 fixed roof tank)	Tank explosion	Cleaning operations (M&C) (degassing an "empty" tank with air)	Multiple explosions, tank farm fire	Two nearby tanks and several pipes were heavily damaged by the blast. Broken windows and slight deformation of frames in vicinity of site (50 m?).
FR/1987/001	Gasoil, gasoline and additives	Storage depot (multiple fixed roof tanks)	Release in pumping station	Modification works on site (M&C) (not clear if works were only cause of release of only of ignition)	Flash fire in pumping station followed by multiple explosions and tank farm fire [3]	Severe structural damage on site and vehicles on nearby parking lot destroyed.
PT/1988/001	"Various fuels"	Fixed roof storage tank (>3700m^3)	Tank explosion	Maintenance works (M&C)	Tank explosion and subsequent fires	Destruction of the tank and surrounding equipment.
FR/1989/001	Benzene	Storage tank (2000 m^3)	Tank explosion	Maintenance works (M&C) on tank presumed to be empty	Tank explosion	Tank destroyed.
FR/1991/002	Gasoline	Pipeline (underground)	Leak from inspection pit	Maintenance works (M&C) on piping	Flash fire and subsequent pool fire	
DE/1993/013	Crude oil	Pipeline	Release from open end in pipe	Maintenance (M&C) (pipe welding)	Local flash fire	
GB/1994/008	Petroleum	Pipeline	Release from valve	Hammer after closure of valve (M&C)	Vapour cloud fire (cloud length > 100 m)	
GB/1998/002	Gasoline	Storage tank (11,000 m^3)	Leak from drain weld	Erroneous application of drain welds (M&C)	No ignition	
NL/1998/001	Pentane	Storage tank	Tank explosion	Cleaning operations (M&C)	Tank explosion	
FR/2001/004	Gasoline	Internal floating roof storage tank (5000 m^3)	Tank explosion	Cleaning operations (M&C)	Tank explosion	Tank destroyed, substantial damage on site.

Incident	Substance	Installation type	LOC scenario	Cause [(1)]	Consequence	Blast damage (if any)
NL/2003/004	'K1'	Transfer to/from ship	Release from pipeline	Maintenance (M&C)	Flash fire with secondary release from blocked piping (labelled 'fireball')	
Overfill error (3 cases):						
IT/1985/003	Unspecified petroleum product	Storage tank	Overfill	Unknown overfill error (OE)	Violent explosion, fire, tank farm fire, secondary explosions	Twenty-five storage tanks were damaged by the blast. Destruction of buildings nearby. Serious damage to buildings within various hundred meters.
GB/1997/007	Motor spirit	Storage tank (1200 m^3)	Overfill (50 ton)	Defective level gauge and ineffective level trip (OE)	No ignition	
BE/2001/002	Hexane	Storage tank (> 1000 m^3)	Overfill (60 ton)	Miscalculated tank capacity and defective high level alarm (OE)	No ignition	
Unknown cause (3 cases):						
GR/1986/001	Fuel oil	Storage depot (multiple tanks, biggest tank 62,000 m^3)	Pipe failure	Unknown (Un)	Fire spread and affected multiple tanks, explosion of multiple oil tanks and BLEVE of a 70 m^3 water tank.	Not clear whether damage was result from fire or from explosion. No damage reported off site.
FR/1991/003	Unleaded petrol	Storage tank (est. 25000 m^3)	Leak from transfer line [(4)]	Unknown (Un)	Violent explosion and subsequent pool fire	Heavy material damage on site and broken windows up to 700 m distance (estimated TNT equivalent 1800-3600 kg).
ES/2003/002	Gasoline	6 storage tanks	?	Under investigation (Un)	Fire with explosion	?

