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Liability Risk Assessment at Skarvik Port

Master of Science Thesis in Product Development and Complex Adaptive Systems

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Abstract

The study was conducted for insurance purposes at the oil refinery Preemraff Göteborg. Preem facilities in Skarvik port are surrounded by the facilities of other companies. In case of an accident caused by Preem there would be potential liability claims. Insurance risk assessment is a well-developed approach for insurance of a company's own property, it is not normally used for liability risks. This study suggests methodology for determination of liability insurance values. Based on the obtained results and calculations of replacement values, the worst case scenario for Preem in Skarvik was chosen and recommendations were made regarding the liability risk.

Acknowledgement

First we would like to thank our examiner, Mohammad Shahriari, for giving us the opportunity to write this study at Preem and guiding us on the way.

We are also very grateful to our supervisor at Preem, Mats Lindgren, for advising and helping us at every step. His encouragement, supervision and support from the first to the last stage of the project enabled us to develop a deeper understanding of the subject.

It is a pleasure to thank those who made this thesis possible - Mikael Gustavsson, Jon Engelsen, Inge Österberg, Ari Niemi, Robin Savelid; Catrin Arngården and Kristina Hillström from Scanlube; and Jan Ahlbom from Miljöskyddsenheten.

Finally we would like to thank Preemraff Göteborg for providing us with an office and free tea.

Abbreviations

ETA – Event Tree Analysis
Göteborg Energy – Göteborg Energi AB
Nordic Storage – Nordic Storage AB
Norsk Hydro – Norsk Hydro ASA
Preem – Preem AB
Saybolt – Saybolt Sweden AB
Scanlube – Scanlube AB
St1 – St1 Oy
Vopak – Vopak Sweden AB

1. Introduction

Background

Accidents in oil and chemical industry might bring very large damages, both to the company where the accident happens and other companies if their facilities lie close to the place of the accident.

Preemraff Göteborg is an oil refinery located in Gothenburg, at the island of Hisingen. Preem is the largest supplier of petroleum products in Sweden and its two refineries, one in Göteborg and one in Lysekil, represent two-thirds of Sweden's refining capacity. The facilities produce liquefied petroleum gas, gasoline, diesel and heating oil for both the Swedish and foreign markets.

The company has an oil terminal and depot at Skarvik port, a part of the Port of Gothenburg. Several companies operate in this area close to each other with activities such as storage, loading and unloading of petroleum products and chemicals to and from ships, rail cars and road tankers (See Appendices 1 and 2). Preem's facilities are situated closely to facilities of other companies, such as Scanlube, Nordic Storage etc. This in turn means a potential for damages claims if there is an accident at Preem's facilities which brings destruction of property and business interruption to other companies.

Figure 1. Map of Skarvik port

Consequence modelling for insurance risk assessment is a well-developed approach for insurance of a company's own property. It is not normally used for liability risks.

Purpose

The purpose of the study is to suggest methodology for determination of liability risks and to determine liability risk in Skarvik including the total limit (maximum insurance value that can be paid) for Preem.

Aim

The aim of this study is to make recommendations to Preem regarding a) insurance against legal liability for damages to other parties and b) risk mitigation options given the liability risks assessment.

Objectives

The study is divided into 3 parts.

- literature study
- modelling of potential accidents at Preem facilities in Skarvik
- assessment of potential liability claims from other companies

The objective of the literature study was to find the accidents in the oil and chemical industries with the biggest damages to other companies and extract information about business interruption claims in these cases.

Thereafter modelling of such accident scenarios was done to determine potential damages from such accidents to other companies, neighbours of Preem at Skarvik port.

The final part of the study assess the potential business interruption damages caused by Preem to the other companies in Skarvik in case of serious accidents such as fire, explosion or uncontrolled release caused by Preem.

Limitations

Limitations for this study primarily concern the limitations of the software used (it does not have a capability to handle multi-component mixtures etc). Time frame was also the limitation.

Business interruption claims is a matter most often solved privately and thus it was hard to find open references about it.

The objective of this study was to assess specifically property and business interruption damage, the possible effect of the accidents to people and environment and also the effect of the accidents that are not Preem's fault (i.e. force majeure) has been excluded from it.

2. Theoretical Background

2.1 Fire and explosion

2.1.1 Vapour cloud explosion

Vapour cloud explosion (VCE) can be defined as 'an explosion caused by the instantaneous burning of vapour cloud formed in air due to release of flammable chemical' (Khan, 2004). Usually if there is loss of containment in a refinery, vapour or gas fuel is released. In order for a VCE to occur there must be a large release of flammable material in the atmosphere, a subsequent dispersion phase, and after some delay, an ignition of the vapour cloud (Guidelines for evaluating the characteristics of vapour cloud explosions, flash fires and BLEVEs – Centre for Chemical Process Safety (CCPS)). Due to the explosion overpressure which propagates outwards from the explosion site a pressure wave is produced (Gowl, 2003).

Not all of the released material participates in a VCE. The lowest percentage of the substance in air (the lowest concentration) that will burn when an ignition source is present is known as the Lower Flammable Limit (LFL). If the concentration is lower than LFL, the mixture is too 'lean' to burn. Upper Flammability Limit (UFL) of a vapour or gas is the highest percentage of the substance in air (the highest concentration) that will produce a burn when an ignition source is present. For concentration higher than UFL, the mixture is too "rich" or "overcarbonated", to burn (Wagner-Meinert, 2008).

A VCE can be classified as either confined or unconfined. A confined explosion is one that occurs inside a process vessel or a building. In this type of explosion even a slow combustion process will generate overpressure (Bjerketvedt et. al, 1993). An explosion for which there is no venting or heat loss is known as fully confined explosion. This type of explosion generates high overpressure in the range of a factor eight times the starting overpressure. If there is region with obstacles, known as a congested region, there will be increased turbulences because the flow is obstructed by objects. Explosions in open areas are known as unconfined explosions. If it is truly unconfined, for an unobstructed gas cloud ignited by a weak ignition source, only a small overpressure while burning, a so called flash fire, will be produced (Bjerketvedt et. al, 1993).

A vapour cloud generally has three regions (CCPS, 1994). Near the point of the release is the rich region, at the edge of the cloud is the lean region and between these two is the flammable region. In order to have an extensive overpressure a sufficient amount of the cloud must be within the flammable range of the material. Other factors that influence the vapour cloud in each region are: type and amount of material released; pressure and time of release; size of release opening; wind, humidity, and other environmental effects (CCPS, 1996).

2.1.2 BLEVE

If a) the boiling point of a liquid is above ambient temperature and b) the liquid is heated before release by an external heat source to a temperature above its boiling point - it can cause a Boiling Liquid Expanding Vapour Explosion (BLEVE).

BLEVE is defined as 'an explosion resulting from a failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure (CCPS, 1994).

A liquid does not have to be flammable to cause BLEVE, which is the main difference between this type of explosion and VCE (see above).

Non-flammable liquid BLEVE can cause two effects: overpressure due to the expansion of the vapour in the container with flashing of the liquid, as well as fragmentation of the container. Since liquids within containers are a combination of liquid and vapour, before container's rupture the liquid phase is in equilibrium with the vapour phase. When it comes to a rupture of the container the vapour is vented and the liquid's surrounding pressure drops sharply. In case of a higher than boiling liquid temperature but lower than the superheat temperature, instantaneous boiling may occur throughout the bulk of the liquid. This will in turn cause formation of large number of vapour bubbles in the liquid. This means that within a very short time a large fraction of the liquid will vaporize. In such cases the energy for the blast and fragment generation is mainly due to the expansion of the vapour in the space above the liquid. On the other hand, if the temperature of the liquid is higher than the superheat limit temperature, very high energy will be liberated. This will cause high blast pressure and generation of fragments with high initial velocities, which can be thrown long distances.

A container can fail due to: excessive pressure inside of it, long time exposure on external heating, such as fire, corrosion etc. BLEVEs are usually associated with release of flammable liquids from vessels as a result of external fires, which means that BLEVE's effects are determined by the condition of the contents in the container and of its walls at the moment of the containers failure. If a container with flammable liquid is heated its metal is heated and loses mechanical strength. The heat is transferred to the liquid and liquid's temperature rises. When the boiling point is reached vapour bubbles are formed at the active sites that occur at interface with solids, including vessels walls. This type of BLEVE is accompanied by a fireball. A cloud of almost pure vapour and mist is formed due to the rapid vaporization, expansion and loss of containment. After the vapour is ignited it starts to burn at the surface where it's mixed with air. The combustion propagates to the centre of the cloud and a fireball is obtained.

An accident such as that, which includes a fireball, is followed by a powerful heat radiation – heat flux. Parameters that affect the radiation effects are: the diameter of the fireball as a function of time, the maximum diameter of the fireball, the height of the centre of the fireball above its ignition position as a function of time (after lift-off), the surface – emissive power of the fireball and the duration of combustion (CCPS, 1996).

The consequences of the radiation are determined by the distance of the fireball to targets and atmospheric transmissivity.

2.1.3 Pool fire

A pool fire can be defined as 'a turbulent diffusion fire burning above a horizontal pool vaporising flammable material under conditions where the flammable material has zero or very low initial momentum' (Cowley and Johnson, 1991). The most characteristic thing for this type of fire is that there is a heat transfer back from the fire to the pool. This means that the rate of evaporation is influenced, or even controlled, by that feedback, which makes fire size and some other characteristics to depend on it as well.

Liquid fuels can burn either in an open storage container or on the ground or in the form of a spill. For a given amount of fuel, spill with a large surface area will have a high Heat Release Rate (HRR) for a short duration, and spills with a smaller surface area will have a lower HRR for a longer duration (Tewarson, 1995). If a flammable liquid is spilled it may form a pool of any shape and thickness and once it's ignited the fire will spread rapidly over the spilled area.

The shape (form) of the fuel material together with the fuel composition (chemistry) influences the burning duration. Pool fires can have different diameters depending on: release mode, release quantity, burning rate etc. There can be confined pool fire e.g. in a case of release into containment dikes, and unconfined e.g. in a case of releases from LPG or gasoline road tanks.

2.1.4 Dense gas explosion

Dense gas can be defined as 'gas which has a higher specific weight than the surrounding ambient air' (Britter and Griffiths, 1982). Most flammable gases are denser-than-air, as a consequence the flammable dense gas cloud will normally remain in the lower part of the atmosphere and it will largely spread in the lateral direction and it will not disperse as fast as a light gas. Due to that reason, a release of a dense gas has a higher potential of forming larger fuel air clouds than a release of a light gas (Bjerketvedt et. al, 1993).

A large number of materials can form dense gas clouds. Within the refinery industry many products are vapours under atmospheric pressure. However, these products are commonly stored or transported as liquids, maintained in that phase at, or near, their saturation temperature at atmospheric pressure by refrigeration and insulation, or at ambient temperature by pressurisation (Yellow Book, ch. 4.11). If somehow containment like that is lost, most or all of the liquid will vaporize.

For risk assessment purposes there are three primary ways of release: rapid-in a case of catastrophic failure of a pressure vessel; continuous-if the release is through a small hole in the vapour space of a pressure vessel; and combination of the two mentioned above-if a low boiling point liquid from a refrigerated vessel is released onto land. In that case, assuming that the pool spread is limited, there will be an initial rapid boil – off, followed by a more steady evolution of vapour.

2.2 EFFECTS 8.1. Yellow Book

The work on the 'Coloured books' was initiated by the Dutch Government in the 1990's. The task was given to Netherlands Organisation for Applied Scientific Research (TNO). Now the books ('Yellow book', 'Green book', 'Purple book' and 'Red book') are used around the world as a standard reference material for safety studies (TNO, The Colored Books, 2011).

In 2007 TNO used the 'Yellow Book' and the 'Green Book' as a basis for software called EFFECTS. The 'Yellow Book' provides information about consequence analysis while the 'Green Book' describes the relationship between physical phenomena and the resulting damage.

EFFECTS is used by many industrial companies, governments and research institutions around the world. The latest version of the software by the time of this study is EFFECTS 8. It is used to perform safety analysis for the petrochemical industry. EFFECTS 8 offers calculation models for accidents with storage and transportation of chemicals (TNO, 2011. EFFECTS).

A large variety of chemicals can be handled by this the software, since it has a database containing toxic, flammable and thermodynamic properties. (TNO, 2011. EFFECTS). However there is also a possibility for the user to extend the database with chemicals that are needed for some specific work.

The calculations and physical effects of any accident scenario with toxic and/or flammable chemicals made with EFFECTS are given in tables, graphs and on geographical maps. Also, valuable information for hazard identification, safety analysis, quantitative risk analysis (QRA) and emergency planning is provided through the contours of effects, such as overpressure, heat radiation and consequences like lethality and structural damage.

2.3 ETA

In many industries, including oil and petrochemical, a lot of techniques for risk assessment are used. Mainly, when there is a potential hazardous event the Event Tree Analysis (ETA) is used as a technique for identifying the consequences of it. This technique provides possibility to predict the frequency of all potential accident scenarios in a case of such an event. The event that triggers hazardous situation is known as initiating event. ETA is an inductive technique because it examines all possible responses that can be cause from the initiating event. Each branch of the tree structure represents success, failure or partial failure of the events related to the initiating event.

It can be seen that when a tree like this is constructed several steps need to be included. First of all the initial event that triggers unwanted consequences needs to be identified as well as the consequences resulting from it. Next thing that need to be done is to determine the frequency of the accidental event as well as the accident event and the probabilities of the branches in the tree. At the end, the probabilities (frequencies) for the outcomes (consequences) are calculated and the results are presented.

3. Method

Literature study

The project started with literature search in two directions.

To begin with, data about previous serious accidents in oil and chemical industries was gathered from a number of sources including Chalmers library and internet resources such as Scopus and Elsevier. This was done to determine the most common causes and consequences of major accidents and to determine the scenarios with the highest damage potential for Preem facilities at Skarvik port. A literature search of legal liability precedents followed using the same sources.

Preem Safety report was used to determine other probable accidents causes based on the analysis conducted by work environment coordinators of Preemraff Göteborg.

Interviews and personal visits

When the aim and objectives of the study were set a visual inspection and a number of interviews were conducted at Skarvik port with the purpose of reviewing the business and operations in Skarvik port. Information about other companies' tanks, their locations and contents was taken from Miljöskyddsenheten (Environmental Protection Division of County Administration for Västra Götaland county.).

Selection of scenarios to model

Preem safety report (Preemraff Göteborg, 2005) as well as the results of the literature review were discussed and analyzed. 'What-if' analysis and brainstorming techniques were used to select the final list of 6 scenarios for modelling. Event tree analysis was used to determine the chain of events leading to the accident.

Modelling

The scenarios from the final list were modelled using software developed by the Netherlands Organisation for Applied Scientific Research (TNO), called EFFECTS 8.1. Methods of calculation of physical effects ('Yellow Book') and EFFECTS manual were used to calculate necessary input values. Some additional manual calculations were performed (See Ch.4).

Discussion of mitigation techniques

Mitigation techniques for the final list of scenarios were discussed using Preem safety report (Preemraff Göteborg, 2005)

Evaluation of replacement values for other companies' property considering possible domino effects

Calculation of replacement values for other companies' tanks, structures etc. was conducted using the data from Preem's Insurance Valuation done by King Sturge (King Sturge Plant&Machinery, 2008) and Scanlube 'Summary of property values' provided by Scanlube (G-O Forsberg Risk Consulting, 2009).

4. Description of Skarvik Port

Skarvikshamnen (Skarvik harbour) is Preem’s major product and chemical harbour. It is used mainly for petrol products, chemicals and import of bitumen crude (August Leffler & Son, 2011).

Preem Skarvik depot is located on the island of Hisingen, in Gothenburg. The depot was built in the early 1970-s by Swedish BP.

Skarvik is different from other depots of Preem by its proximity to the refinery, Preemraff Göteborg. Most of the products are pumped to Skarvik through 6 km long pipeline from the refinery. Apart from usual oil products Preem stores a range of special products, 'environmental gasoline' and diesel in Skarvik. It also operates a gas depot.

The depot is divided into three sections. The main products are on the East depot (Östra depån) and special fuel is on the West (Västra depån). Also there is a separate gas unit. The annual throughput of the depot has varied over the years. Now it is around 1.3 million cubic meters, which means that the facilities are visited by more than 38 000 petrol trucks (See Appendices 1 and 2).

The depot is open for loading 24 hours a day.

As it can be seen from Appendices 1 and 2, Preem facilities in Skarvik are surrounded by the facilities of other companies:

Göteborg Energi AB is an energy company that operates a range of energy services and provides electricity supply. (Göteborg Energi AB, 2011)

Nordic Storage AB is an independent storage company for petroleum products and petrochemicals. Nordic Storage owns 24 tanks and 4 caverns in Skarvik suitable for storage of middle distillates, fuel oils, bio fuels, petroleum based special products and chemicals. (Nordic Storage AB, 2011)

Norsk Hydro ASA is a Norwegian aluminium and renewable energy company. In Skarvik, in close proximity to Preem facilities, Norsk Hydro owns tanks containing different petrochemicals with different types of roof. (Norsk Hydro ASA, 2011)

Saybolt is an independent consulting firm, specializing in quality and quantity control.
Saybolt Sweden AB is a service center, which provides information about the quantity and quality of all types of products during shipping, processing and storage. (Saybolt Sweden AB, 2011)

Scanlube AB is a lubricant plant partially owned by Preem. The site consists of offices, machines, storage facilities and various tanks and containers. (Scanlube AB, 2011)

St1 Oy is a Finnish energy company owning the St1 gas stations' chain in Sweden among other countries. In Skarvik St1 owns a large facility containing tanks of different types and sizes. (St1 Oy, 2011)

Stena/Recycling Ciclean Ciclean AB receives and treats oil-contaminated water from ships and waste oil and emulsions from industries in the western parts of Sweden. (Stena/Recycling Ciclean, 2011)

Vopak Sweden AB is a part of Royal Vopak N.V., a Dutch company that stores and handles various oil and natural gas-related products. Vopak Sweden is an operator of independent tank storage facilities in the Nordic countries. It owns 161 tanks and 3 rock caverns in Skarvik. (Vopak Sweden AB, 2011)

4.1 Preem's capabilities in fire fighting and mitigation in Skarvik

Preem has no own rescue personnel resources at Skarvik area. Minimum staffing is at night when the two operators are available to the terminal. In addition to these, the port's Office of traffic inspection and the guard in Skarvik port play an important role in preparing and receiving the local emergency services (Räddningstjänsten Storgöteborg, 2011).

