Risk Analysis of the oil depot in Örfirisey

Thorvaldur Helgi Audunsson

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik
Lunds tekniska högskola
Lunds universitet

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Abstract
This thesis estimates the risk of the activity at the oil depot in Örfirisey and its location, to its nearby population. The thesis will consider possible risks from the oil depot it self in case of fire, today, in relation to health and safety. Transportation of the fuel from the depot through the city will be discussed in an attempt to see if other depot locations or strategies can lessen the risk involved. The method used in this thesis is the Chemical Process Quantitative Risk Analysis model or CPQRA. Evaluation of the risk was mostly based on individual risk and societal risk. Tolerable risk and risk perception is briefly discussed as well as uncertainty. The attempt to reduce the risk or control it is examined later on in the thesis. Finally future alternatives are discussed for ODR to put up other smaller depots outside the capital area, beside the depot in Örfirisey, to minimize the transportation of the fuel through the city of Reykjavík.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 - 222 73 60

Department of Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se/english

Telephone: +46 46 222 73 60

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Summary

The oil depot in Örfirisey is the largest depot in Iceland and serves today as a storage and distribution depot for petroleum products in ownership of Olíudreifing ehf. (ODR) and Skeljungur hf. (Shell). It was built in the 1950's and is located in Reykjavík.

The depot has been considered a threat to nearby population and surroundings for some years now, without those opposed providing any strong arguments against it in the form of risk analysis. Because of that it was considered of interest to estimate the scale of the threat and to get a better understanding of the risk.

To estimate the risk caused by the operation in the depot, three fire scenarios where analyzed for with five different approaches for ignition. The scenarios are:

- Fire starts in the gasoline loading rack
- Fire starts at the gasoline fuel storage area
- Fire in the whole depot

Risks in transportation of the fuel outside the operation area are also partially accounted for and discussed, since much fuel is transported to different locations around the south-west corner of Iceland.

To evaluate the possible risk to nearby population from those scenarios, the frequency and consequences were estimated using the Chemical Process Quantitative Risk Analysis model (CPQRA). This method is a quantitative risk analysis method (QRA) which gives the user the option to estimate consequences by predicting the size, shape or orientation of the risk that could be created by the release of hazardous material. Individual risk and societal risk have been calculated for those individuals working within the operation area since the radiation from the fire scenarios was estimated not to affect nearby population.

Fire and the resulting smoke is considered the largest threat for the operation in the depot. The energy release can be enormous for some of the scenarios considered and in cases of fires in some of the storage tanks, extinguishing them will certainly be a challenge for Capital District Fire and Rescue Service (CDFRS) and demands much manpower, equipment, good knowledge and well organized plans, water availability and foam.

Leakages at the gasoline rack and overfilling of the trucks are far too common. Because of that the probability for a fire to occur is rather high and therefore those leakages should be managed better. Leakages at the depot are about 20 times more common than the same numbers for OK-Q8 depots in Sweden. However is considered probable that the fire protection system at the depot would extinguish the fire before it could spread out any further.

It is considered that the depot is not a major threat to people's lives in nearby surroundings. The radiation from a large scale fire is not causing second degree burn

injuries further away than 100 meters away from the fire, which was used to estimate the casualties for such a scenario. The nearby population is located about 900 meters away from the depot. The smoke could cause problems to large areas in Reykjavik but would probably not be life threatening because of the estimated gaseous concentration in the smoke. Large scale evacuation procedures of the nearby residents might become necessary should a large fire occur. By moving the people from the danger, the risk caused by the smoke would be minimized.

Both individual risk and societal risk are considerably higher than the tolerability criteria determined by the Icelandic Environmental Ministry for deaths related to avalanches in Iceland and the criteria from Det Norske Veritas respectively. That can partly be explained by the fact that the leakages at the depot are far too common and thereby increasing the probability of a fire to occur.

The statement made by ODR that their drivers have only had one accident per year makes them 5 times less probable for having an accident compared to other drivers driving trucks above five tons. The probability for an accident to occur was calculated to be 2% per truck belonging to ODR, compared to 11% for other trucks. The consequent return period for an accident involving a fire in an oil truck is 12 years and 66 years respectively. This data from ODR is limited to ten years and merely ten observations. Two rollover accidents this year, including one where several tons of gasoline were released, do change this statistic to some degree and should lead to the conclusion that the probability for an accident is somewhere between 2-11% per truck annually.