Table C.2 Details for incidents related to transfer (selection)

Incident	Substance	Operation	LOC scenario	Cause [(1)]	Consequence	Blast damage (if any)
DE/1986/003	Benzene	Transfer to ship	Compartment explosion (110 m^3)	Ignition during transfer of product while sampling a tank compartment (FoB)	Explosion of compartment, shortly afterwards followed by an explosion of an empty tank nearby	Tank compartment heavily damaged, nearby empty tank destroyed.
GR/1989/001	Gasoline	Transfer to ship	Fire and explosions	Damaged flanges in engine room (FoB)	An explosion and subsequent fire in engine room escalated after 6 hours.	Ship destroyed.
ES/1989/001	Crude oil	Transfer from ship	Pipe rupture (500 kg released)	Bad weather (C&I)	No ignition	
GB/1992/005	Benzene	Transfer from ship	Release from open valve (1 kg/s)	Human error (OE)	No ignition	
ES/1993/001	Gasoline	Docking at jetty	Pipeline rupture	Crash of ship into jetty (C&I)	Pool fire (on water)	
PT/1998/001	Crude oil	Transfer from ship	Release from pipeline (210 m^3)	Human error (OE)	Flash fire	
GR/1998/001	Gasoline	Transfer from ship	Pipeline rupture (under water)	Heavy wind (C&I)	Flash fire and subsequent pool fire (on water)	
GB/1999/002	Condensate	Transfer	Leak from open valve in pipe manifold (30 m^3)	Operator error (OE)	No ignition	

(1) Causes were defined and categorised by RIVM. The following categories are distinguished: Collision of ships and impact with the jetty (C&I, 3x), Overfill error (OE, 3x), Fire on board of ship (FoB, 2x).

Appendix D - Summary of most relevant literature

Buncefield Major Incident Investigation Board, Initial report, 2006 [15]
In [15] the Buncefield Major Incident Investigation Board published a list of six incidents that have ‘similarities with the Buncefield incident’. The following incidents are mentioned:

- Houston, Texas USA, 1962; explosion after a leak from a storage tank, probably due to overfilling gasoline. Few details available.
- Baytown, Texas USA, 1977; explosion following overfilling of a ship, possibly involving a ‘congested’ are. Only limited details available.
- Newark, New Jersey USA, 1983; heavy explosion following overfilling of a storage tank. with unleaded gasoline.
- Naples, Italy, 1985; heavy explosion following overfilling of a storage tank with unleaded gasoline.
- St. Herblain, France, 1991; heavy explosion following leakage of gasoline from a pipeline.
- Jacksonville, Florida USA, 1993; heavy explosion after overfilling a storage tank with unleaded gasoline.
- Leam Chabang, Thailand, 1999; heavy explosion after overfilling a gasoline storage tank

The correspondence between the incidents is that large quantities of gasoline were released (over 100 tonnes) due to overfilling of a tank or by leakages from pipework in a bund, and that the wind speed was very low.
In two or possibly three cases the cloud was in a congested area. In two of the remaining cases the incident descriptions do not contain sufficient detail to give a reliable estimate of the magnitude of the overpressure.

Chang JI and Lin CC, A study of storage tank incidents, J. of Loss Prev. 19, 2006, p.51-59 [17]
Chang and Lin describe the causes of storage tanks on industrial sites in general. Their article used at least ten different sources for input. 74% of the total number of incidents concern petroleum products (involving refining processes, transportation or storage). 85% of the analysed incidents lead to a fire or explosion. Lightning stroke is the most common cause (33%), followed by errors during maintenance work (13%), errors of operators (12%), failing instrumentation and equipment (8%), sabotage (7%), tank ruptures or fissures (7%), pipe leaks or ruptures (6%), static electricity (5%), open fire (3%), natural disasters (3%) and runaway reactions (8%).
If flammable liquids are released in an overfilling incident, ignition is very likely.

Marsh Risk Consulting, Large property damage losses in the hydrocarbon-chemical industries - a thirty year review, 19th edition, 2001 [33]
Marsh Risk Consulting published a series of reports on incidents in the ‘hydrocarbon-chemical industries’ that occurred during the last 30 years. The 19th edition is based on 380 incidents. Distinction is made between refineries (128 incidents), petrochemical plants (108 incidents), gas processing plants (14 incidents), storage terminals (39 incidents) and off shore activities (91

incidents). The incidents in each category are further subdivided with respect to ‘equipment type’ (for example ‘process’, ‘storage’ or ‘pipework’), ‘event type’ (for example ‘fire’ or ‘explosion’) and ‘operating type’ (different subcategories for each industry type).

- In refineries 12% of the incidents occur within the storage area (possibly more, as there is an obscure category ‘other’ containing 32% of the incidents).
- In petrochemical plant the contribution of storage is 6% (category ‘other’ 40%).
- Within storage terminals 18% of the incidents involve pipelines, 21% storage tanks and 21% product transfer from ships. The category ‘other’ involves 41% of the incidents. It is expected that a considerable amount of this category ‘other’ also involves the storage tanks themselves.