To reduce the risk of serious accidents the company has invested in a number of preventive measures:

- Tank and piping systems controlled under the regulations and activities are analyzed and inspected regularly for hazards.
- The relevant staff is continuously trained in fire, environmental and safety risks.
- The area is largely aligned against the release and fire.
- Unloading and associated equipment is equipped with alarm systems that shut power if any malfunction occurs.
- Tanks and piping are maintained and inspected in accordance with applicable regulatory requirements.
- Custody staff and drivers are continuously undertaking fire training, emergency and evacuation drills, and other industry-specific training.
- The company has a computerized maintenance program that ensures that all inspections, servicing, alarm functions, etc. are maintained and controlled within the intended time interval.

The business has also invested in fixed facilities and materials to reduce impact and increase the ability to deal with a past incident, i.e:

- Sprinklers for cooling LPG tanks.
- Foam sprinklers to fight fire in connection with loading.
- Fixed facilities for the convenience of rescue services.
- Sprinklers for cooling certain endangered cisterns.
- Systems for additional fire fighting water.
- Access to fire equipment for the staff to begin fire fighting.
- Fire alarm with automatic and manual alarms.
- Limitations to prevent the spread of oil leakage.
- Collection equipment, booms, etc.
- In addition to the local emergency services there is an agreement with Preem Extinguishing Media Centre for extinguishing large fires.
- Preem can also deploy the staff of the refinery, where appropriate, to support the local emergency services effort in Skarvikshamnen, i.e. to add more foam to the site.

If an alarm goes off to rescue to be in Skarvikshamnen within ten minutes.

On suspicion of an accident in Skarvikshamnen alerted immediately resources from fire stations in Lundby, Torslanda, Frölunda and management personnel. Additional resources can be called if needed, partly from other fire stations in Greater Göteborg Rescue Service or from adjacent municipalities.

In case of a fire in larger tanks, work will begin to limit the fire while resources from a contingency organization called Extinguishing Media Centre AB (SMC) obtained for the oil fire. Such an effort could last for several hours, up to a day.

In order to meet the requirements of oil companies, in 1994 SMC was formed in Sweden (SPI, 1994). SMC primarily provides knowledge and equipment for quick deployment in a case of large fires or industrial accidents in the oil industry and also other types of fires that cannot be extinguished in any other way.

There are four resource depots in Sweden: in Stockholm, Gothenburg, Malmo and Sundsvall, and each of the Swedish oil terminals belongs to one of those depots. For each resource depot there is a SMC-coordinator in charge of training activities, training maintenance and other SMC-issues. All SMC's operations are handled through contacts with the four resource depots and the personnel working with SMC in each city is trained on special equipment and tank fire.

The release of gas can be mitigated with the help of knowledge and equipment of a regional/ national resource known as Gas Emergency Service.

In case of emergency Preem's alarm and emergency procedures are started, while the municipal rescue services are alerted.

An important part of efforts to deal with the accident is to coordinate resources.

The company's local representative needs to coordinate with authorities, media, environment, family and group management.

The public is warned and informed of a serious accident.

In a case of *fire in a tank* first of all emergency response plan is initiated. The strategy for extinguishing a fire in that case starts with stopping all tanker movements and closing valves to and from the tanks. If the valves are not closed on time the outflow cannot be stopped (Preemraff Göteborg, 2005). Adequate resources of foam liquid must be provided before the attempt for extinguishing. In a very short time SMC is alerted and intermediate strength and fire fighting equipment is delivered from the refinery. Company's head at the scene proceeds to act as a link between company's organization and SMC, and as an advisor to SMC. When the foam application starts there are attempts to place foam on the tank or on the ground before the spill and also to cool the nearby equipment. If the cooling water that is used is spilled in damming the flow, the burning surface will be large. Cooling water should be used only after the foam leak operation is commenced because the cooling water breaks down the foam layer. Also, the intensity of a fire can be increased if the cooling water is used directly into the fire. After cooling the hot surfaces and maintaining a foam layer on the surface of flammable substances, evacuation of redundant staff and closing down the danger zone begins. Having done that, all tank contents are gravitated or pumped to secure tanks.

If there is *overfilling of a tank or spill and fire at loading facility* all the pumping and any ongoing work in or near the tank is stopped immediately and all personnel is evacuated from the area. Emergency services are called and the application of foam across the borders is started. The traffic is redirected, if necessary and the emergency response plan is activated. At the end the spill is cleaned by suction.

5. Review of historical cases

After the review of 242 accidents of storage tanks that occurred at industrial facilities since 1960s the conclusion had been made by scientists from Taiwan that almost ninety percent of the industrial accidents, among those they reviewed, occured in petroleum industry. Among them roughly 1/3 were caused by lightning and 1/3 - by human error. The remained 1/3 of accidents happened due to other factors, i.e. mechanical failure etc. (Chang and Lin, 2006)

The following are the examples of big industrial accidents in the fields of oil and chemical industry over the last 40 years.

BP Texas City Refinery Explosion

BP, March 23, 2005, Texas city, USA; 15 fatalities, 170 injured

The Texas City Refinery was active for about 70 years before tha accident, but had not been well maintained for several years. The conditions of the plant were found very poor 2 months prior to the accident. (Lyall, 2010).

The incident was caused by overfilling and overheating of one of the towers contents. Vapour cloud explosion that happened afterwards was caused by the ignition of hydrocarbon vapour by the unknown ignition source (it was suspected that it was a vehicle engine). (Mogford et al., 2005).

Occupational Safety and Health Administration ultimately found numerous safety violations and fined BP 21 million dollars. (Lyall, 2010).

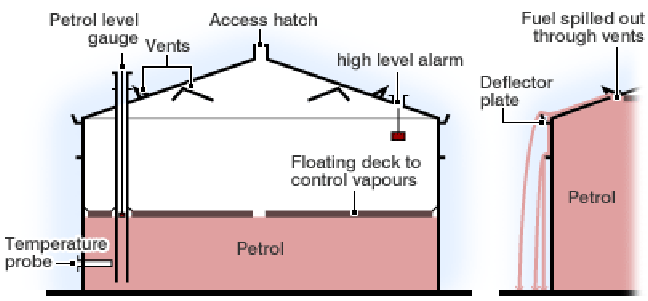
In 2008, BP plead guilty to the violations of environmental regulations and agreed to pay a fine of fifty million dollars. Blast victims and their relatives were against the plea. So far, BP has paid about one and a half billion dollars to compensate victims (Click2Houston.com, 2008).

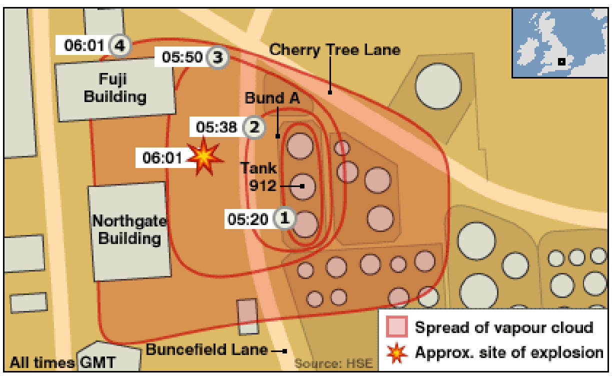
Buncefield Oil Depot Explosion and Fire

TOTAL UK Limited and Texaco, 11 December 2005, Hertfordshire, England; 43 injured

Hertfordshire oil storage terminal fire started with explosion early in the morning on Sunday, December 11, 2005. There was an overfilling in one of the tanks when motor fuel was being pumped into it. Further explosions happened shortly afterwards and the fire eventually caught in 20 other tanks.

Petrol level gauge on the tank failed and this was unnoticed by the staff. A thick vapour cloud formed after the overfilling, it started spreading. (Buncefield Investigation Homepage, 2008).



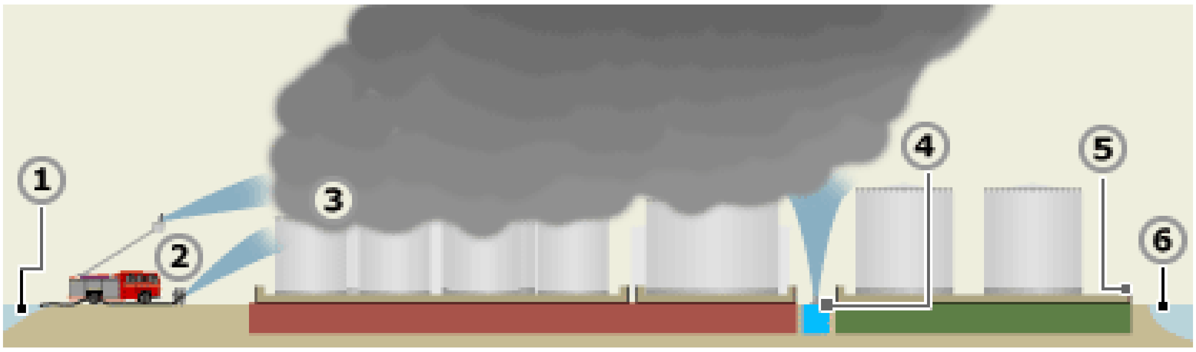


Source: (BBC News Online, July 2006)

Below is the sequence of events that happened, according to BBC News Online:

Fuel overfills the tank and formes a rich fuel and air mix, which collects in bund A. CCTV footage shows vapour flowing out of bund A. The cloud thickens from 1m to 2m deep. Vapour starts flowing towards the junction of nearby streets. The rate of fuel being pumped into tank 912 slowly increases. The first explosion occurs when the vapour cloud gets to the buildings next to the site. (Here and further (BBC News Online, July 2006).

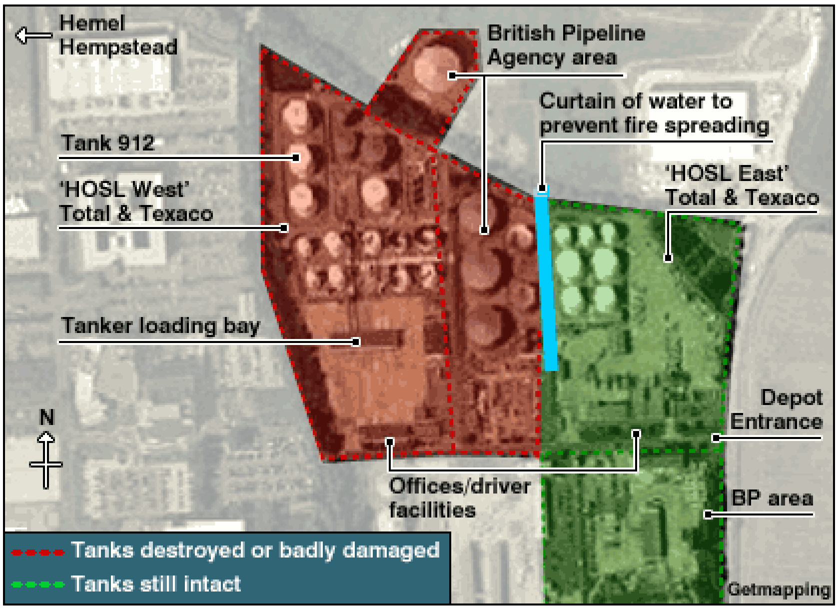
Huge firefighting effort began afterwards after major emergency was declared.



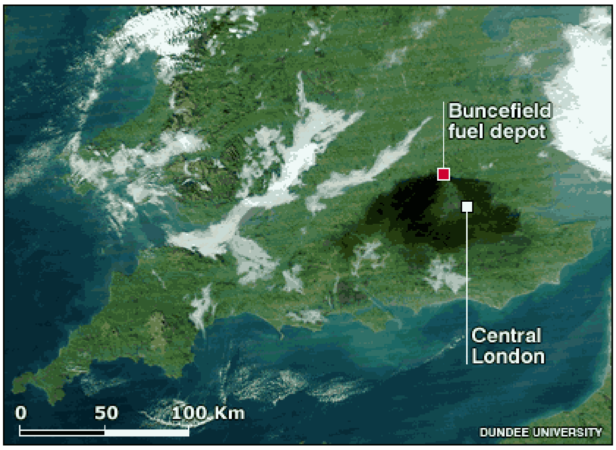
Source: (BBC News Online, July 2006)

Emergency services created an artificial pool with water that was pumped from a nearby lake. This water was used to create foam-water mix. Fire engines, foam cannon and fixed fire-fighting units pumped mixture onto blaze. Fire brigade water curtain protected intact tanks on eastern part of site. A mix of firefighting water and escaped fuel was escaping through the bunds surrounding the tanks.

The owners of the terminal were Total and Texaco. Some parts were owned by BP and the British Pipeline Agency. The plant suffered extensive damage, although the water curtain helped save large areas.



Source: BBC News Online, July 2006



Source: Dundee University in BBC News Online, July 2006

Here are the descriptions of the damage from the incident:

- broken windows at various buildings including the local church and school
- heavy damage or total destruction of front doors and a wall in a warehouse about 800 meters from the site
- damage to buildings in St Albans including the Abbey;
- serious blast damage for Townsend School (British Geological Survey, 2005).

The office blocks next to the site were damaged as the explosion went directly through them. Nearly all the windows were broken. If the explosion happend during the working day, there would be multiple fatalities.

Buildings next to the site were evacuated by police because of the danger of collapse (British Geological Survey, 2005). There were 43 reported injuries, the condition of the injured was not life-threatening.

Over 2000 people had to find another place to stay because many homes were evacuated from the area. (British Geological Survey, 2005).

As the result of the fire and blasts there were also notable transport and business disruptions.

92 firms belonging to the Maylands business park, were directly affected by the explosion (BBC News Online, July 2006).

A lot of buildings in the area were severely damaged by the accident. Some of them were later demolished (White, 2006).

Total was found liable for the blast (Taylor, 2009). Taccording to the judge, the companies had to pay damages of around 700 million pounds (Hemeltoday, 2009).

Hertfordshire Oil Storage Limited was fined 1.45 million pounds and 1 million pounds in costs. The British Pipeline Agency was fined 300,000 pounds plus 480,000 pounds in costs. Motherwell Control Systems and TAV Engineering were fined 1,000 pounds each.

Fire similar to Buncefield fire also happened at oil terminal in Newark, New Jersey, in 1983. (BBC News Online, February 2006).

Cataño Oil Refinery Fire

Caribbean Petroleum Corporation oil refinery and depot, October 23, 2009, Bayamón, Puerto Rico, 3 injured.

This was also a case of a vapour cloud explosion followerd by fire. Initial explosion destroyed 11 tanks with gasoline and other fuels. Then the fire spread to the other tanks.

The investigation team considered the explosion to be not intentional. The result of an investigation was that the reason of the explosion was a malfunctioning tank fuel gauge (CNN US, 2009).

Jaipur oil depot fire

Indian Oil Corporation, October 29, 2009, Jaipur, Rajasthan, India; 12 fatalities, over 200 injured

The fire broke out at the oil depot's tank holding 8,000 kilolitres of oil. The blaze was out of control for over a week after it started and during the period 500 000 people were evacuated from the area (The Times of India, 2009).

The incident occurred when petrol was transferred from the oil depot to a pipeline. There was a leak of fuel from the pipeline The staff of the terminal was not able to contain the leak. They reported the matter to police. Nobody had any plan to deal with the situation.

The large explosion that followed destroyed the leaking tank and several other tanks neraby. The experts from Mumbai and the army were called to contain the fire (New Delhi Mail Today, 2009). After 2 days fire spread to fifty thousand km of diesel and petrol leaked from the storage tanks. (CNN-IBN, 2009). The District Administration and Indian Oil Corporation (the owner of the refinery) did not have any disaster management plan. The fire killed 12 people.

Indian Oil Corporation was procecuted for violating the environmental regulations, 9 senior company officials were arrested on charges of criminal negligence. The trial is still ongoing by the time of conducting this research.

The following are some examples of the biggest chemical industry accidents for the last 40 years.

Accident Caused by Lightning Strike

Dronka – Egypt, 2/11/1994

In Dronka, Egypt in 1994, lightning struck the complex of eight fuel tanks. Three of the storage tanks, each holding about 5,000 tons of aircraft or diesel fuel for the army, exploded and spilt burning fuel into the village. More than 410 people were killed (International Lightning Protection Association, 2010). More than 200 houses were destroyed and at least 20,000 terrified people fled and headed towards the provincial capital, Assiut city, five miles away (The Independent, November 3, 1994).

There was no secondary containment in place to contain the release. If well designed bunding and good drainage systems had been in place, the burning fuel may have been contained on the site without spreading the fire (Health and Safety Executive, UK; 2001).

The fuel tanks at Dronka are operated by a subsidiary of the state-run Egyptian General Petroleum Corporation. The total financial lose of this accident was $25 million (Risk Analysis of a Chloralkali Industry Situated in a Populated Area Using the Software Package MAXCRED-II).