Transportation of fuel to areas outside the capital area should not be through the city of Reykjavík. If a few other smaller depots would be placed around the southern and western part of Iceland, fuel transportations through the city could be reduced considerably. If the storage tanks in Helguvík (Reykjanesbær) would be used for storing the fuel for the international airport in Keflavík, the transportations could at least be reduced by 20%. By taking into operation other depots, petroleum transports would be reduced further through Reykjavík city center and almost eliminated through sensitive areas such as the Hvalfjörður tunnel and water protection areas.

However, while setting up other depots would probably reduce the transportation risks considerably, it could be a very costly operation. A thorough cost-benefit analysis as well as risk analysis, of such an action would need to be conducted before any clear statement of the benefits and drawbacks can be made.

Sammanfattning (summary in Swedish)

Oljedepån på Örfirisey i Reykjavik är Islands största depå. Den ägs av Olíudreifing ehf (ODR) och Skeljungur hf (SHELL) och fungerar som logistiskt centrum för oljeprodukter. Den byggdes på femtiotalet.

Under många år har depån ansetts utgöra ett hot mot omgivningen och dess befolkning, utan att några riktiga riskanalyser utförts. Därför var det intressant att beräkna hur stort detta hot egentligen är och få en bättre uppfattning om riskbilden.

För att uppskatta risken som verksamheten vid depån utgör har tre brandscenarier analyserats med fem olika alternativ för antändning. Scenarierna är:

- Brand startar vid bensinomlastningen
- Brand startar vid bensinförvaringen
- Hela depån brinner

Risker vid bränsletransporter utanför verksamhetsområdet har också delvis analyserats eftersom mängder av bränsle transporteras med tankbilar från Örfirisey till olika platser på sydvästra Island.

För att få grepp om vilka risker scenarierna ovan skulle utgöra för befolkningen i omgivningen har frekvens och konsekvens beräknats med hjälp av CPQRA (the Chemical Process Quantitative Risk Analysis model). Detta är en kvantitativ riskanalysmetod (QRA) som gör det möjligt för användaren att beräkna konsekvenser genom att förutspå omfattning, utformning och orientering av risken som kan följa ett utsläpp av farliga ämnen. Individrisk och samhällsrisk beräknades slutligen endast för personer inom depåområdet, eftersom beräknad strålning från brandscenarierna inte torde påverka befolkningen i omgivningen.

Brand och tillhörande rökutveckling bedöms vara det största hotet av verksamheten i depån. Energiutvecklingen kan vara enorm för vissa av scenarierna, och släckningen av en tankbrand på depån skulle vara en stor utmaning för Huvudstadsområdets Räddningstjänst (CDFRS) och kräva mycket manskap, utrustning, kunskap och bra responsplaner, vattentillgång och skumvätska.

Analysen har visat att läckor vid bensinomlastningen och överfyllning av tankbilar är alldeles för frekventa. Sannolikheten för brand är därför relativt hög och följaktligen måste omlastningen hanteras bättre. Läckor vid depån är ungefär 20 ggr vanligare än vad OK-Q8 anger för sina anläggningar. Däremot anses det sannolikt att områdets släckanläggning skulle hindra en brand från att spridas från lastningsområdet till förvaringsområdet.

Depån kan inte anses utgöra ett stort hot mot befolkningen i omgivningen. Strålningen från en storbrand orsakar inte andra gradens brännskador (vilket användes för bedömningen av antalet omkomna) utanför en 100 meters radie, medan närmaste bostadsområde ligger ungefär 900 meter från depån. Röken skulle kunna orsaka problem i stora delar av Reykjavik, men skulle förmodligen inte vara livshotande på grund av utspädningen. Ett behov för storskalig evakuering av omgivningens befolkning skulle kunna uppstå. Genom att förflytta folk från riskkällan skulle risken som röken utgör för liv och hälsa minimeras.

Beräknade individ- och samhällsrisker är markant högre än de tolerabilitetskriterier som användes, det vill säga isländska miljöministeriets lavinfarokriterium och det Norska Veritas kriterium. Detta kan delvis förklaras av den höga frekvensen av läckor inom depån och följaktligen förhöjd brandrisk.

Uttalandet från ODR att deras chaufförer endast har varit inblandade i en trafikolycka per år antyder att de är 5 ggr mindre olycksbenägna än andra chaufförer av fordon över fem ton i den isländska trafiken. Olyckssannolikheten för en ODR tankbil skulle då vara 2% årligen jämfört med 11% för övriga tunga fordon. Dessa frekvenser ger återkomsttider för en olycka med brand i en oljetransport på 12 respektive 66 år. Data från ODR är begränsat till tio år och endast tio observationer. Två rullningsolyckor i år (2006), varav den ena med ett utsläpp av flera ton bensin, ändrar denna statistik något och leder till att olycksrisken per tankbil anses ligga någonstans mellan 2-11% årligen.