Within storage terminals 41% of the reported incidents result in a fire, and 33% of the cases (predominantly) result in an explosion. (Note that this information cannot be used to quantify the probability of ignition, as the Marsh reports involve incidents with substantial damage only).

Marsh’s Risk Consulting Practice, Large property damage losses in the hydrocarbon-chemical industries - The 100 largest losses 1972-2001, 20th edition, 2003 [16]

The 20th edition of Marsh Risk Consulting’s analysis gives an overview of the ‘100 largest losses 1972-2002’. The following incidents are relevant for the current investigation:

- Sriracha, Thailand, 1999; an incident caused by overfilling. Five storage tanks were lost. A high level alarm was heard but the filling process wasn’t stopped. Apparently an explosion occurred at 23:30 and a fire lasted for 35 hours. Eight fatalities and 13 injured were counted.
- Shuaiba, Kuwait, 1981; explosion of a naphtha cloud (?) resulting in a ‘tank farm fire’.
- Philadelphia, Pennsylvania USA, 1975; ignition of vapours from a storage tank with crude oil being overfilled gives primary explosion and escalates into a fire with secondary explosions.
- Naples, Italy; 1985; a heavy explosion following overfilling of storage tanks.
- Newark, New Jersey USA, 1983; a heavy explosion following overfilling of storage tanks.
- Bantry Bay, Ireland, 1979, ‘massive explosion’ of a ship containing crude oil after an on board fire.

(Note that the incidents in Naples, Newark and Thailand have also been mentioned in the Buncefield Major Incident Investigation Board overview.)

Persson H and Lönnermark, A, Tank fires - Review of fire incidents 1951 - 2003, Brandforsk Project 513-021, 2004 [18]

The report of Persson and Lönnermark describes the fire fighting activities for 31 incidents. Though it is not intended to describe the cause of the fire, it can usually be retrieved from the incident description. The most frequent cause is lightning stroke, followed by maintenance operations. Both causes often result in a tank explosion (explosion within the proper tank or in the space between a floating deck and a fixed roof). A tank explosion results in rocketing tank parts and may further lead to a tank fire (fire inside remaining tank) or a bund fire. For one incident, substantial damage off site was reported (broken windows in a distance up to 1000 m).

Tank fires and bund fires may lead to explosions of nearby tanks, leakage from nearby tanks or pipework, and therefore to propagation of the fire to nearby bunds. Most other incidents concern sunken roofs (for example as a result of heavy rainfall) leading to tank roof fires (also ‘surface fires’) and possible escalation to a bund fire (and possibly secondary explosions).

Overfilling is mentioned four times as a cause, and gave bund fires with escalations to surrounding equipment in three occasions. An exceptionally heavy overfilling incident involves the Steuart Petroleum disaster in Jacksonville, Florida (1993). Persson and Lönnermark report a vapour cloud explosion but do not mention overpressure values. The incident is also reported in other literature sources (notably [15]).

Worth noticing is that almost all incidents had ignitions prior to the release of liquid to a bund. Late ignition of a vapour cloud only occurred with overfilling incidents.

Table D.1 Summary of incidents reported in [18]