Ammonium Nitrate Explosion in Toulouse

France, 21/09/2001

A devastating chemical explosion happened on 21 September 2001 in Toulouse, France. Two production halls of the AZF fertilizer factory, a subsidiary of AtoFina and part of the oil giant

TotalFinaElf (owner of AZF), literally flew into the air (Arens an Thull, 2001). It caused the death of 30 people, of which 22 inside the factory and 8 outside. The total number of injures is said to be 2,442 and more than 350 people were in the plant at the time (266 AZF employees and 100 subcontractors) (UNEP, 2011). Due to the explosion two chimneys collapsed and all that remained from the two halls at the centre of the explosion was a crater 10 meters deep and 50 meters wide.

The pressure from the explosion caused a nearby shopping centre to collapse, severely damaged all buildings in the surrounding area, windows in a radius over 5 kilometers were shattered and many students at a secondary school in the neighborhood suffered injuries. The city motorway towards the south was transformed into a field of rubble by a rain of dust and bricks, which damaged numerous cars and injured their drivers (Arens an Thull, 2001). The explosion caused earth tremors measuring a magnitude of 3.4 on the standard seismic scale which makes the explosion at Toulouse one of the biggest in modern industrial history.

There are several versions of the story how the accident happened. According to TotalFinaElf, owner of AZF, the explosion was caused by an electric arc between two transformers located outside the plant. But, the judicial enquiry says that the explosion was caused by a human handling error. A worker from a subcontracting company is said to have mistaken a 500-kilo sack of a chlorine compound (dichloroisocyanuric acid) for nitrate granules and poured it onto the stock of ammonium nitrate in Shed 221 a quarter of an hour before the explosion. The mixture is said to have produced nitrogen trichloride, an unstable gas that explodes at normal temperatures. It's also very important to mention that the warehouse, where the explosion happened, did not conform to current regulations. The site of the AZF factory housed a total of 6 000 tones of solid ammonium nitrate, as well as other dangerous substances (including 6 300 tones of liquefied ammonia, 100 tones of liquefied chlorine and 2 500 tones of methanol) (Mapping the impacts of recent natural disasters and technological accidents in Europe).

In the end of 2011 the total economic losses from the disaster are estimated at between 900 million and 1.2 billion euro (Prefecture of Haute-Garonne). On and offside damage that was estimated by the insurers is 1500 million euro.

Release of Anhydrous Ammonia

Potchefstroom, South Africa, 13/7/1973

On 13 July 1973 an ammonia bullet tank in Potchefstroom failed, releasing 38 metric tons of anhydrous ammonia (Emergency Planning and the Acute Toxic Potency of Inhaled Ammonia). This incident resulted in 18 fatalities, 6 of them outside the works fence, up to 200 meters from the tank. An additional 65 cases of nonlethal gassing were reported (Ammonia and urea production:). It has to be mentioned that workers in building 80 m from the release survived, but people who left their houses 180 – 200m from it died (Lee's Loss Prevention in the Process Industries, 2005). This accident actually demonstrated survival of 97% of 350 employees (most outdoors) and of 100% of those outdoors who were exposed to ammonia at ≤33,737 ppm – v for 5 minutes (Michaels, 1997).

This clearly demonstrates the inability of air measurements taken only hours after a release to give an accurate measure of the levels present in the air at the time of the release (McMullen, 1976).

Released Isobutane from a Polyethylene Reactors

Pasadena – Texas, 23/10/1989

On October 23, 1989, there was a release large amount of flammable chemicals: isobutene, ethylene, hexane and hydrogen. This mixture was ignited and caused fire and explosion at the

Phillips 66 Company's Houston Chemical Complex. The explosion was equal to a force of 2.4 tons of TNT (Bethea, through LSU).

In some of the plants of the Phillips Complex a polyethylene with high density is produced. That process is carried out in long pipes in which under elevated pressure and temperature ethylene gas is dissolved in isobutene and some additional chemicals are added in order to obtain the desired characteristics. This mixture in combination with elevated pressure is extremely flammable. The initial release of ethylene and isobutane occurred through an 8 inch diameter ball valve on the No. 4 settling leg of a reactor in Plant V. The major function of this pneumatic valve is to isolate the settling leg and other downstream equipment from the reactor for maintenance. The company maintenance procedures for opening a settling leg included closing the ball valve, inserting a lock-out device into this closed valve, closing the block valves to the air hoses for the valve operator, and disconnecting these air hoses. Company personnel confirmed that these maintenance procedures were performed on Saturday, October 21. Due to changes in maintenance priorities, the work on settling leg No. 4 was not started until Monday, October 23 (MARSH, 2003).

After the explosion, investigations indicated that the lock-out device had been removed from the valve and the air hoses had been reconnected to the valve operator on settling leg number 4. 21 employees at the facility together with 2 workers, part of the maintenance crew which were at the place of release, were killed.

This accident resulted in significant losses of life and numerous injuries but it also affected all facilities within the complex, causing $715.5 million worth of damage plus an additional business disruption loss estimated at $700 million. The two polyethylene production plants nearest the source of the blast were destroyed, and in the HCC administration building nearly 0.5 mile away, windows were shattered and bricks ripped out. This incident represents the largest single-owner Property Damage loss to occur in the petrochemical industry.

Bhopal Disaster

Bhopal – India, 3/12/1984

The Bhopal disaster, that occurred on the night 2 – 3 December 1984, is the world's worst industrial catastrophe. It happened at the Union Carbide India Limited (UCIL) pesticide plant, an Indian company in which Union Carbide Corporation held just over half the stock. The other stockholders included Indian financial institutions and thousands of private investors in India. Union Carbide India Limited designed, built and managed the plant using Indian consultants and workers (Union Carbide Corporation, 2001).

During the night of December 2–3, 1984, water entered a tank containing 42 tons of MIC. The resulting exothermic reaction increased the temperature inside the tank to over 200 °C (392 °F) and raised the pressure. There are several theories of how the water entered the tank. At the time, workers were cleaning out a clogged pipe with water about 400 feet from the tank. The operators assumed that owing to bad maintenance and leaking valves, it was possible for the water to leak into the tank (Choulan et.al., 2003). The other theory is that the water in the tank is sabotage by a disgruntled worker via a connection to a missing pressure gauge on the top of the tank.

There are a lot of factors that contributed this disaster such as: lack of skilled operators, reduction of safety management, insufficient maintenance, and inadequate emergency action plans (Eckerman, 2001; Eckerman, 2005). On the other hand some of the equipment used was malfunctioning. The vent-gas scrubber, a safety device designer to neutralize toxic discharge from the MIC system, had been turned off three weeks prior (Shrivastava, 1987). Apparently a faulty valve had allowed one ton of water for cleaning internal pipes to mix with forty tons of MIC (Fortun, 2001). A 30 ton refrigeration unit that normally served as a safety component to cool the MIC storage tank had been drained of its coolant for use in another part of the plant (Shrivastava, 1987). Pressure and heat from the vigorous exothermic reaction in the tank continued to build. The gas flare safety system was out of action and had been for three months. At around 1.00 AM, December 3, loud rumbling reverberated around the plant as a safety valve gave way sending a plume of MIC gas into the early morning air (Health and Safety Executive, 2004). Within hours, the streets of Bhopal were littered with human corpses and the carcasses of buffaloes, cows, dogs and birds. According to the state government of Madhya Pradesh, approximately 3,800 people died and several thousand other individuals experienced permanent or partial disabilities (Union Carbide Corporation, 2001).

UCC offered US $350 million, the insurance sum. The Government of India claimed US$ 3.3 billion from UCC (Eckerman, (2005). In 1989 a settlement was reached. In that settlement mediated by the Indian Supreme Court, UCC accepted moral responsibility and agreed to pay $470 million to the Indian government to be distributed to claimants as a full and final settlement (Broughton, 2005). Ten days after the decision, UCC and UCIL made full payment of the $470 million to the Indian government (Union Carbide Corporation, 2001).

Eight people were convicted, among which: the chairman of the Indian arm of the Union Carbide (UCIL), the managing director, the vice – president, the works manager, the production manager, the plant superintendent and the production assistant. All of them were Indians. The seven former employees, some of whom are now in their 70s, were also ordered to pay fines of 100,000 Indian rupees ($ 2, 125) apiece (BBC News Online, June 7, 2010).

There is no source what’s actually included in the compensation.

Esso Longford Gas Explosion

In the morning 25 September 1998, a pump transferring heated lean oil to heat exchanger GP905 in Gas Plant #1 went offline for four hours. Due to the failure of the lean oil pump, some parts of the heat exchanger experienced temperatures about −48 °C. Ice had formed on the unit, and it was decided to resume pumping heated lean oil in to thaw it. When the lean oil pump operation resumed, it pumped oil into the heat exchanger at 230 °C - the temperature differential caused a brittle fracture in the exchanger.

About 10 metric tonnes of hydrocarbon vapour were immediately vented from the rupture. A vapour cloud formed and moved downwind. When it reached a set of heaters 170 metres away, it ignited. This caused a deflagration (a burning vapour cloud). The flame front burnt its way through the vapour cloud, without causing an explosion. When the flame front reached the rupture in the heat exchanger, a fierce jet fire developed, it lasted for two days.

The rupture of GP905 led to other releases and minor fires. The main fire was an intense jet fire emanating from the heat exchanger. There was no blast wave - the nearby control room was undamaged. Damage was localised to the immediate area around and above the GP905 exchanger. The fire at the plant was burning for two days more.

2 people were killed in the accident and eight others were injured (Hopkins, 2000).

6. Review of legal liability issues

When the business is interrupted it is logical that the company which has the losses wants to get back the money, i.e. for sales, it would have had normally, without interruption. But this issue is a complex one. Often it is a great challenge to prove projected or estimated amount of compensation. The term business interruption means that the business operations of a certain company are stopped from being conducted as the result of events beyond the company's control. In legal and insurance-related documents this term usually refers to the financial impact of such an interruption over a period of time.

All of this numbers are very subjective and they can be difficult to estimate since there are a lot of grey areas here. It is considered to be not easy for both parties to pursue these cases in court. As the result, such claims tend to be resolved through a traditional claim adjustment process rather then in court. That might be one of the main reasons why it is so difficult to find any actual numbers of compensations paid. Another reason might be the fact that some details of these agreements were not made public on purpose, because of confidentiality reasons.

Given the aim of this research we are interested in such claims made after accidents at oil and chemical terminals.

6.1. Review of historical legal liability cases

- Bunsfield oil depot fire (see above) seriously damaged Maylands Business Park situated right next to it.

However after the trial of the case in court there was no mentioning of business interruption clames. (Health and Safety Executive, UK). It is important to mention that many businesses affected by this incident were either underinsured or inappropriately insured. Many of the organizations that were underinsured faced a struggle for survival. They were put in a position where their ability to generate normal trading revenue was severely curtailed because of operational issues and because they had insufficient funds to replenish stock levels due to insurance shortfalls. The precise nature of cover is also an issue worthy of review. One organisation had sub-contracted staff working at several locations in the affected area and was under the impression that its business interruption insurance provided revenue protection. Soon after the explosion it began receiving calls to say that around 100 of its temporary staff were no longer required. Unfortunately, when the company made a claim, it was told that the business interruption insurance only covered its principal place of business and not those of its clients. (SDPL Partnership, 2006). There is also data suggesting that most of the businesses did not have business interruption insurance whatsoever. However some of them still received coverage of costs to rent alternative premises 'and some other payments' from the oil companies, this being a small part of business interruption losses (according to their estimation) (Brignall, 2008).

Adjusting and claim management companiy Cunningham and Lindsay made a conclusion that the business interruption aspects of Buncefield seemed to be peppered with gaps in policy cover that have not been so evident in other area damage situations we have handled. They advise the insurers not to focus solely on their own property damage and attendant business interruption risk but to examine the relationships they have with suppliers and customers and adapt policy cover to suit. They provide the following example. "A major service company that relied on traffic travelling to and from the oil depot for the bulk of its business is set to lose a six-figure sum. Although it had business interruption cover for the damage to its own premises, as soon as these are reopened there will be little or no work for them to do while the depot remains closed. The depot was not a customer of the service business, it was simply the 'honey pot' that attracted the traffic it serviced, so a customer extension would have been no help'. (Cunningham&Lindsay, 2006).

- Cataño fire

At October 26, 2009 US District Court for the district of Puerto Rico, agreed that as a direct result of the fire Vinos Seleccion Inc. has sustained economic losses due to its business interruption. Due to the great extension of the damages caused by the explosion there were hundreds of other similarly situated businesses that had sustained economic losses due to their business interruption.

Therefore, Plaintiffs and Class Members were entitled to receive monetary compensation, among other things, for: 'Their businesses interruption of operations, economic losses and any other economic damages and/or losses caused by the explosion blasts, fire and toxic gases' in the amount of no less then 'hundreds of millions of dollars'. (US District Court for the district of Puerto Rico, 2009)

- Esso Longford gas explosion

Besides being fined for the breaches of Occupational Health and Safety Act 1985 and paying $32.5 million to businesses which suffered property damage as a result of the incident, Esso was also sued for 500 million dollars for economic damages caused as a result of interruption of the natural gas supply. The company was found **not liable**. (Marsh Ltd., 2003)

6.2. Preem Legal liability Review

An analysis of liability amount was conducted at Preem in 2007 by Willis AB. The focus of this report was at Preem refineries, as opposed to the depot and termianal in Skarvik, which is a focus of this study.

As a background, here is a cursory overview of Preem's liability insurance. Liability insurance function and purpose is to protect the insured against any claims that may be directed against him for personal and/or damage to property and pure economic loss as a result of insurance conditions compensable claim.

The insurer determines whether liability exists and negotiates with the party claiming damages bringing the insured's case to trial or arbitration. The insurer shall pay any damages that Preem is liable to pay. The insurance also consists reasonable mitigation costs.

However insurance does not cover "other property damage", i.e. such a financial loss that is not a result of compensable injury or property damage under the condition. The insurance does not cover damage to the delivered product, i.e. cost for the recall, and false product's value is not covered by insurance. It also does not cover anything which is not a pure financial loss, i.e. an injury which does not affect others' property or is not a personal injury.

7. Identification of typical serious accident scenarios

7.1 Literature search

After the review of 242 accidents of storage tanks occurred at industrial facilities since 1960s the conclusion had been made by scientists from Taiwan that almost ninety percent of the industrial accidents among those they reviewed occured in petroleum industry. Among them roughly 1/3 were caused by lightning and 1/3 - by human error. The remained 1/3 of accidents happened due to other factors, i.e. mechanical failure etc. (Chang and Lin, 2005)

Types of tank contents for accidents, according to the research, in decreasing order, are crude oil, oil products, gasoline/naphtha, petrochemicals, LPG, waste oil water. Most common tanks for accidents were atmospheric external floating roof tank (the most frequent) and the atmospheric cone top (second most frequent). Both types were used extensively for the storage of crude oil, gasoline, and diesel oil.

Figure 7.1 shows fishbone diagram of accident causes, according to Chang and Lin (2005).

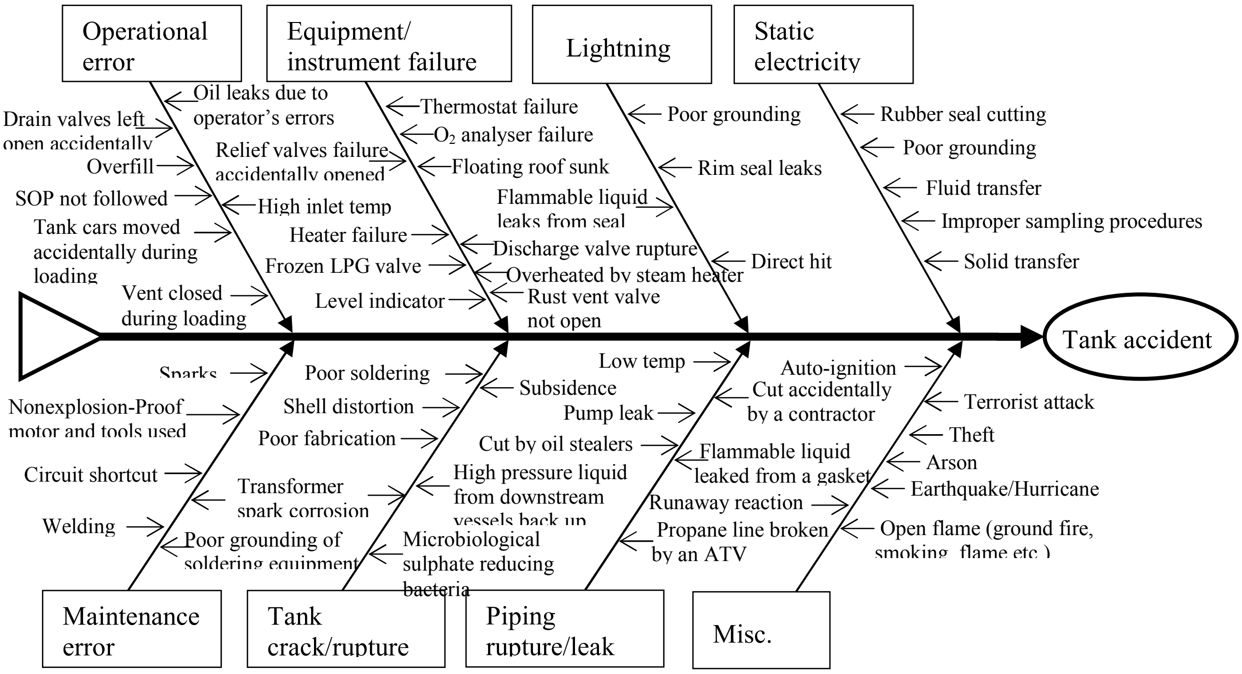


Figure 7.1 Fishbone diagram of accident causes. Source: Chang and Lin, 2005

Fire and explosion seem to be the most relevant type of accident at oil terminals and depots that may lead to large compensation claims. The following potential scenarios are considered to be serious in Preem Depot and Terminal Safety Report (Preemraff Göteborg, 2005).