Transporter av bränsle till områden utanför huvudstadsområdet bör inte ske genom Reykjavík. Om några mindre depåer placeras runt om Islands sydvästra hörn kan transporter genom Reykjavik reduceras markant. Om befintlig oljedepå i Helguvik (Reykjanesbær) skulle användas för den internationella flygplatsen i Keflavik skulle transporterna minska med minst 20%. Genom att ta i bruk ett par andra depåer skulle oljetransporter reduceras ytterligare genom Reykjavik och nästan elimineras genom känsliga områden så som Hvalfjörðurtunneln och vattentäkter.

Även om transportrisker förmodligen skulle minska markant vid igångsättandet av dessa mindre depåer, kan detta vara en kostsam åtgärd. En grundlig kostnad-nytta analys samt riskanalys av dessa alternativ måste genomföras innan ett riktigt uttalande kan göras om fördelar respektive nackdelar.

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1 Introduction

1.1 Background

Oil depots are found all over the world, some large, other small, depending on the purpose and role of each one. They have a number of factors in common that can be shown easily. They store large amounts of flammable petroleum that can cause explosions or big fires, they can affect the environment and people's health in case of leakages and they are usually located near populated areas due to shorter transportation routes. Some are even located next to or inside a populated area. That is the case with the oil depot in Örfirisey.

Örfirisey is a peninsula located in the north-west part of Reykjavík, Iceland. This peninsula is most often referred to as an island as can be seen from its name "Örfiris – island", even though it is connected to the landmass of Reykjavik.

Figure 1. Location of Örfirisey in relation to Reykjavík.

Only a few oil depots have been established in Iceland, the oil depot in Örfirisey is one of them and also the largest. This depot is used for storage and distribution of petroleum products for Olíudreifing ehf (ODR) and Skeljungur hf (Shell).

Olíudreifing ehf is a co-operation between Olíuverslun Íslands hf (Olís) and Olíufélagið hf (holder of the brand ESSO in Iceland). This co-operation was established in 1995 to reduce operational costs. The role of ODR is storing and distributing petroleum products for the owners and operation of specialized maintenance for service stations and own equipment.

The development of the depot started in the 1950's, when it was one of three main depots found in the country. Over the years it grew larger with increasing activity and complexity. Today there is a total of 32 tanks in the area of all sizes and the products are gasoline, diesel, fuel oil, JET A-1, aviation gasoline, white spirit and waste oil. Boundaries between the petroleum types divide the area into a few individual perimeters, in an attempt to increase safety of the depot.

1.2 Objective

The objective of the thesis is to estimate the risk of the activity and the location of the oil depot in Örfirisey, to its nearby population. The thesis will consider possible risks from the oil depot itself, today, in relation to health and safety. Individual and societal risk will be shown for the people living near the depot and/or the people working there. One of the objectives is to suggest strategies to reduce the risks to as low as reasonably practical (ALARP), after they have been identified.

If the depot is creating too much risk for the nearby population a comparison of moving the depot to another location situated further away from the city will be considered to see if those possible risks or consequences of them will decrease. Transportation of the fuel from the depot through the city will be discussed in an attempt to see if other depot locations or strategies can lessen the risk involved.

1.3 Method

The method used in this thesis is the one called Chemical Process Quantitative Risk Analysis model or CPQRA. This model is used in quantitative risk assessment within the chemical process industry and is therefore suitable for this kind of activity.

Information has been gathered by literature study, interviews and calculations. Information from the Capital District Fire and Rescue Service (CDFRS), Olíudreifing ehf., Icelandic Fire Authority and the City of Reykjavík was also of great help in this relation.

1.4 Limitations

The project emphasizes on health and safety and does not consider the environmental issues of a HSE analysis.

Definition of tolerable risk is a matter that will not be discussed thoroughly in this project but a definition of this concept exists in relation to avalanches in Iceland and that will be used as a benchmark.

The methods used to calculate the rise in temperature in this work must be considered to be very approximative and simplistic. Far more sophisticated methods are available, involving Finite Element heat transfer methods coupled with Computational Fluid Dynamics programs, but the complexity in using such methods is considered to be outside the scope of this work.

The assessment of transportation risks caused by transporting the fuel from the Örfirisey depot will not be considered thoroughly, but some suggestions will be made to diminish those risks.

1.5 The initiative behind the project

Because of the short distance from residential homes the activity in Örfirisey has been considered dangerous, but exactly how dangerous no one knows. Today even politicians have used that argument in their pleading to move the activity from the peninsula and build residential homes instead. Land for housing in Reykjavík is considered a problem today and that is possibly why politicians are interested in moving the oil depot and developing the area. It is of interest to calculate the scale of the threat in quantitative terms and help people understand if the depot is really causing any significant threat or not, and if it is – to which degree.