Date	Cause	Substance	Result
26-6-1971	Lightning	Crude oil	Tank fire, bund fire, secondary tank explosion and boil-over
25-9-1972	Overfill	Gasoline	Late ignition, bund fire, tank fires, secondary tank explosion
24-9-1977	Lightning	Diesel	Rocketing roof, damage to secondary tanks, bund fire
21-2-1978	Overfill	Gasoline	Late ignition, bund fire and flange fire
??-??-1980	Overfill	Gasoline	Late ignition, bund fire
??-11-1982	Unknown	Gasoline	Two gasoline tanks on fire
30-8-1983	Unknown	Crude oil	Tank fire escalating to bund fire
31-8-1983	Unknown	Gasoline	Tank fire, escalating to bund fire
5-8-1984	Lightning	Isopropyl alcohol (IPA)	Rocketing roof causing broken windows and other damage in a radius up to 1000 m.(1) Bund fire.
23-10-1985	Heavy rains	Jet fuel	Sunken roof resulting in tank fire and flange fires.
1-10-1986	Lightning	Crude oil	Tank fire with froth over (wooden roof tank)
26-7-1987	Lightning	Crude oil	Tank fire (wooden roof tank)
11-4-1988	Unknown	Slurry	Rocketing roof, tank fire
17-6-1988	Maintenance	#6 Fuel oil	Rocketing roof, tank fire
23-3-1989	Unknown	Isohexane	Leak in floating roof, resulting in tank fire
24-12-1989	Domino	Ethane/propane, heating oil	An explosion of a ethane/propane tank set two heating oil tanks on fire
2-1-1993	Overfill	Gasoline	Late ignition resulting in vapour cloud explosion, bund fire with escalation outside bund
7-11-1994	Heavy rains	Unknown	Sunken roof resulting in tank fire
30-3-1995	Crack in tank roof	Heated res. fuel	Ignition of heated residue fuel

4-6-1996	Lightning	MTBE	Rocketing roof, bund fire
11-6-1996	Lightning	Gasoline	Rocketing roof, tank fire
19-7-1996	Lightning	~ gasoline	Tank fire
18-2-1998	Domino	Ethanol	Substantial external heat radiation causing a tank fire
28-10-1999	Maintenance	Gasoil	Rocketing roof, tank fire
7-6-2001	Lightning	Gasoline	Sunken roof resulting in tank fire
10-7-2001	Unknown	Heated asphalt	Tank explosion with subsequent tank fire
15-8-2001	Unknown	Heated asphalt	Liquid heated asphalt (see previous incident) ignited by unknown source during transfer
5-5-2002	Lightning	Crude oil	Rocketing roof, tank fire escalating to bund fire
18-8-2002	Pipe rupture	Heated res. fuel	A rupture of a pipe with heated residue fuel causing a bund fire
7-3-2003	Sabotage	Petrol	Bund fire after mortar attack
3-5-2003	Sampling	Gasoline	Rocketing roof and subsequent tank fire

(1) The reported distance of 1000 m is exceptional. The incident is not reported in the MARS database. It is expected that the reported damage was caused by debris.

Bouchard JK, Gasoline storage tank explosion and fire - Newark New Jersey January 8 1983, NFPA Fire investigations [34]
The incident in Newark (7 January 1983) took place after a 1,760,000 gallon (6500 m^3) storage tank was overflowing unleaded gasoline from the vent pipe for an unknown amount of time. Around midnight several small explosions were quickly succeeded by a ‘tremendous blast’. The expected source of ignition was 300 m away from the release location. Damage included a flattened tank at 400 m distance from the release location (200 m from the ignition source), flattened railroad cars and structural damage to various surrounding industries. [34] It is expected that the cloud area was not (or hardly) congested or obstructed.

Maremonti M et al., Post-accident analysis of vapour cloud explosions in fuel storage areas, Trans IChemE Vol. 77 Iss B, p. 360-365, 1999 [35]
The incident in Naples (21 December 1985) occurred after a tank had been overflowing with gasoline for at least 1.5 hours. Ambient temperature was about 8 °C and wind speed 2 m/s. The resulting flammable cloud was assumed to be about 120 m long and 300 m wide. The cloud entered a ‘highly confined’ area, covered with tanks, walls, buildings and an embankment. A strong vapour cloud explosion followed ignition with maximum overpressure estimated at 500 mbar. Minor effects were reported up to 5 km distance. [35]

Lechaudel JF and Mouilleu Y, Assessment of a vapour cloud explosion - A case study: Saint Herblain, October the 7th 1991, France, Proceedings of the 8th International Loss Prevention Symposium, p. 333-348, 1995 [36]

The Saint-Herblain incident (7 October 1991) occurred after erroneous opening of a valve on a transfer line transporting gasoline. The incident took place at about 4 a.m. in the morning under stable wind conditions, low temperature (5 °C) and high humidity (nearly 100%). The flammable cloud was estimated to be at least 23,000 m^3 and was eventually ignited at a distance of 50 m from the release location. The maximum overpressure values at the Saint-Herblain incident are estimated at 250 mbar. A row of parked tanker trucks is considered to have contributed significantly to the occurrence of the blast. Overpressures of 100 mbar were reached at a distance of 100 - 150 m from the parked tanker trucks. Window panes were broken in a 2 km radius. [36]