Tank fire. Reasons which can lead to it:

- Product leaks to the top of the floating roof due to leaking tank seals, wear of the roof, failure in mounting of the roof, corrosion or failure in material.
- Sudden ignition from static electricity, mechanical friction heat, sparks or lightning.

Property damage from such fires is said to be 'relatively minor' if the fire is timely detected and successfully extinguished (Preemraff Göteborg, 2005).

Gas leak followed by fire. Reasons which can lead to it:

- Drain valve is left open.
- Corrosion leads to exceeding pressure limit.

- Ignition from collision with passing by heavy vehicles or from static electricity.
- Seal failure or leakage caused by incorrect mounting or mechanical wear

In this scenario there is a serious risk of the fire spreading to other tanks and damage of property (repair and replacement costs (Preemraff Göteborg, 2005).

Overflow of product tank. Reasons which can lead to it:

- Failure of alarm system.
- If tank is being filled from a ship – failure to communicate with said ship.
- Failure to determine capacity of the tank.
- Error of the operator.
- Error in pumping.

There is a serious risks of loss of product, replacement and repair costs and business losses if such an accident would occur (Preemraff Göteborg, 2005).

Accident at LPG tanks. LPG, or liquefied petroleum gas, is a flammable mixture of hydrocarbon gases used for example as a fuel in heating appliances and vehicles. The risks surrounding it are following:

- Collision of LPG cistern with other heavy vehicle.
- Gas leak could occur through the storm water system.
- Failure to communicate with the Port authorities.
- Accident might happen if the valve for draining water from the surface is opened.
- Accident might happen if gas cisterns are not equipped with excess flow valves.

Pool fire while pumping C4 from refinery, steam fire while storing C3 and C4 and vapour explosion and fire while unloading may also occur, so this risks must be taken into consideration.

7.2 Event Tree analysis

After literature search and careful discussion of probable accidents with Preem’s risk manager a preliminary list of scenarios was compiled. For some of them generic event tree analysis (ETA) was used. Some information for ETA was taken from Vilchez et al., 2009. Scenario in this thesis is defined as a sequence of events leading to an accident.

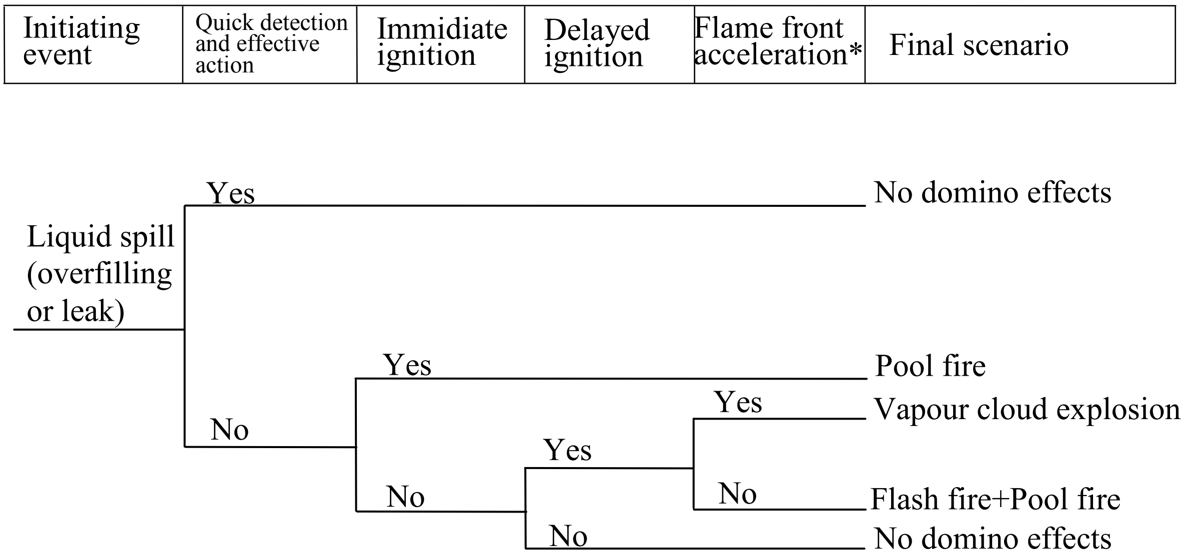


Figure 7.1 Event tree analysis for liquid spill.

* - depends on confinement level of the explosion, turbulence etc.

Separate ETA were compiled for Pool fire and Vapour cloud explosion (VCE).

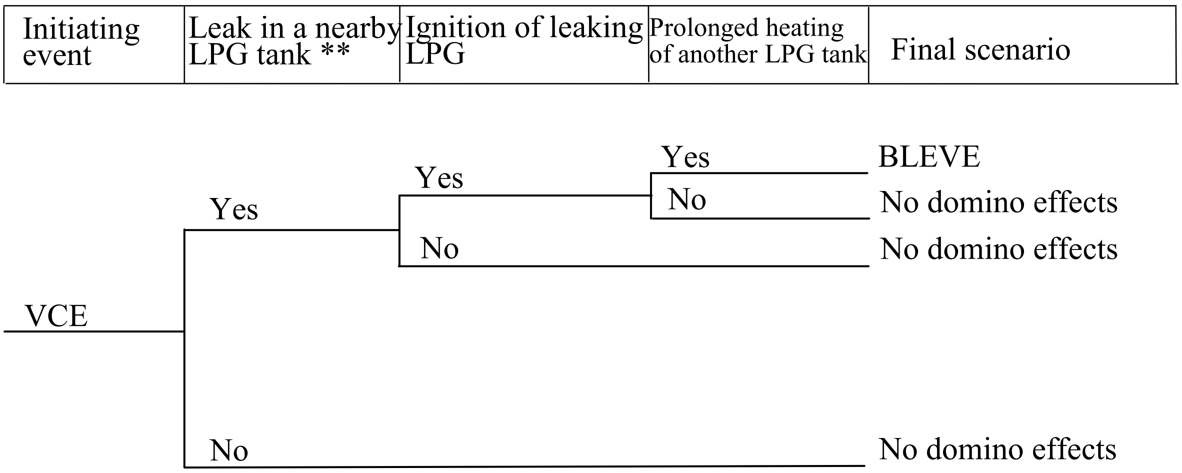


Figure 7.2 Event tree analysis for VCE.

** - due to the effect of the explosion

As for pool fire, given quick and effective fire response it will not have consequences, but othervise it will lead to secondary fires.

8. Modelling

The final list of scenarios (see ch.7) was modelled using a software developed by the Netherlands Organisation for Applied Scientific Research (TNO), called EFFECTS 8.1. Methods of calculation of physical effects (‘Yellow Book’) and EFFECTS manual were used to calculate necessary input values as follows.

For modelling of all of the scenarios the background map was georeferenced, meaning that pixel coordinates were translated to real world coordinates using a utility included in EFFECTS. The other parameters for modelling were calculated as follows.

Equivalency factor

Equivalency factor is considered to be 10% according to Effects manual. The reactivity is considered to be medium.

TNT Equivalency Method

The TNT equivalency method is based on the assumption that a vapour cloud explosion can be compared to an explosion of trinitrotoluene (TNT) (Ledin, 2002).

A pressure-distance curve yields the peak pressure, when the distance is scaled with a TNT mass equivalent. The TNT equivalent can be calculated as the product between the explosion yield and the mass of hydrocarbons in the vapour cloud (Lundkvist and Gustavsson, 2008).

$W_{TNT} = 10 \cdot \eta \cdot W$ [kg TNT]

where η is the empirical yield factor (0.03-0.05 is normally used), because most hydrocarbons have a heat of combustion 10 times higher than TNT, the factor 10 is used. Also sometimes, instead of the factor 10, the quota between the different heat of combustion is used to allow the for other fuel types then hydrocarbons.

TNT method is that it is based on empirical data and is not theoretically proven which is its weakness. Since the physical behaviour for gas explosions differs from solid explosives, TNT method is not completely suitable for them. This is most true close to the centre and far away from the centre of the explosion. In summary the method has a relatively weak theoretical basis, but it is simple and most of the times gives a reliable upper estimate (Lundkvist and Gustavsson, 2008).

TNO has developed the **Multy-Energy Method (MEM)** as an alternative to the TNT equivalency method. But, TNT equivalent method is mostly applied in cases where the main parameter used for modeling is the mass of flammable gas within a structure. Since the modeling is based on Buncefield scenario (taking that 10% goes into vapor), that is the main reason why in these thesis it’s chosen to be used TNT equivalent method instead of MEM.

The model for a **pool fire** that is used in EFFECTS calculates the total duration of the pool fire in such a way that the total mass that is released is divided by the combustion rate. If there is a pool fire with some polygon shape the coordinates of the corner points need to be given. Regarding the burning rate it can be defined by the user or it can be calculated by the program. On the other hand, by multiplying the poll surface area with the pool burning rate, the total combustion rate is obtained.

In EFFECTS there is no particular model for **jet fires**. Neither pool fire nor jet fire scenarios were calculated since they bring relatively small damage and the purpose of the study was to find a worst-case scenario.

Example of calculation of fraction of flammable cloud confined

The example is calculated for Scenario 1, tank 130 (see 9.2.1). The same calculations are used for the other scenarios requiring fraction of flammable cloud confined.

According to EFFECTS manual (TNO Built Environment & Geosciences, 2010), 'Fraction of flammable cloud confined [is] the volume percentage of the explosive cloud (part of the vapour cloud within explosive limits) which is confined/obstructed. […] The fraction of flammable cloud confined is of great importance, as the mass of chemical found in the confined region is the one used by the model to do the calculations. It has been experimentally demonstrated, as can be found in the 3rd edition of the Yellow Book, that only the confined/obstructed parts of the explosive cloud contribute to the deflagration/detonation phenomenon'.

Fraction of flammable cloud confined is calculated to be equal to v_{gr}/v_c (Yellow Book, 8.35).

where v_{gr} is 'volume of vapour within the obstructed region' or 'maximum part of the cloud that can be within the obstructed region' (Yellow Book, 8.5).

v_c is 'cloud volume at stoichiometric concentration' (Yellow Book, 8.35).

Volume of a vapour cloud was calculated as follows. Upper and lower explosive limits of gasoline were taken from the literature. These concentrations are given per unit of volume. It can be reasonably assumed that the limits would be about the same given per unit of mass.

LELgasoline = 1,4%
UELgasoline = 7,7% (Missouri Department of Natutral Resources, 2009).

Tank 130 overfills for 15 minutes, while pump flow is 800 m^3/h. It is assumed that 10% of leaked mass turns into vapour, like in Buncefield (Buncefield Major Incident Investigation Board, 2008). $V_{leaked} = 200\ m^3$; $V_{gasoline\ turned\ to\ vapour} = 20\ m^3$; $m_{gasoline\ vapour} = \rho \cdot v = 719{,}7\ kg/m^3 \cdot 20\ m^3 = 14394\ kg$.

Average concentration of gasoline in the vapour is (1,4+7,7)/2 = 4,55%. This concentration was used in the calculation as vapour concentration in the vapour cloud.

$0{,}0455 = m_{gasoline\ vapour}/m_{cloud}$;

$m_{cloud} = m_{gasoline\ vapuor}/0{,}0455 = 14394\ kg/\ 0{,}0455 = 316\ 351{,}6\ kg$

$(1-0{,}0455) = m_{air}/m_{cloud}$;

$m_{air} = 0{,}9545 \cdot 316351{,}6\ kg = 301\ 957{,}6\ kg$.

$v_c = v_{air} + v_{gasoline\ vapour} = (m_{air}/\rho_{air})+(m_{gasoline\ vapour}/\rho_{gasoline\ vapour}) =$
$= (301\ 957{,}6\ kg/1{,}22521\ kg/m^3)+(14394\ kg/719{,}7\ kg/m^3) = 246473{,}8\ m^3$.

Methodology from Yellow book was then used to determine the obstructed region. It is made to try to take into account the effect of the obstacles to the turbulence in the expansion flow ahead of the flame. A zone with obstacle induced turbulence will exist behind an obstacle. The procedure given is considered safe and conservative in the sense that normally too large a volume of the obstructed region is selected (Yellow Book 5.44).

In accordance to the method the structures were broke down into basic geometrical structural shapes. As can be seen in figure Tank 130 is surrounded only by other tanks. Since the diameter of tank 130 is 20m and the height is 18m,

$D_1 = 18m$; $10\ D_1 = 180m$

$D_2 = 20m$; $10\ D_2 = 200m$,

Where D_1 is smallest dimension of obstacle perpendicular to flame propagation direction and D_2 is dimension of obstacle parallel to flame propagation direction (Yellow Book, Ch.5, List of symbols).

An obstacle belongs to an obstructed region if the distance from its centre to the centre of any obstacle in the obstructed region is smaller than 10 times D_1 or 1,5 times D_2 of the obstacle under consideration in the obstructed region (D_1 and D_2 belonging to any obstacle in the obstructed region). However, if the distance between the outer boundary in the obstructed region and the outer boundary of the obstacle is larger than 25m, then the obstacle does not belong to the obstructed region (5.5.3. Yellow Book).

It is naturally assumed that tank 130 where overfilling happened is a part of the obstructed region. To determine whether tank 131 is a part of the obstructed region, the distance between the outer boundary of the obstructed region and the outer boundary of the obstacle (in this case tank 131) is measured. This distance is 13m which is smaller that 25m which means that tank 131 can be a part of the obstructed region.

The distance from the centre of the tank 130 to the centre of tank 131 is 30m which is smaller than 10 times D_1. One of the conditions is fulfilled and therefore tank 131 is considered to be a part of the obstructed region.

Similarly, tanks 132 and 133 are also parts of the obstructed region. Tank 235 is not a part of the obstructed region since the distance from its outer boundary to the outer boundary of tank 235 is 28m which is larger than 25m. LPG area is not a part of obstructed region. Tank 236 is a part of obstructed region since the distance from its centre to the centre of the tank 133 is smaller than 10 times D_1 and the distance from its outer boundary to the outer boundary of tank 133 is 22,5 which is less than 25m. And as it is clear from the picture both tank 134 and pump station do not belong to obstructed region because the distance from its outer boundaries to the outer boundary of tank 133 is more than 25m.

Therefore the obstructed region for the vapour cloud explosion after overfilling of the tank 130 includes tanks 130, 131, 132, 133 and 236. In accordance with the method the obstructed region also includes the bullet-shaped protective walls around the tanks 130-133.

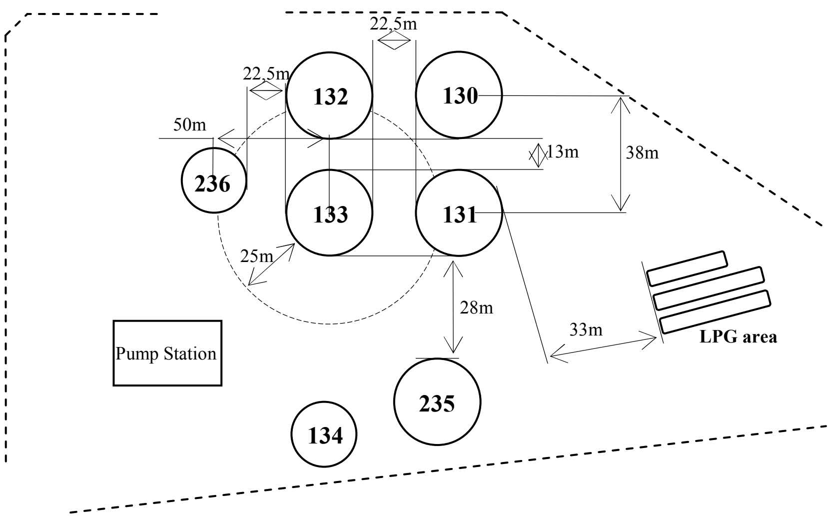


Figure 8.1 Determination of the obstructed region

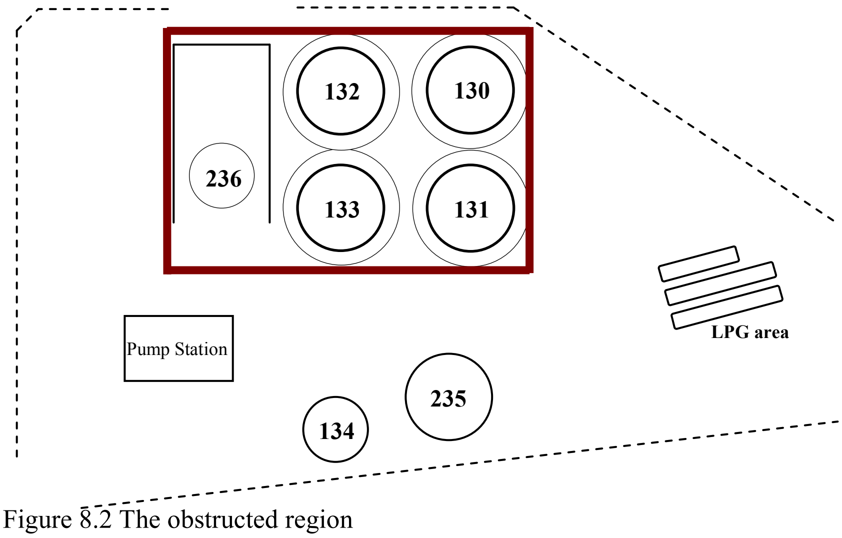


Figure 8.2 The obstructed region

After that the 'box containing the obstructed region' was defined (Yellow Book, 5.57), see Figure 2.3.2. Again, the procedure given is thought to be safe and conservative in the sense that always too large a volume of the obstructed region was selected. (Yellow Book, 5.44).

Other structures like stairs, supports, pipes are not considered here, since the dimensions of the large obstacles will dominate the process of building an obstructed region. (Yellow Book, 5.54)

The obstructed region above can be divided into two boxes.