1.6 Acronyms and abbreviations

ALARP	As Low As Reasonably Practical
ALOFT	A Large Outdoor Fire Plume Trajectory
AOSH	Icelandic Administration of Occupational Safety and Health
BLEVE	Boiling Liquid Expanding Vapor Explosion
CBA	Cost Benefit Analysis
CDFRS	Capital District Fire and Rescue Service
CEA	Cost Effectiveness Analysis
CPQRA	Chemical Process Quantitative Risk Analysis model
DWT	Dead Weight Tonnage
FAR	Fatal Accident Rate
HRR	Heat Release Rate
HSE	Health, Safety and Environment
ICER	Incremental Cost Effectiveness Ratio
IDLH	Immediately Dangerous to Life and Health
ISGOTT	International Safety Guide for Oil Tankers and Terminals
LC_{50}	Lethal concentration
LY	Life Years
NATO	North Atlantic Treaty Organisation
NFAR	None Fatal Accident Rate
NIOSH	National Institute for Occupational Safety and Health
ODR	Olíudreifing ehf.
QALY	Quality Adjusted Life Years
QRA	Quantitative Risk Analysis
SMC	Släckmedelscentralen
WTP	Willingness to Pay

2 The operation in Örfirisey

In order to understand the thesis one must also know the main aspects of the operation in Örfirsey. This chapter describes the main aspects of the operation regarding safety and incident response.

To operate an oil depot in a responsible manner is very complex and requires accuracy, planning and preparation. Many things can go wrong and therefore safety is extremely important. Safety and operational safety has been highlighted in Örfirisey from the beginning of the operation in the 1950's with the help of numerous regulations and permits.

Three major depots are found in Iceland, though the one in Örfirisey is by far the largest. Other minor depots are available but they are mostly used as service depots for smaller towns and communities. Some of them are scheduled to be closed in the near future because of economical reasons.

One role of the operation in Örfirisey is to receive and store petroleum products; another one is to distribute the products to different locations around the south-west part of Iceland, including the capital area where two-thirds of the Icelandic population is located. This transportation is mostly done by transportation trucks but some by vessels in ownership of ODR and Shell.

This operation at that location has been criticized because of the nature of the activity. Some say this is a threat to people living close to the area but no one has come up with argument or proof that shows how big the threat is. In this relation it has to be mentioned that the depot was built before most of the surrounding activity and residential homes, but not the other way around.

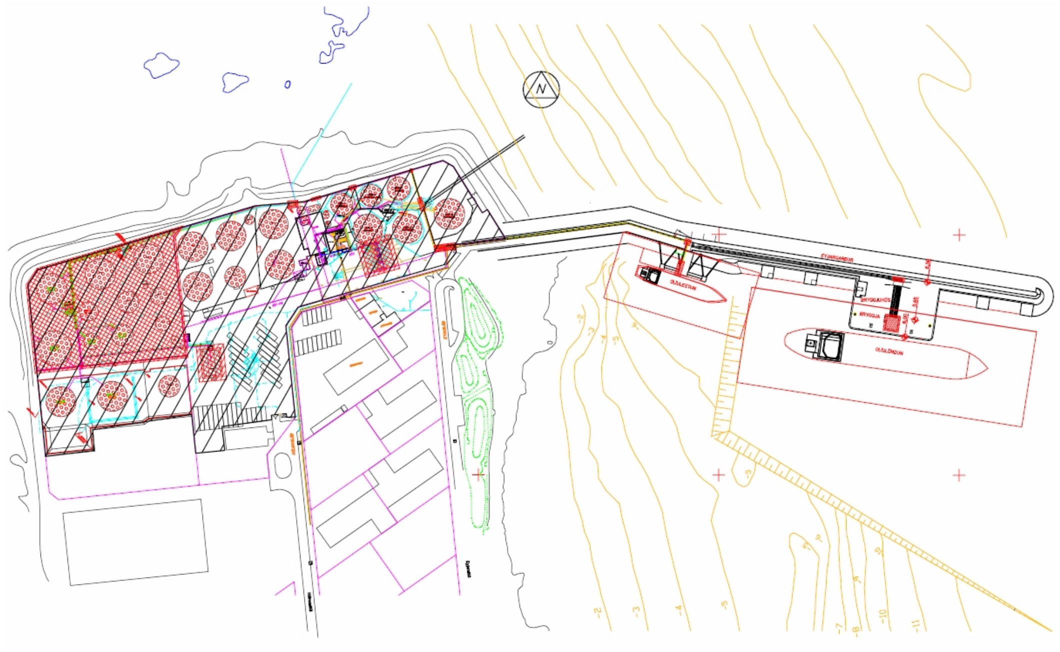


Figure 2. Position of the petroleum tanks and the harbor in Örfirisey.