Christou MD, Analysis and control of major accidents from the intermediate temporary storage of dangerous substances in marshalling yards and port areas, J. of Loss Prev. 12, 1999, p. 109-119 [20]
Christou studied incidents at rail marshalling yards and port areas, for which he used five databases. With respect to explosions involving flammable liquids, three incidents are reported that involve explosions on or near ships (respectively in Ireland, Spain and Iran) and one explosion involving a rail ranker on a marshalling yard (in India):
- In Ireland (1983) a tanker broke due to improper ballasting while unloading oil. The spill caught fire which was followed by an explosion, resulting in 50 fatalities. Fragments were reported to have travelled 10 km.
- In Spain (1985) there was an explosion and fire on two ships (one containing gasoline, the other containing naphtha) in the jetty area during transshipment.
- In Italy (Naples, 1985) overfilling of a tank during transshipment resulted in an explosion with considerable overpressures.
- In India (1983) an explosion of a leaking rail tanker filled with kerosene resulted in 47 fatalities.

Lautkaski R, Evaluation of BLEVE risks of tank wagons carrying flammable liquids, J. of Loss Prev. 22, p. 117-123 [[23]]
Lautkaski discusses that possibility that rail wagons carrying flammable liquids will rupture when engulfed in a fire. In total he studied 30 collision and derailment incidents, which were reported in the ARIA database, the GUNDI database, and the MHIDAS database. In six of these incidents, tank ruptures were reported that were clearly the result of exposure to an (engulfing) fire, namely:
- Brachwede, Germany, 1974
- Hannover, Germany, 1985
- Rude, Sweden, 1986
- La Voulte sur Rhône, France, 1993
- Elsterwerda, Germany, 1997
- Mount Saint-Hillaire, Canada, 1999.

Some additional information is given on the incident in Rude, Sweden (1986). The reported diameter of the fireball was 100 m. Two firemen were knocked down by the corresponding pressure wave.

Oggero A et al., A survey of accidents occurring during the transport of hazardous substances by road and rail, J. of Hazardous Materials, A133, 2006, p.1-7 [25]
Oggero used accidents reported in the MHIDAS database (property of the UK Health and Safety Executive) for a statistical analysis of consequences of road and railway accidents. The analysis includes releases of both toxic and flammable substances. Accidents during loading and unloading operations are explicitly excluded from the study.
According to this study, 33% of the releases have an ignition (early or late). It is further analysed how many of these ignition involve fires and how many explosions. However, as no distinction is made between gasses and liquids, the results cannot be used for the current Buncefield study.

Ronza et al., Using transportation accident databases to investigate ignition and explosion probabilities of flammable spills, J. Haz. Mat., Vol. 146, p. 106-123, 2007 [26]
Ronza analyses the probability of ignition for road, railway and water incidents, using USA databases (HMIRS and MINMOD). The study distinguishes between different types of substances. For liquid petroleum products it is calculated that explosions occur in 18 to 58 percent of the ignited releases (Table 5, releases larger than 100 kg). As the term 'explosion' it is not properly defined, and as USA codes and standards deviate from European ones, the relevance of the presented figures for the Buncefield study is limited.

FACTS
The TNO FACTS database [13] contains information on more than 22,000 incidents, more than a hundred of which were studied for this project. Below, very relevant incidents are summarised for which FACTS supplied key data that are not available from public sources.

- FACTS 204 – Roosendaal, the Netherlands, 1975: A gasoline storage tank overfills during transshipment from a ship. Vapours ignited and a vapour cloud explosion occurred. Reportedly, buildings were destroyed, but no further details are provided. Glass breakage occurred within a radius of 900 m.
- FACTS 9667 – Herborn, Germany, 1987: A road tanker filled with gasoline and diesel overturned and started leaking flammable liquids. Part of the liquid spilled into the sewer system and surface water drains. The overpressure following the ignition of the vapours damaged several nearby buildings and several people were knocked down by the pressure wave. No further details are provided on the specific damage to the buildings.
- FACTS 11611 – Zurich, Switzerland, 1994: Eleven rail tankers derail and leaking flammable liquids ignite causing severe damage to nearby houses. After the extinguishment of the fire, fuel leaks into the city water drainage system and ignites multiple times. Streets are lifted by these explosions over a length of 400 m and eighty-five damages to buildings are reported.
- FACTS 18785 – New York, USA, 2003: An explosion occurred during transfer of gasoline from a barge to a terminal. A defective pump is expected to have been the cause. The explosion caused cracks in the foundation of a house at three locations and broke a dozen of windows. The distance between the barge and the house is not reported.