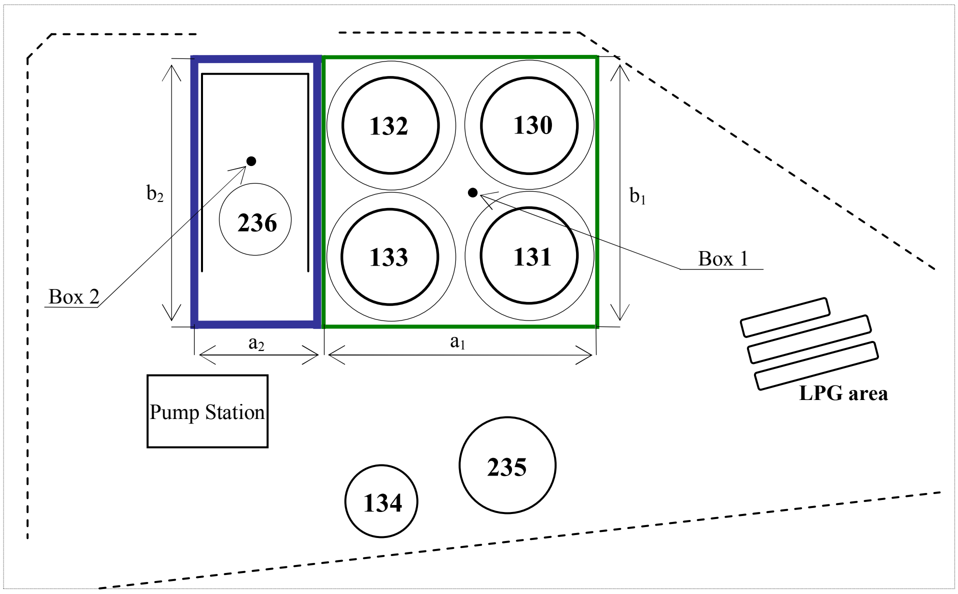


Figure 8.3 Division of the obstructed region into two boxes

The volume of the obstructed region V_{gr} is the sum of the volume of the boxes minus the space occupied by obstacles (Yellow Book 5.60).

Volume of Box 1: $v_1 = a_1 \cdot b_1 \cdot h_1$

The dimensions of the boxes were taken from the map of the port.

$a_1 = b_1 = 57{,}5\text{m}$
$h_1 = h_2 = 18\text{m}$ (the height of all 5 tanks in both of the boxes)

$v_1 = 57{,}5 \cdot 57{,}5 \cdot 18 = 59512{,}5\text{m}^2$

Volume of Box 2: $v_2 = a_2 \cdot b_2 \cdot h_2$; $v_2 = 40 \cdot 57{,}5 \cdot 18 = 41400\text{m}^3$

Volumes of tanks are taken from Preem Safety report (Preemraff Göteborg, 2005) and volume of the fence is considered negligible in this case.

$v_{gr} = (v_1+v_2) - (v_{130}+v_{131}+v_{132}+v_{133}+v_{236}) = (59512,5+41400) - (4900+4900+4900+4900+5000) = \quad =76312,5m3$

$v_c = 246473,8\ m^3$ (see above)

Fraction of flammable cloud confined equals $v_{gr}/v_c = 76312,5m3/246473,8\ m^3 = 0,3096 \approx 31\%$

Distance from release (Xd)

Downwind horizontal coordinate (Xd) from the point of study (i.e. the point where the concentration is to be calculated) to the release point, the outer limit of calculations (TNO Built Environment & Geosciences, 2010).

Threshold overpressure

This is the overpressure value (in mBar) for which we want to calculate the distance from the centre mass position where it is reached (output value). It is also the threshold value to be used when calculating the output contour plot of all the positions where this overpressure is reached. (TNO Built Environment & Geosciences, 2010). This is an arbitrary value which is plotted on the map but it has been decided not to plot it in one of the damage contours.

Explosion damage contours

- Total destruction (> 83 kPa)
- Heavy damage (35 - 83 kPa)
- Moderate damage (17 - 35 kPa)
- Minor damage (3.5 - 17 kPa)

The damage is thus dependent upon the overpressure. (TNO Built Environment & Geosciences, 2010)

Thermal radiation damage contours

Heat flux, kW/m^2	Damage level
4,7	10%
8	30%
12,6	50%
18	80%
23	100%

Figure 8.4 Thermal radiation damage contours (Dreher, 1999).

It is said in the source that ‘the available information on the effects of heat radiation does not differentiate between various types of structures. Therefore a single set of damage criteria [is] used for heat radiation’ (Dreher, 1999).

Burst pressure vessel

The absolute pressure inside the vessel at the moment of rupture. The failure overpressure is assumed to be 1,21 times the opening pressure of the safety valve (TNO Built Environment & Geosciences, 2010). Opening pressure of the safety valve of LPG tanks in Skarvik is 21 bar, according to maintenance technician at Skarvik.

Heat radiation levels are also taken from Dreher, 1999 (see Appendix 3):

These values have been translated into damage to structure in accordance to Figure 8.4.

Damage to structures (empirical) at Xd

This is the damage suffered by a structure if it was situated at the point of study (TNO Built Environment & Geosciences, 2010; Empirical damage to structures).

19 different situations can be found:

- The supporting structure of a round storage tank has collapsed (100 kPa)
- Brickstone walls (20-30 cm) have collapsed (50 kPa)
- Displacement of a cylindrical storage tank, failure of connecting pipes (50-100 kPa)
- Loaded train carriages turned over (50 kPa)
- Collapse of a pipe-bridge (40-55 kPa)
- Displacement of a pipe-bridge, rupture of piping (35-40 kPa)
- Damage to a fractioning column (35-80 kPa)
- Plating of cars and trucks pressed inwards (35 kPa)
- Breakage of wooden telephone poles (35 kPa)
- Cladding of light industry building ripped-off (30 kPa)
- Collapse of steel frames and displacement of foundation (20 kPa)
- Industrial steel self-framing structure collapsed (20-30 kPa)
- Cracking in empty oil-storage tanks (20-30 kPa)
- Slight deformation of a pipe-bridge (20-30 kPa)
- Large trees have fallen down (20-40 kPa)
- Walls made of concrete blocks have collapsed (15-20)
- Minor damage to steel frames (8-10 kPa)
- Connections between steel or aluminium ondulated plates have failed 7-14 kPa)
- The roof of a storage tank has collapsed (7 kPa)

9. Findings

Modelling results and consequences

Scenario 1 is modelled to be similar to Buncefield accident (see Literature study). The others are chosen to be the most likely to occur at Preem.

9.1 'Buncefield-type' scenario (Scenario 1)

Tank 130 overfills for 15 minutes, while pump flow is 800 m^3/h. It is assumed that 10% of leaked mass turns into vapour, similar to Buncefield accident (Buncefield Major Incident Investigation Board, 2008).

$V_{leaked} = 200\ m^3$;

$V_{gasoline\ turned\ to\ vapour} = 20\ m^3$; $m_{gasoline\ vapour} = \rho \cdot v = 719{,}7\ kg/m^3 \cdot 20\ m^3 = 14394kg$. For the determination of input parameters see ch.8 'Modelling'.

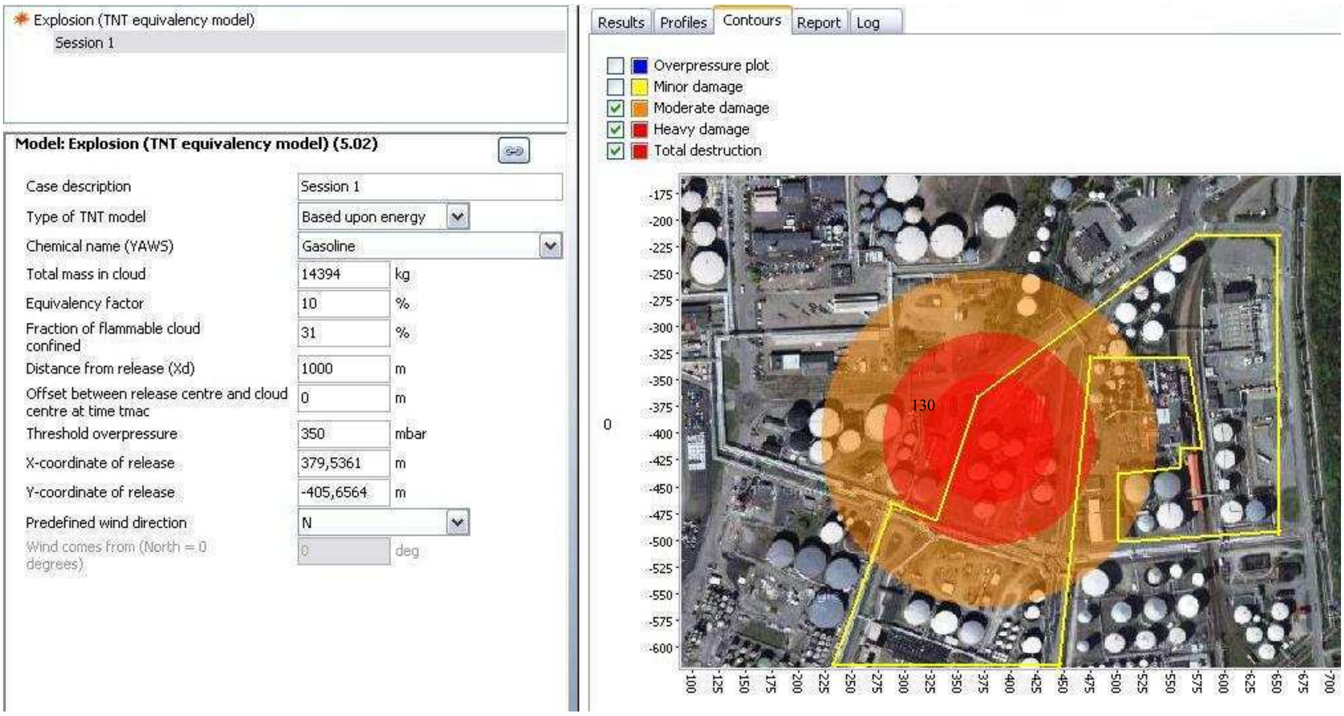


Figure 9.1 Modelling results for Scenario 1 at tank 130 with highlighted borders of Preem facilities

Possible Consequences

Such an explosion would cause total destruction and heavy damage to Preem facilities but for the scope of this study we are interested only in potential damage to the other companies.

It is possible that vapour cloud explosion would set fire around LPG tanks. From heavy damage the LPG tanks or the pipeline can fail and start leaking. The LPG can ignite and start to heat itself or the other tanks which in its turn can cause BLEVE (Scenario 2) which in its turn can cause damage to other companies.

Regardless, scenario 1 would destroy water treatment plant Ciclean1, storage container, control facility, switchboard, transformer and parking spaces, cause heavy damage to the loading station and STENA/RECYCLING CICLEAN tanks containing oil/water/solvent mixture and one tank with water.

The office of Scanlube and the one of Saybolt Sweden will be completely destroyed (TNO Built Environment & Geosciences, 2010, Empirical damage to structures; Chapter 8, ‘Modelling’, Explosion damage contours).

Moderate damage will be caused to two STENA/RECYCLING CICLEAN tanks containing oil and one Nordic Storage tank with unknown contents. Moderate damage can also be caused to St1 tank containing aviation fuel, most of the Scanlube offices (which have lower threshold pressure value than tanks (Chapter 8, ‘Modelling’, Explosion damage contours), so they might be completely destroyed) and one tank of Vopak containing fuel oil. (See more in ch.9.7 Calculation of total replacement costs).

Scenario 1 can also happen at tank 137.

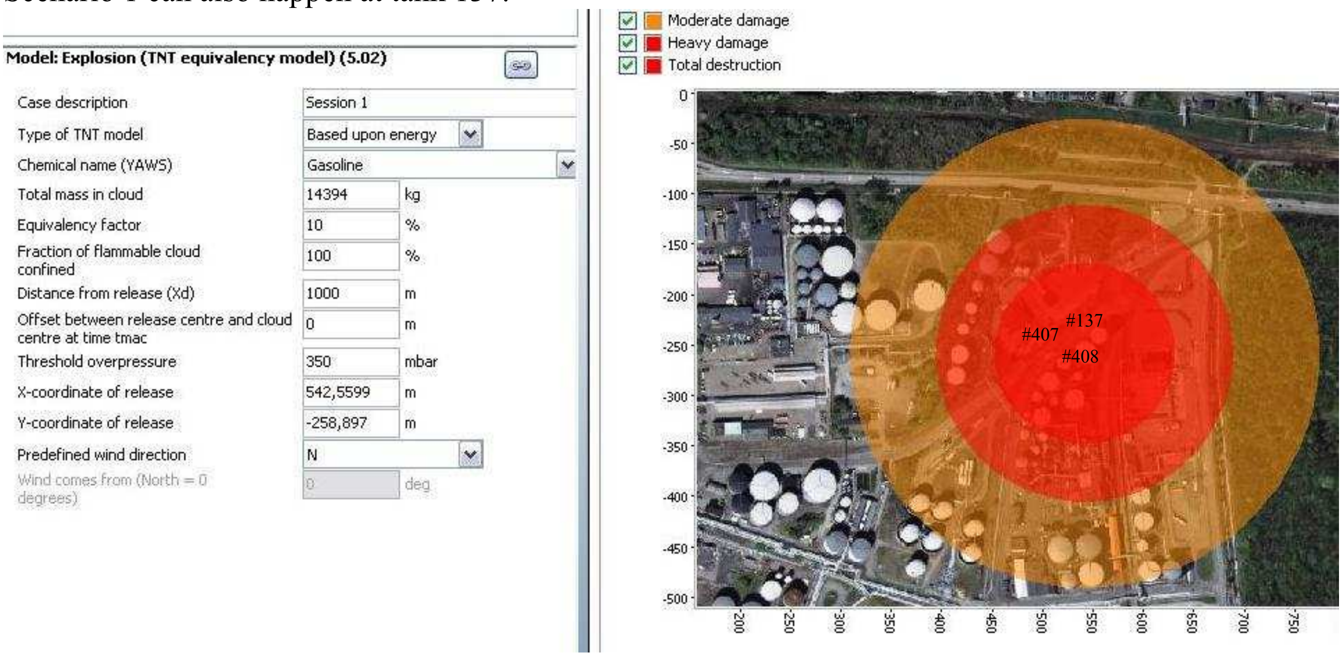


Figure 9.2 Modelling results for Scenario 1 at tank 137

Possible Consequences

Given the fact that pump-in value and time until detection of overfilling are the same, this explosion in EFFECTS 8.1 looks exactly the same as above mentioned.

Scenario 1 was also modelled for tank 117.

Pump-in flow here is up to 350 m^3/h. $v_{leaked} = 87{,}5\ m^3$; $v_{gasoline\ turned\ to\ vapour} = 8{,}75 m^3$
$m_{gasoline\ vapour} = \rho \cdot v = 719{,}7\ kg/m^3 \cdot 8{,}75\ m^3 = 6297{,}38 kg$

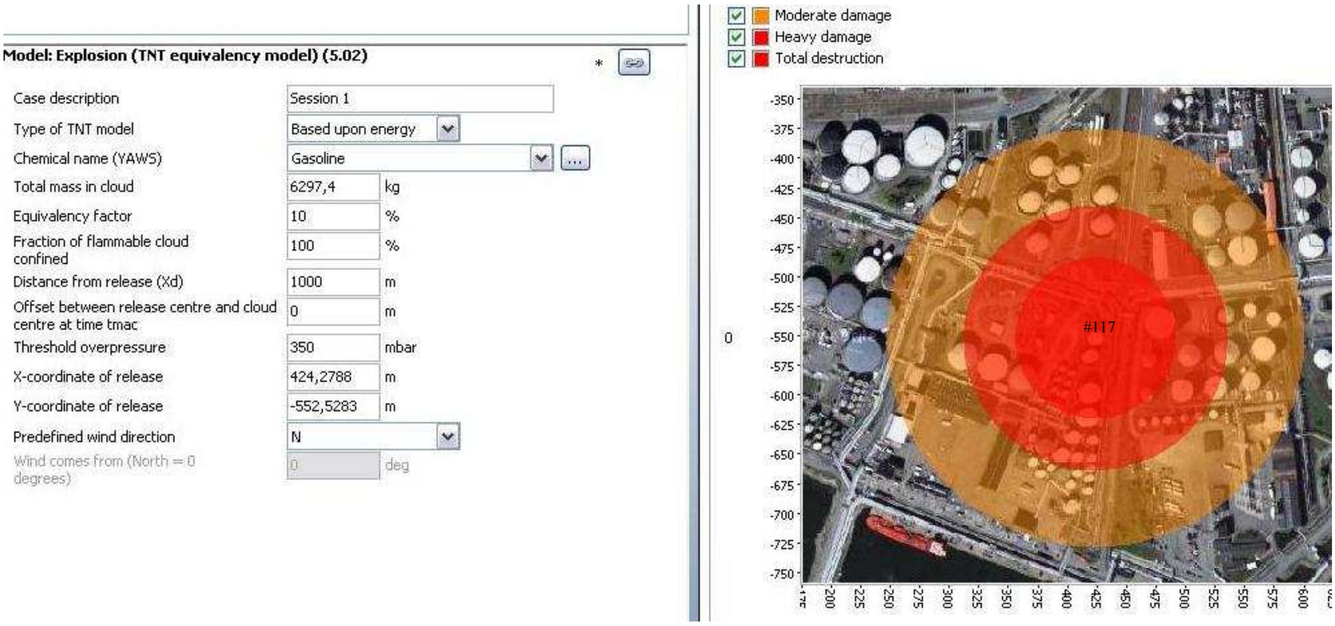


Figure 9.3 Modelling results for Scenario 1 at tank 117

For consequences see ch. 9.7 Calculation of total replacement costs.

9.2. BLEVE at LPG storage (Scenario 2)

The scenario is the following consequence of events. Pipe rupture during transfer of LPG causes leak from a gas (i.e. propane) tank, propane ignites and heats another tank. This eventually triggers BLEVE.

Scenario 2 can also be triggered by the consequences of Scenario 1 (see above). Thermal radiation damage levels are taken from Figure 8.4. It is said in the source that 'the available information on the effects of heat radiation does not differentiate between various types of structures. Therefore a single set of damage criteria [is] used for heat radiation' (Dreher, 1999).

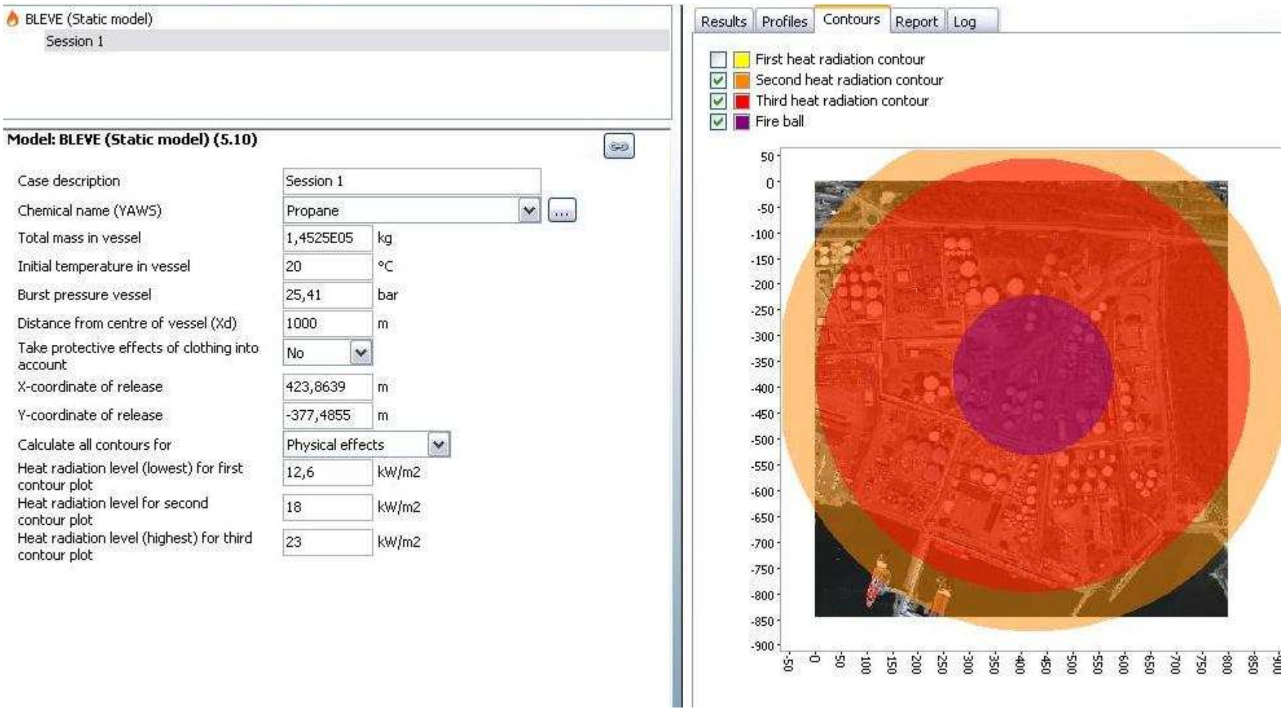


Figure 9.4 Scenario 2

Second heat radiation level shows 80% damage (Figure 8.4.). This result is considered to be overly conservative because of the short heat duration. This shows the need for more precise heat flux values for process industries.

9.3 Leak from a hole in gasoline tank (Scenario 3)

In this scenario tank starts to leak, detection time 15 min. Estimated fraction of product to turn into vapour is 10%, similar to Buncefield accident (Buncefield Major Incident Investigation Board, 2008).

The scenario was modelled for Preem tank 137. First, the mass of released liquid is calculated with the help of EFFECTS model 'Liquid Release'. It calculates the mass escaped from the 80% full tank.

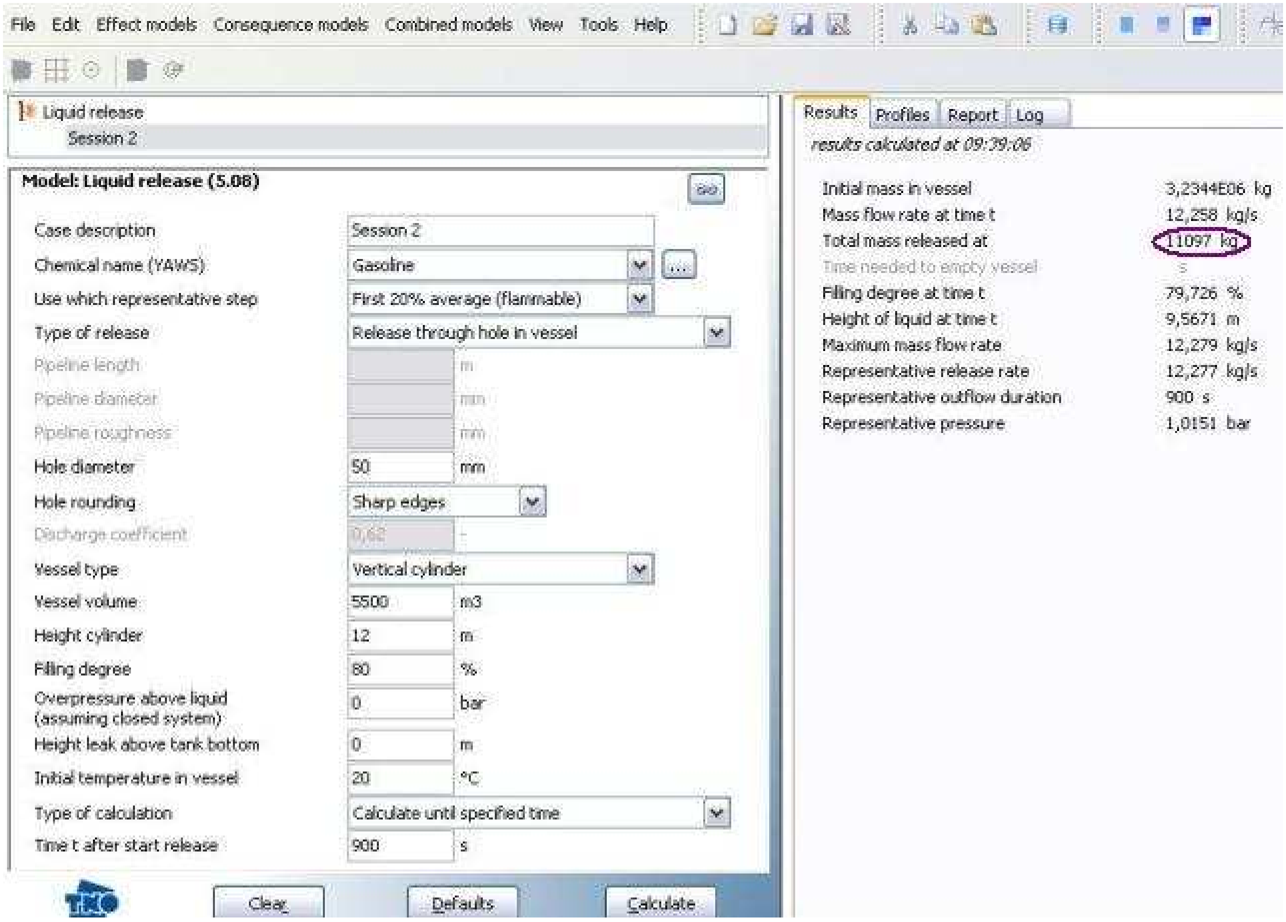


Figure 9.5 Total mass released

$m = 11097$ kg

$m_{vapour} = 10\% \cdot 11097$ kg $= 1109{,}7$ kg

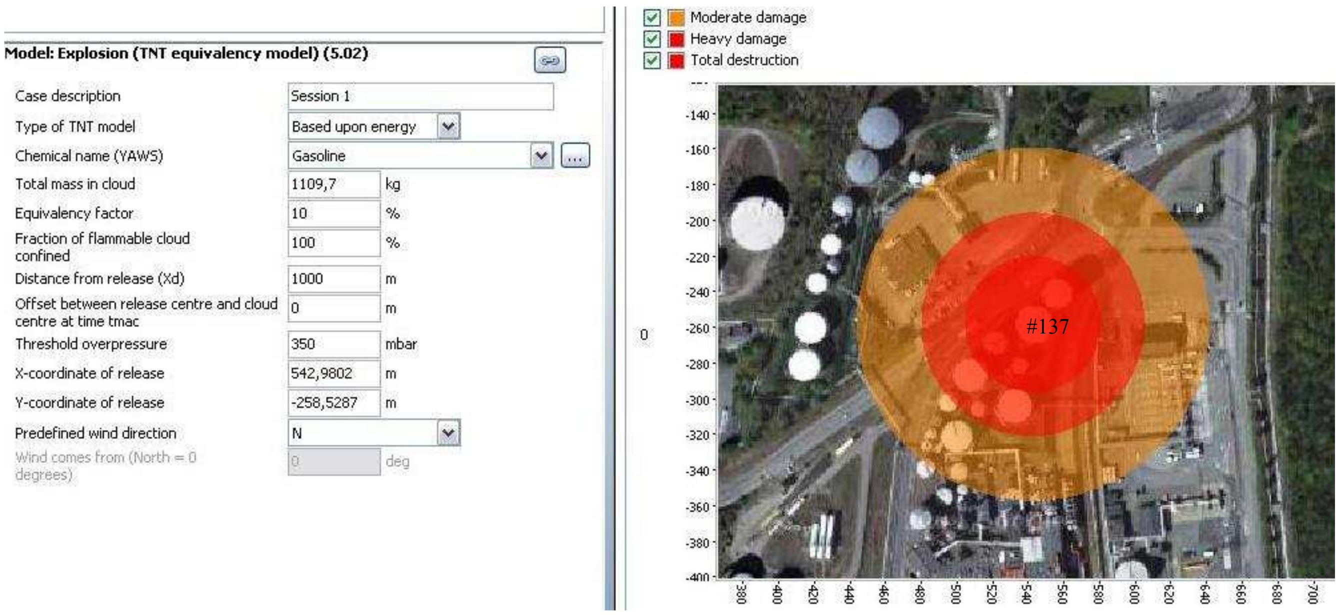


Figure 9.6 Scenario 3 at tank 137

Another way of doing the calculation of total mass in the cloud would be through EFFECTS models ‘Pool evaporation’ and ‘Dense gas dispersion: Explosive mass’. However EFFECTS does not have a capability to handle multi-component mixtures. During evaporation process only shorter and lighter components of gasoline actually evaporate while they are still liquid during liquid release. This is impossible to model in this version of EFFECTS so it is decided to estimate the ‘Buncefield-type scenario’ as the worst-case.

9.4 LPG leak, dense gas explosion (Scenario 4)

In this scenario propane leaks from the bottom of the tank which leads to explosion. To model such an explosion it is necessary to reference several EFFECTS models (see below, starting from the first one).