Aria

The French Aria database [14] contains information on (at least) three incidents with rail cars that gave violent explosions after the release of gasoline:

- ARIA 2438 – Chavanay, France, 1990: A train derails. Nine fuel tanker cars catch fire and explode. The flames reach nearby houses and fuel leaks into the sewers. In an area of 1 km long and 400 wide, 8 houses, 2 garages and 30 cars are destroyed, five more houses are damaged.
- ARIA 4225 – La Voulte sur Rhône, France, 1993: A train derails. Four tanker cars start leaking and a violent fire occurs. Twenty minutes later, the violent and complete fissure of the side of a tanker car leads to an explosion and a fireball. Streams of burning hydrocarbons flow into the terrain and generate a series of explosions in the sewage system.
- ARIA 5073 – Zürich, Switzerland, 1994: A train derails, catches fire and explodes in a railway station. Fuels leaks into the sewers and explosions occur. A crater with a diameter of 10 m is formed. A rain water collection system is damaged. Two more explosions occurred, one of which during the next day.

world wide web

Information on the world wide web provided additional information for several cases:

- The rupture of a 40,000 m^3 crude oil storage tank in Belgium (October 25, 2005) is described in detail in [19]. The released contents remained largely in the bund (3 m^3 overtopping) and did not ignite.
- The explosion of a ship's compartment in New York (November 9, 1975) is described in detail in [30]. Extensive damage and window breakage at one-half mile distances was reported.

The internet also provided additional information on the supposed explosion of kerosene in India ([20]). According to [21] the incident involved an explosion of two tankers loaded with gasoline at a station. The information was apparently retrieved from the MHIDAS database, which is the same source that [20] used for his article.

Appendix E - Description of the Buncefield incident

Cause:
The cause of the Buncefield was an overflow of unleaded petrol from a large storage tank (tank 912, 6000 m^3 nominal tank volume) with subsequent formation of a flammable mixture in open air and ignition.

Formation of the cloud:
At the time of the overflow the tank was being filled from a (large distance) 14” pipeline. When the tank started to overflow (around 5:20 am), the flow rate was about 550 m^3/hr. Between 5:50 am and 6:00 am the flow rate gradually increased to 890 m^3/hr ([15], p.7).

Outflow was from eight ventilation holes at the top of the tank (estimated about 15-20 m above ground), each ventilation hole about 0.07 m^2 in size. The outflowing product was scattered by a deflector plate and a wind girder. ([39], p.11/12)

The temperature was about 0 °C, wind 0-3 m/s, humidity close to 100% and atmosphere stable (Pasquill class F). ([40], p.17)

CCTV footage first shows a mist escaping from the bund towards the west around 05:38 am. At the time the cloud was about 1 m deep. Around 05:46 the cloud was about 2 m deep and was escaping the bund in all directions. Around 05:50 the cloud started flowing off site, direction west, crossing Buncefield Lane towards the Northgate House and Fuji Building car parks. ([15], p.7) The cloud footprint is estimated to have been just over 300 m x 200 m in size prior to ignition. The cloud height seems to have differed from 1 m in the south, to 7 m in the north. ([39], p.13) The total amount of flammable mass in the cloud has not yet been reported.

Ignition:
Ignition took place around 06:01 am. At the time the vapour cloud had extended towards Boundary Way (200 m west of the bund), Catherine House (150-200 m northwest of the bund), Tank 12 (100 m northeast of the bund), the BPA site (100-150 m east of the bund) and across the HOSL West site (below 100 m south of the bund). ([15], p.7). It is estimated that an area of around 120,000 m^2 was covered by the cloud, and that the cloud had an average height of 2m ([42]). The most likely candidate for ignition is a pump house located about 70 m away from tank 912 ([42]).