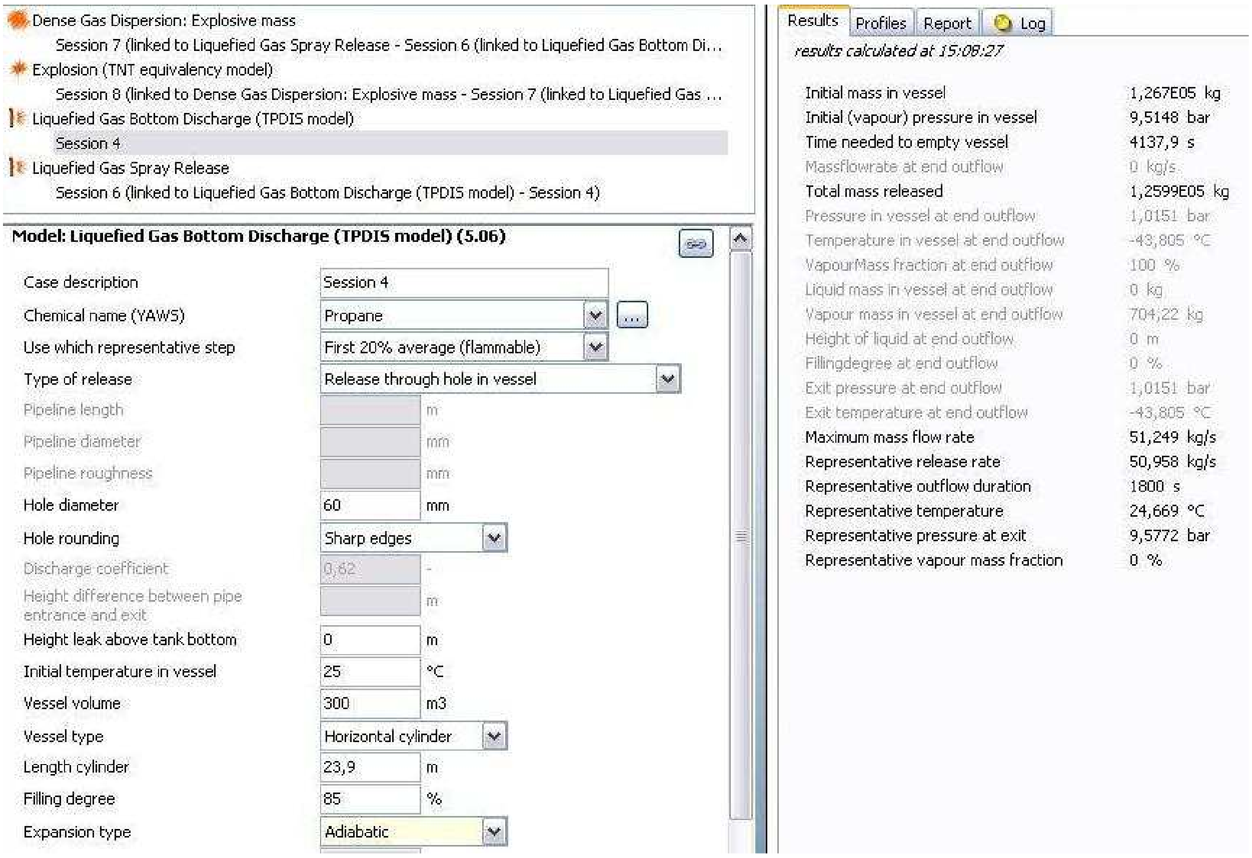


Figure 9.7 Scenario 4, Liquefied gas bottom discharge

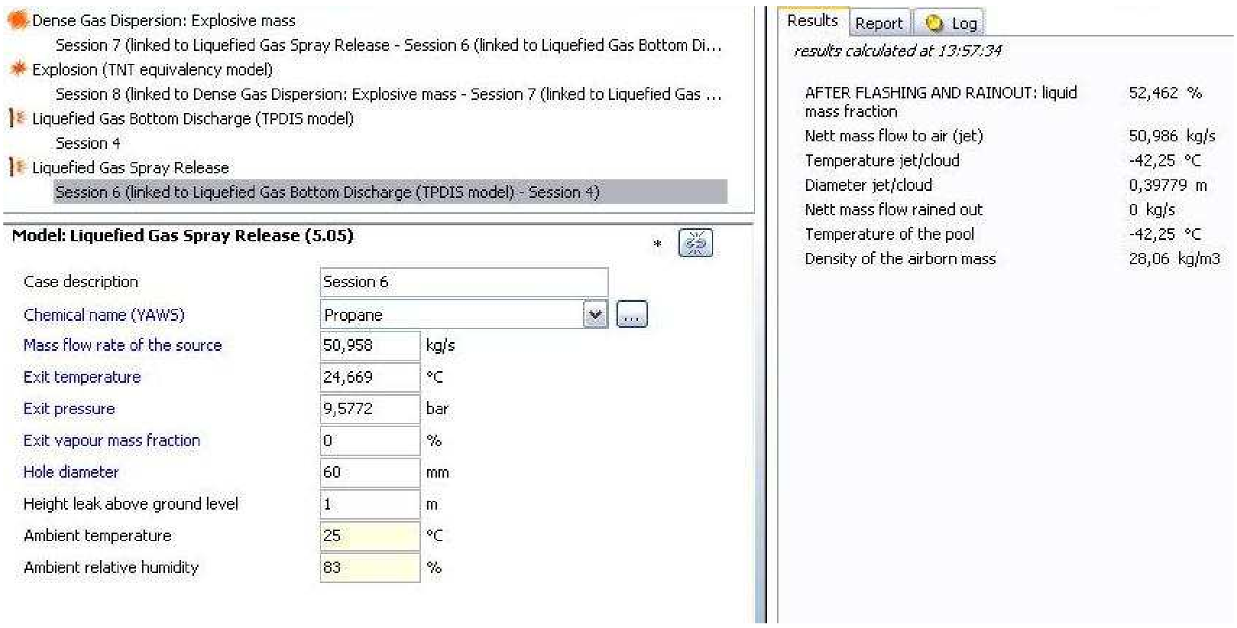


Figure 9.8 Scenario 4, Liquefied gas spray release

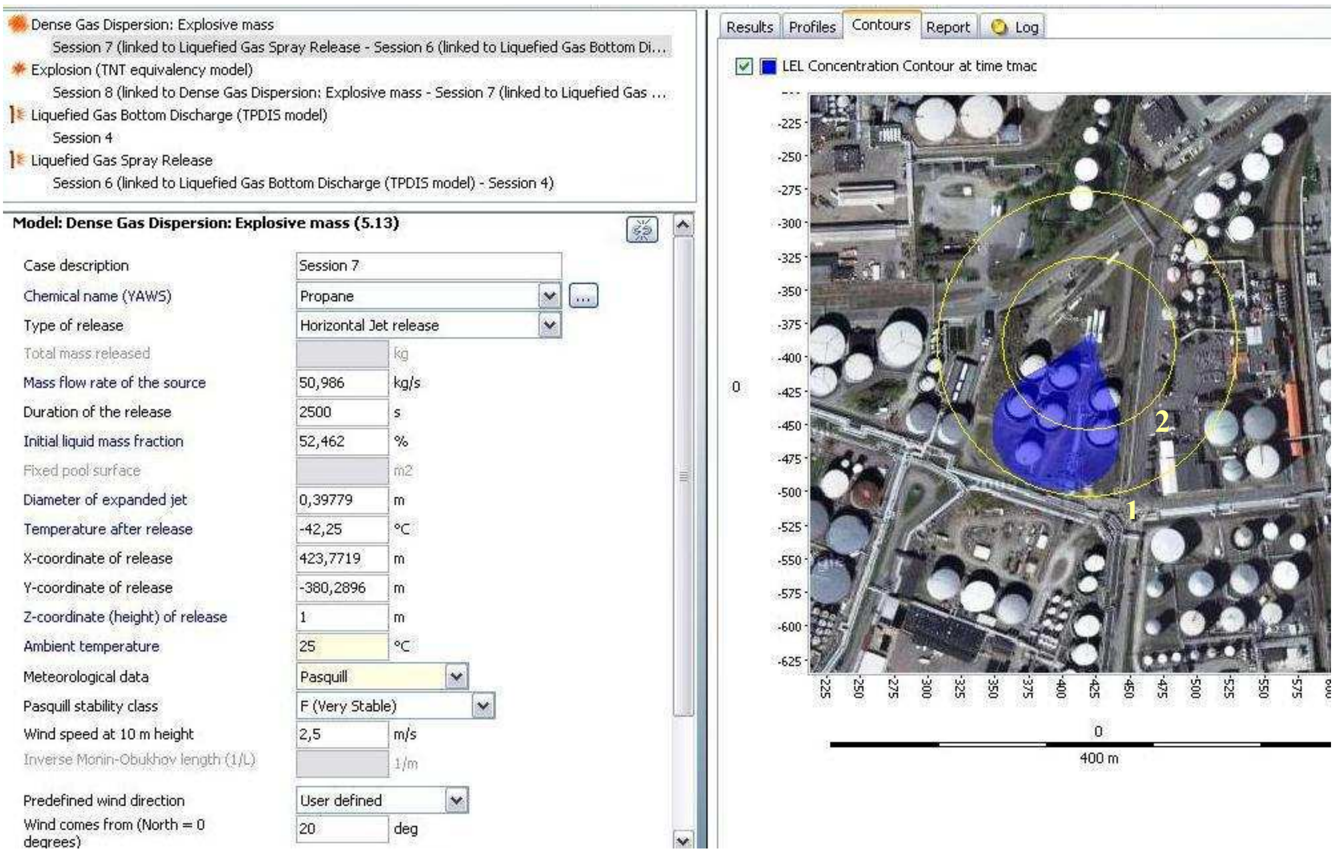


Figure 9.9 Scenario 4, Dense gas dispersion: Explosive mass

Depending on a wind direction the cloud can take any direction inside of circle 1. Centre of the explosion then would lie on the circle 2 (Figure 9.2.4.3). Circle 3 shows all the possible borders of the explosion in this case (See Figure 9.2.4.4). However it can be reasonably assumed that Figure 9.2.4.3 shows the worst possible location of the cloud given the high level of confinement.

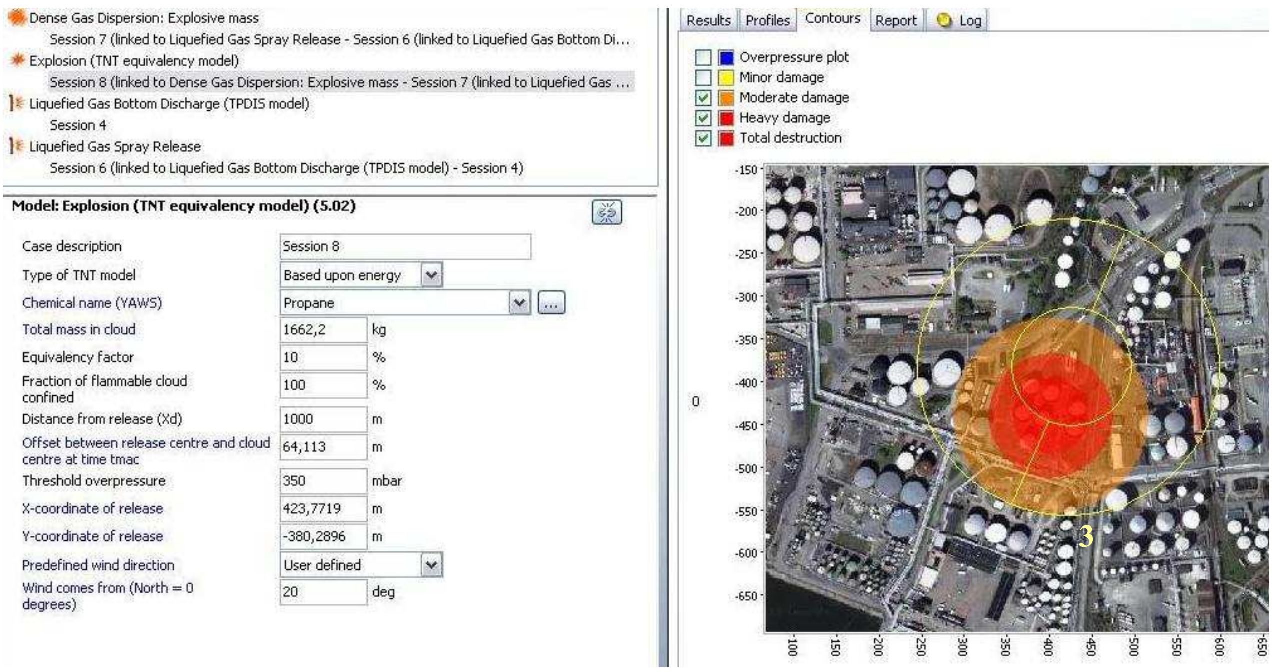


Figure 9.10 Scenario 4, TNT equivalency model

The cause of leak could be e.g. human error during maintenance (hot work or cold work, i.e. dismantling of flanges without proper isolation and depressurisation, and different ignition source in the vicinity), or mechanical impact e.g. collision, or pump seal failure.

LEL of propane is 2 %
UEL ≈ 9,5% (Nolan, 1997)

So concentration of propane in the cloud is considered to be (2+9,5)/2=5,75%

$0,0575 = m_{propane}/m_{cloud}$;

$m_{cloud} = m_{propane} /0,0575 = 4070,96$ kg/ 0,0575 =70799,304 kg.

$(1-0,0575) = m_{air}/m_{cloud}$;

$m_{air} = 0,9425 \cdot 70799,304$ kg = 66728,34kg.

$v_c = v_{air} + v_{gasoline\ vapour} = (m_{air}/\rho_{air})+(m_{gasoline\ vapour}/\rho_{gasoline\ vapour}) =$
$= (301\ 957,6\ kg/1,22521\ kg/m^3)+(14394\ kg/719,7\ kg/m^3) = 246473,8\ m^3$.

9.5 Rupture of propane vessel (Scenario 5)

In this scenario propane vessel ruptures from metal fatigue of flanges.

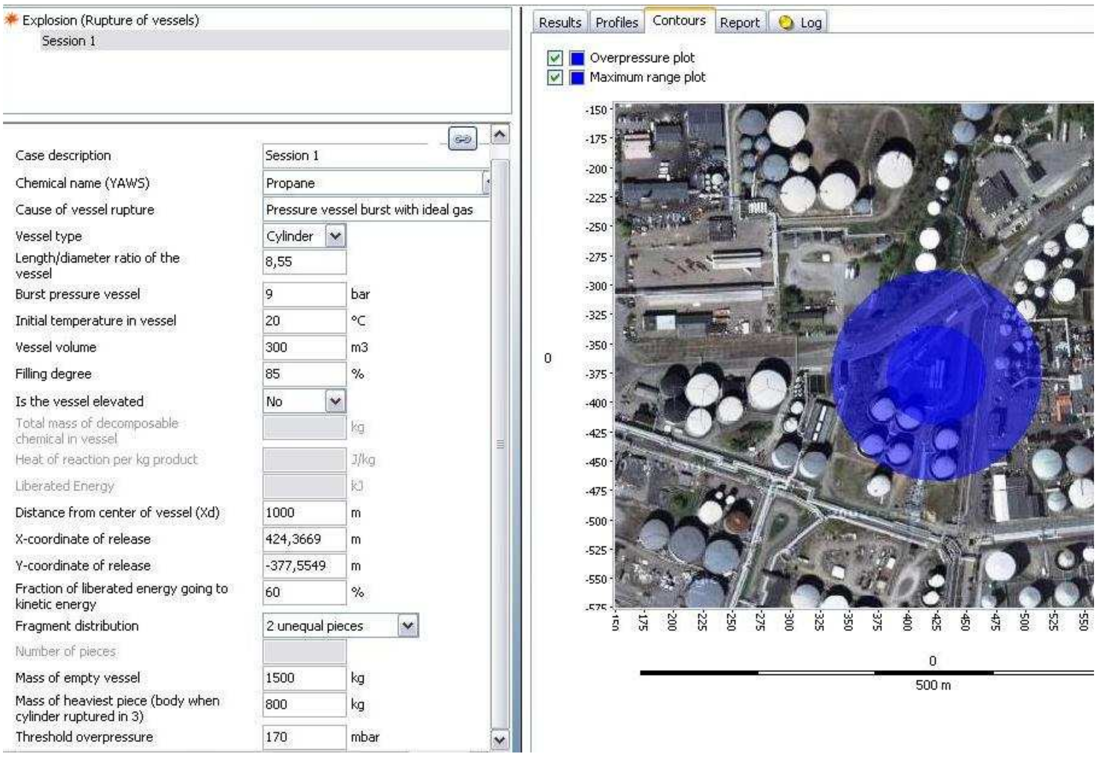


Figure 9.11 Scenario 5

9.6 Diesel Pool Fire (Scenario 6)

Diesel pool fire consequences are considered lighter then the consequences of gasoline pool fire (Schnepp, 2009). So given the fact that diesel is not in EFFECTS database it is decided to model gasoline pool fire instead and consider it a worst/case scenario. The scenario modelled is a fire in one of the storage tanks. The outer circle shows the edge of the second heat radiation contour for all possible wind directions.

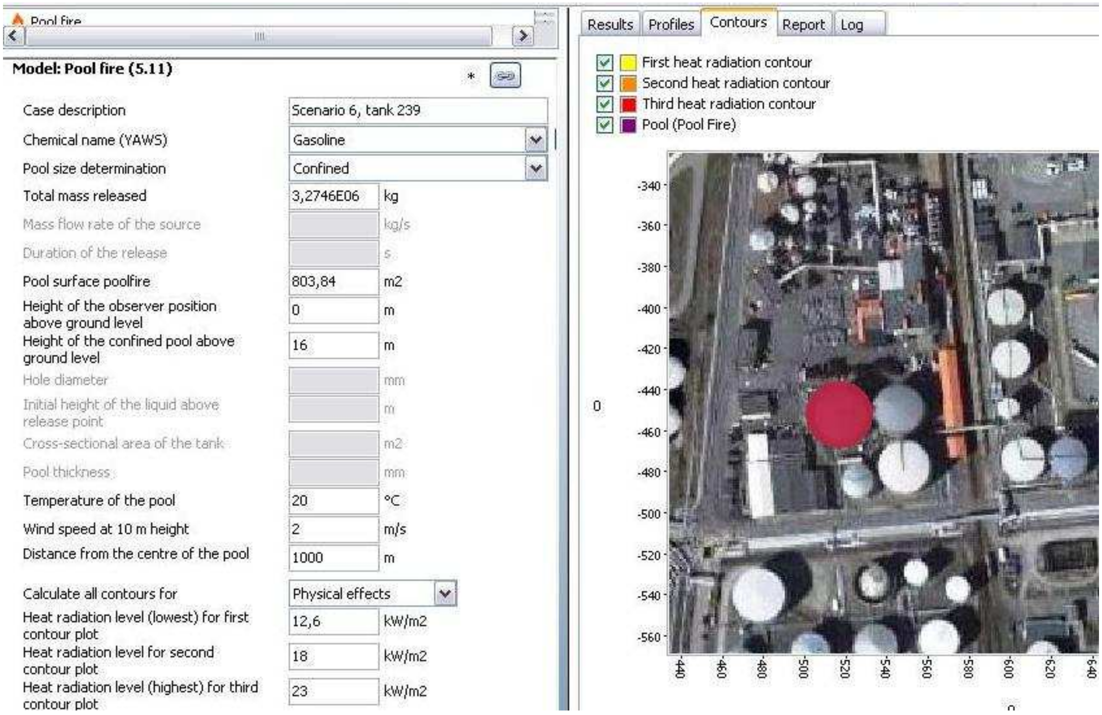


Figure 9.12 Scenario 6 at tank 239

9.7 Calculation of total replacement costs for worst-case scenarios (including domino-effects)

In this chapter possible domino effects (secondary damage) for each of the above mentioned scenarios are reviewed. Total replacement costs for the tanks, product inside of the tanks, clearance of the debris, fire fighting and some others for the companies–neighours of Preem in Skarvik are calculated.

Secondary damage can happen if there is escalation, spreading of the fire etc., i.e. fire in a damaged tank gets to another tank and it also catches fire. EFFECTS does not have calculations for such a possibility therefore it is done manually.

It is reasonably assumed that there is a risk to catch fire for the tanks that are about 1 diameter away from the last tank that is damaged in EFFECTS calculations, according to Preem's judgement.

Since the only replacement values available for this study were given for Preem's groups of tanks (King Sturge Plant&Machinery, 2008), the replacement value for one tank was calculated by dividing that value to the number of tanks in the group. Because of the fact that each tank has different volume, the replacement value per unit of volume was obtained by dividing the replacement value per tank by the volume of the tank.

The following types of roofs can be found on Preem's tanks: dome, floating roof and dome with floating roof inside.

Given that the replacement value per unit of volume was calculated for all the tanks, the average value was calculated for the tanks with the same type of roof and that value was considered to be the replacement value per unit of volume for that type of tank. The procedure was repeated for the other tanks with same type of roof. At the end, from all the values that were obtained the average value was calculated used as a replacement value per unit of volume. That replacement value multiplied with the volume of the tanks that were destroyed gave the replacement value for those tanks.

Information about other companies' tanks, their locations and contents was taken from Environmental Protection Division of County Administration for Västra Götaland county (Miljöskyddsenheten).

Scenario 1 for tank 130

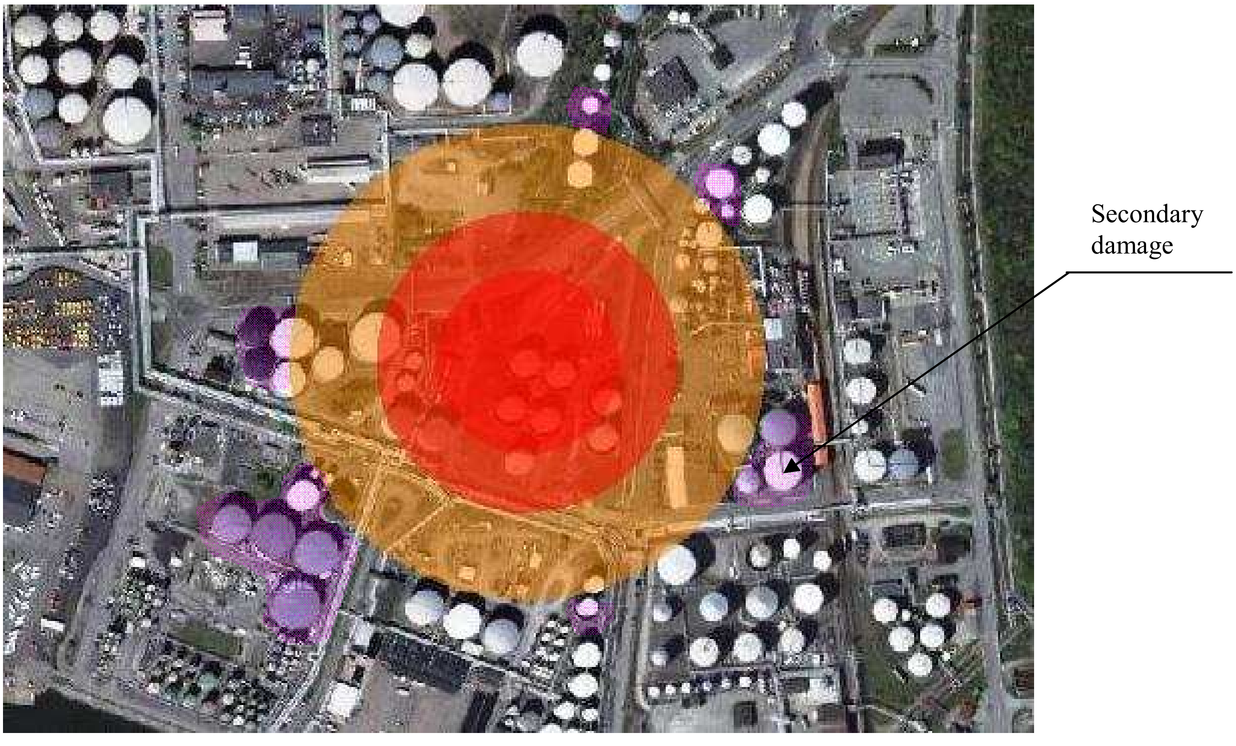


Figure 9.13. Scenario 1 for tank 130 with secondary damage

Threshold overpressure for Moderate damage is 170 mbar = 17 kPa. This overpressure would cause ‘moderate damage’ to the tanks and can cause walls made of concrete blocks to collapse (TNO Built Environment & Geosciences, 2010) which is considered to be ‘total destruction’ for the offices, storage facilities etc.