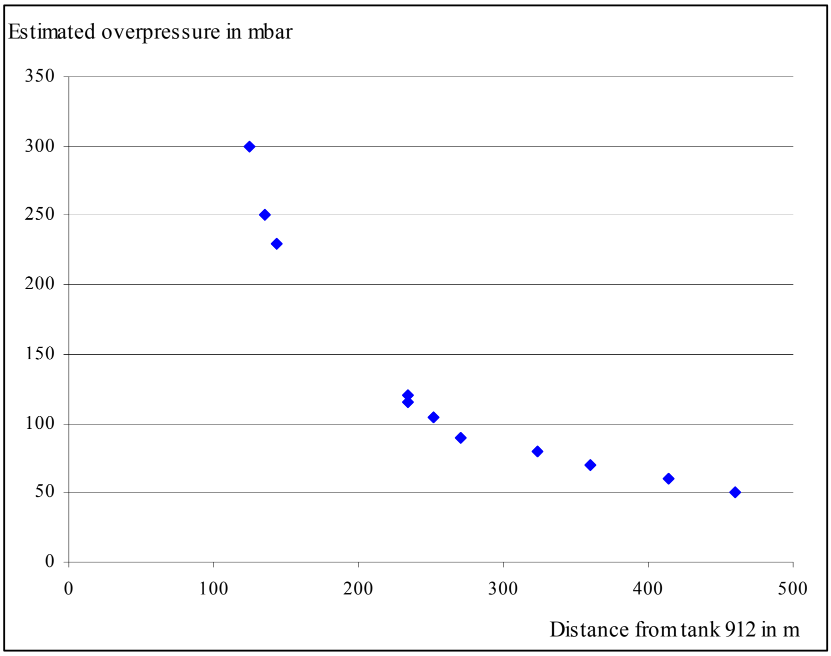
Consequences:
The mechanism of the explosion and the resulting damage is described in detail in a report from the UK Health and Safety Executive ([42]). According to current understanding, overpressures exceeding 2 bar have occurred within the cloud. Outside the cloud, overpressures rapidly dropped, reaching levels of 50 to 100 mbar at 150 m from the cloud edge. Overpressures around 50 mbar were also observed in the far field (2 to 4 km, according to [42]).

According to [42], the flammable cloud detonated near the intersection of Cherry Tree Lane and Buncefield lane, and onwards along Buncefield lane. A set of pressure – distance pairs reported in [42] (Figure F.1 in [42]) and repeated here in Table E.1, showed substantial coherence in pressure versus distance (see Figure E.1 below). Based on an interpolation between these values, overpressures in excess of 300 mbar occurred up to about 120 m from tank 912, and overpressures in excess of 100 mbar up to 270 m. It is noted that these values are very specific for the Buncefield incident and will not hold in general for vapour cloud explosions.

Table E.1 Pressure – distance pairs reported in [42]

Distance from tank 912 in meters	Estimated overpressure in mbar
252	105
234	115
324	80
414	60
270	90
125	300
460	50
234	120
360	70
135	250
144	230

Figure E.1 Overpressure versus distance pairs reported in [42] (1)



(1) It is stressed that this correlation is very specific for the Buncefield incident and will not hold in general for vapour cloud explosions!

Appendix F - Members of the Advisory Committee

This report has come about under the guidance of an Advisory Committee with the following members:

Mr. PJMG Frijns
Ministry of Housing, Spatial Planning and Environment (VROM),
Den Haag

Mr. DM Huizinga
Oiltanking
Amsterdam

Mr. C Jacobs
Shell Netherlands Refinery
Pernis

Mr. HW van Lochem
Akzo Nobel Technology & Engineering
Arnhem

Mr. JA Meeusen
DOW Benelux BV
Terneuzen

Mr. R Mante
Ministry of Transport, Public Works and Water Management (VenW)
Den Haag

Mrs. N Schmersal-Hoekstra
Province of Noord-Holland
Haarlem

Mrs. V Sol
Ministry of Social Affairs and Employment (SZW)
Den Haag

Mr. LJ Vijgen
Environmental Protection Agency Rotterdam (DCMR)
Rotterdam

Mrs. C Westerbroek-Thijssen
Shell Netherlands Chemicals
Moerdijk

RIVM

National Institute
for Public Health
and the Environment

P.O. Box 1
3720 BA Bilthoven
The Netherlands
www.rivm.com