Replacement costs estimation:

Type of destruction	**Damage, kPa**	**Object of damage**	**Owner**	**Replacement value, €**
Total destruction	>83	tanks 401-405,407-409,412,413,418-420,422-425,427	Scanlube	32 704 000
		most of the offices (15-20 kPa)		6 009 652
		office (15-20 kPa)	Saybolt Sweden	1 231 252
		control facility, switchboard and transformer station, water treatment plant	STENA/RECYCLING CICLEAN	Lack of data
		offices (15-20 kPa)	Göteborg Energi	1 231 252
Heavy damage	35-83	tanks 101-103, 105,304, 307-310,312,317,318 with gasoline,fuel oil, thermoplastic elastomer and MK-1 fuel	Norsk Hydro	52 109 502
Moderate damage	17-35	tanks 371,373-376, 378,379,381-383 with gas oil, fuel oil and bio oil	Vopak	101 011 517

Figure 9.14 Consequences from Scenario 1, tank 130

Additional 10% are added to the replacement values for clearance of the debris and fire fighting (Willis, 2009).

In total: 194 297 175€ * 1.1 = 213 726 893 € ≈ 215 mil. €

Secondary damage:

Object of damage	**Owner**	**Replacement value, €**
tank 102	Norsk Hydro	6 943 090
tank 403	Scanlube	6 570 000
tank 3371	Vopak	20 509 254
tank 203	Nordic Storage	Lack of data

Figure 9.15 Secondary damage from Scenario 1, tank 130

In total: 34 022 344 € * 1.1 = 37 424 578 €

Total replacement value: 213 726 893 € + 37 424 578 € = 251 151 471 € ≈ **252 mil. €**

Scenario 1, tank 137

Type of destruction	Damage, kPa	Object of damage	Owner	Replacement value, €
Total destruction	>83	tanks 401-405,407-409,412,413,418-420,422-425,427	Scanlube	32 704 000
		most of the offices (15-20 kPa)		6 009 652
		offices (15-20 kPa)	Saybolt Sweden	1 231 252
		offices (15-20 kPa)	STENA/RECYCLING CICLEAN	Lack of data
		offices (15-20 kPa)	Göteborg Energi	1 231 252
		offices (>83kPa)	Norsk Hydro	2 550 086
Heavy damage	35-83	tanks 101-103, 105,304, 307-310,312,317,318 with gasoline,fuel oil, thermoplastic elastomer and MK-1 fuel	Norsk Hydro	52 109 502
Moderate damage	17-35	tanks 371,373-376, 378,379,381-383 with gas oil, fuel oil and bio oil	Vopak	101 011 715

Figure 9.16 Consequences from Scenario 1 at tank 137

In total: 196 847 459 € * 1.1 = 216 532 204 € ≈ 217 mil. €

Secondary damage:

Object of damage	Owner	Replacement value, €
tanks 372, 377	Vopak	33 207 098

Figure 9.17 Secondary damage from Scenario 1 at tank 137

In total: 33 207 098 € * 1.1 = 36 527 808 €

Total replacement value: 216 532 204 € + 36 527 808 € = 253 060 012 € ≈ **254 mil. €**

Scenario 1, tank 117

Type of destruction	Damage, kP	Object of damage	Owner	Replacement value, €
Total destructior	>83	tanks 204,208 (aviation fuel),312 (diesel)	St1	23 353 020
		office	Scanlube	1 231 252
		transformer station, switchboard, lubricating oil supply, lubricating oil storage, stock, steam plant unheated garage, stores, fire shead	St1	Lack of data
Heavy damage	35-83	tanks 311(WRD), 207(aviation fuel), 310(WRD),306(diesel), 103(gasoline), 121-122(empty), 123(ethanol), 314-315(empty)	St1	40 973 150
Moderate damag	17-35	tanks 101-104 with oil-water mixture	STENA/RECYCLIN CICLEAN	7 050 000
		tanks 101,102,105,309,316, 317, 319, 320, 118, 129, 327, 328	St1	20 134 765
		tank 3371	Vopak	20 509 254

Figure 9.18 Consequences from Scenario 1 at tank 117

In total: 113 251 441 € * 1.1 = 124 576 585 € -> 125 000 000 € (125 mil. €)

Secondary damage:

Object of damage	Owner	Replacement value, €
tank 101, 102	Stena Recycling	1 050 000
tank 3370, 3372	Vopak	26 840 970

Figure 9.19 Secondary damage from Scenario 1 at tank 117

In total: 27 890 970 € * 1.1 = 30 680 067 €

Total replacement value: 124 576 585 € + 30 680 067 € = 155 256 652 € ≈ **156 mil. €**

Scenario 2

The result is considered to be overly conservative because of the short heat duration. This shows that there might be the need for more precise heat flux values for process industries.

Scenario 3, tank 137

This type of explosion mirrors Scenario 1 but gives less consequences. Scenario 1 can be considered the worse of them. It can be reasonably assumed that for tanks 130 and 117 Scenario 1 would also have worse consequences then Scenario 3.

Scenario 4

Type of destruction	**Damage, kPa**	**Object of damage**	**Owner**	**Replacement value, €**
Total destruction	>83	storage facilities, office, car loading station,	Scanlube	3 046 208
		transformer, control facility, water treatment plant	STENA/RECYCLING CICLEAN	Lack of data
Heavy damage	35-83	-	-	-
Moderate damage	17-35	tanks 401,402,412, 423, 424,425, 427	Scanlube	7 728 000
		tanks 101, 102, 103,104	STENA/RECYCLING CICLEAN	7 050 000

Figure 9.20 Consequences from Scenario 4

Total replacement value: 17 824 208 € * 1.1 = 19 606 629 € ≈ **20 mil. €**

Scenario 5

Type of destruction	**Object of damage**	**Owner**	**Replacement value, €**
Total destruction	Storage facilities, office, car loading station, workshop boiler	Scanlube	3 585 010
Heavy damage	-	-	-
Moderate damage	tanks 401,402,409 412,423,424,425, 427	Scanlube	8 906 000
	tank 101	Norsk Hydro	6 996 632

Figure 9.21 Consequences from Scenario 5

In total: 19 487 642 €* 1.1 = 21 436 406 € ≈ 22 mil. €

Secondary damage:

Object of damage	**Owner**	**Replacement value, €**
tanks 403, 404, 418,419,420	Scanlube	10 658 000
tank 102	Norsk Hydro	6 943 090

Figure 9.22 Secondary damage from Scenario 5

In total**:** 17 601 090 € * 1.1 = 19 361 199 €

Total replacement value: 21 436 406 € + 19 361 199 € = 40 797 605 € ≈ **41 mil. €**

Scenario 6

There is no damage done to other companies, no matter the wind direction.

9.4 Validation

Validity of obtained results was checked by Preem.

Discussion

The purpose of this study was to determine the liability risk for Preem's facilities at Skarvik port and to suggest a methodology to determine such risks.

Judging by the historical cases – Buncefield accident especially – the consequences of an accident can be relatively unpredictable. The suggested methodology estimated these consequences as precise as it was possible given the data available.

Results like Scenario 2 are extreme and conservative, which suggests that there might be the need for more precise heat flux values for process industries.

Scenario which proved to be the worst case one - Scenario 1 for the tank 137 - is similar to Buncefield accident. Domino effects and projectiles from this and other scenarios were considered manually. There is still lack of data to make a more precise prediction.

The results suggest that to get a more precise liability risk value for a company, surrounded by the facilities of other companies, a lot of external data is needed - i.e. the description of the facilities of the other companies, the contents of their tanks and valuation of the tanks, product inside of them and machinery used at the facility.

Information regarding business interruption is business sensitive and such matters tend to be resolved in secrecy which might be a reason why it is so hard to get meaningful data on this subject. Compensation for business interruption is likely but it is a subject of a legal proceedings and not a situation for modeling.

There was a number of uncertainities in this study. Fraction of flammable cloud confined and some other parameters were calculated manually according to the Yellow Book's methodology which might be overly conservative. Another way of doing the calculation of total mass in the cloud would be through EFFECTS models 'Pool evaporation' and 'Dense gas dispersion: Explosive mass'. However EFFECTS does not have a capability to handle multi-component mixtures.

Wind direction is supported only in some of the EFFECTS models.

There is also concern about fire mitigation activities. Since the damage from explosion or fire can happen simultaneously at the different ends of Skarvik port, it might be very difficult – if possible at all – to conduct fire fighting and mitigation at all of the sources of flame at once.

Conclusion

Methodology to determine the liability risk was developed and tested using EFFECTS 8.1.

The suggested methodology to determine liability risks includes the study of previous accidents, 'what-if' analysis, event tree analysis, modelling of the most probable scenarios in EFFECTS 8.1 and manual consideration of domino effects. Some parameters for the modelling, like fraction of flammable cloud confined, were also calculated manually.

Using the developed methodology worst-case scenario was chosen.

It can be reasonably assumed that Scenario 1 for the tank 130 (tank overfills for 15 minutes, while pump flow is 800 m^3/h, 10% of leaked mass turns into vapour) can lead to BLEVE at LPG storage (Scenario 2). But since it is impossible currently to establish the replacement values of BLEVE consequences – Scenario 1 for tank 137 remains the worst-case cost-wise (≈260 million Euro).

Risk of damage to the environment and people is very important but in this study the scope was only the damage to property of the other companies in Skarvik.

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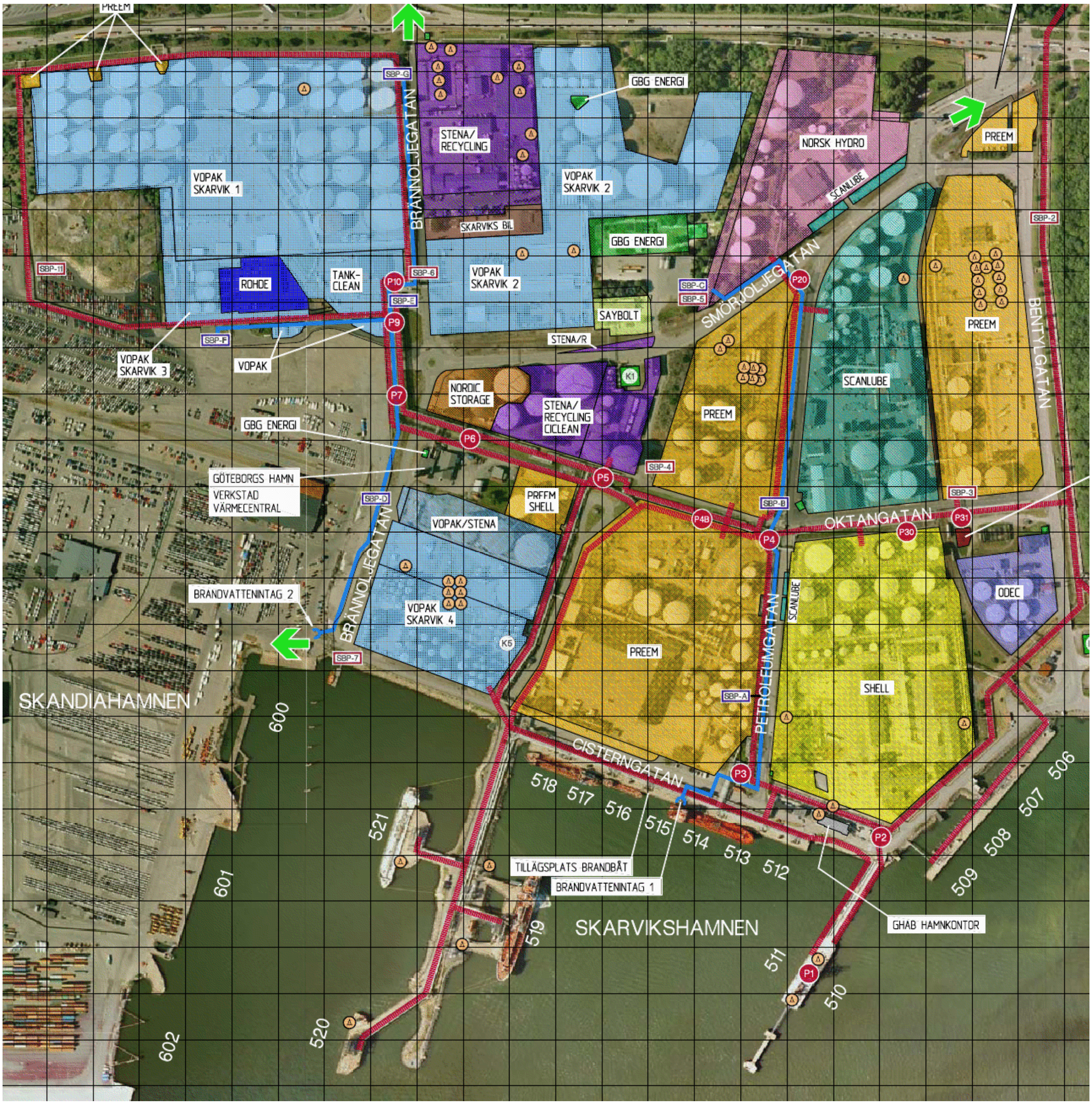
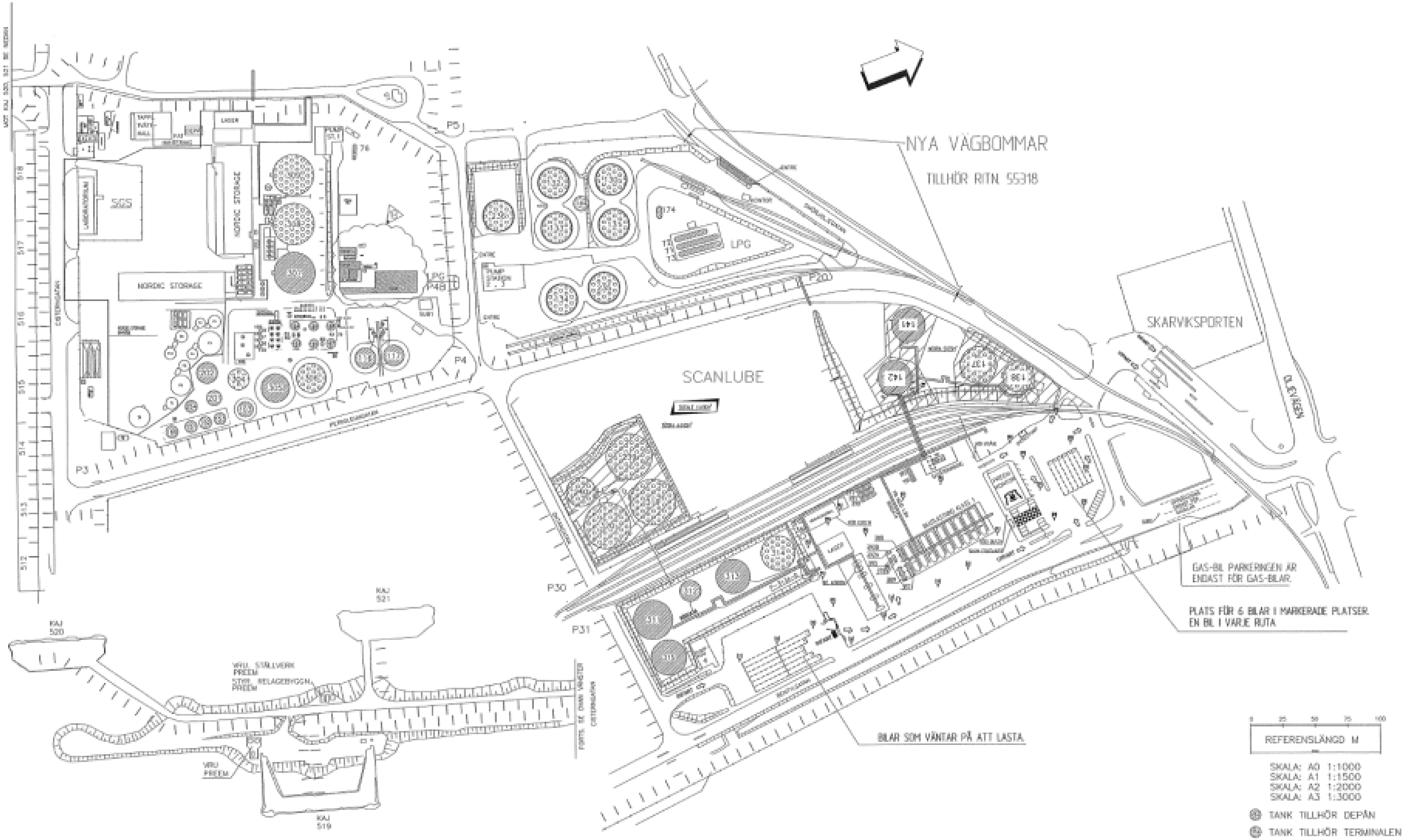
Appendices

Appendix 1. Map of Skarvik port



Appendix 2. Map of Preem facilities in Skarvik port



Appendix 3. Heat radiation levels (Dreher, 2009).

Heat flux	Observed effect
35-37,5 kW/m2	Sufficient to cause damage to process equipment. Cellulosic material will pilot ignite within one minute's exposure.
23-25 kW/m2	Spontaneous ignition of wood after long exposure. Unprotected steel will reach thermal stress temperatures which can cause failures. Pressure vessel needs to be relieved or failure will occur.
12,6 kW/m2	Thin steel with insulation on the side away from the fire may reach a thermal stress level high enough to cause structural failure. Minimum energy required for piloted ignition of wood, melting of plastic tubing.