2.1 Storage of flammable liquids

Storage of flammable liquids in an oil depot is regulated by a regulation no. 263/1998 [1] (hazard analysis in industrial operation – Hættumat í iðnaðarstarfssemi), which is based on the SEVEZO directives. This regulation states that ODR is obligated to come up with a compulsory declaration (stefnumarkandi skjal) that is meant to prevent and respond to major risks in its activity, because more than 5.000 tons of flammable liquids are found in the area. The criteria in this relation applies to chemicals and substances that have flashpoint between 21°C and 55°C and also if the flashpoint is under 21°C and the substance is not defined as extremely flammable. This definition unfortunately does not cover the storage of diesel oil, fuel oil and waste oil, since their flashpoint is above 55°C. ODR has decided however to put those petroleum products into their compulsory declaration to improve their response in case of emergency.

The ODR compulsory declaration mentioned above is based on that the possible risk scenarios are only local to the operation in Örfirisey. Consequences of accidents or risks within the operation area are unknown outside the operational perimeter. A thorough risk analysis of how certain catastrophic events could affect nearby surroundings is not available and that is what will be performed in this project.

2.2 Tank fires

Since the 1950's a total of 480 tank fire incidents have been identified worldwide. The available information for each of the incidents varies from just a short notice in a newspaper to very detailed information regarding the cause of the fire and the fire fighting response. The extent of the fire incidents may vary from just a rim seal fire, being extinguished without difficulty, to fires involving a complete tank storage facility with 30-40 burning tanks. Tank fires are estimated to be around 15-20 every year [2].

It has been noted that practical fire fighting experience is generally limited to tanks having a diameter of 40 to 50 meters or less. The tanks in Örfirisey are all under this diameter. Tanks barely exceeding 20 meters in diameter have however caused problems in fire extinguishing [2]. Fire control and extinguishment have been low through out history when it comes to fuel tanks. Lightning has been identified as the most probable cause of all tank fires, but lightnings are very seldom seen in Iceland. Electrostatic discharge has also been mentioned as a probable cause.

If a fuel tank is on fire there are only two alternatives for fighting the fire, either to let it burn out and thereby self-extinguish or to actively extinguish the fire, using fire fighting foams. Since the burn out procedure will cause more loss of stored products, more damages to the environment, large cooling operation to protect fire spread to adjacent tanks, fire lasting for days and in some cases a boil-over, this is often not an acceptable alternative.

Water needed for such an operation can vary depending on the scale of the fire. When thirty depot fires where studied [2] the water need was 2,2-30 $l/m^2/min$, where the most common use was about 7 $l/m^2/min$. That value could be used as a benchmark for a major fire to be extinguished at the oil depot in Örfirisey.

2.3 Fire protection and response plans

In an operation like this, fire protection is necessary and important since the possible energy release is significant. As has been mentioned earlier, ODR is not the only company storing petroleum products on the peninsula. Skeljungur hf. (Shell) is also storing their petroleum there and that amount has to be accounted for in all calculations in this thesis. The maximum volume of petroleum products belonging to ODR and Shell at each time can be seen in Table 1.

Petroleum	*Volume (m^3)*	*Density at 15°C (kg/m^3)*	*Weight (tons)*
Gasoline	37.151	720-770	27.677
Diesel oil	64.795	800-880	54.428
Fuel oil	12.875	960-980	12.489
JET A-1	21.000	775-840	17.010
AVGAS 100 LL	1.900	700-720	1.349
White spirit	1.300	780	1.014
Waste oil	3.680	900	3.312

Table 1. Volume and density of petroleum products found in Örfirisey.

Detailed information about each tank in the area can be found in Appendix A.

2.3.1 Fire protection systems

Fire protection systems are available at site and they are built according to the NFPA 11 1998 standards [3]. There are two such systems where one is designed to protect the tanks storing the diesel oil and the other to protect the gasoline tanks. The foam is made of fluorine protein, Angus FP70 3%. The gasoline filling rack, which is the loading place for the gasoline, also has its own foam system which is driven by the pumps from the gasoline protective system.

The diesel foam system is supposed to provide 4,1 $l/min/m^2$, according to NFPA 11 1998 [3]. By providing that much volume it should protect the largest tank for about 98 minutes. This system on the other hand was designed to provide up to 4,9 $l/min/m^2$, which is above the NFPA standard. Water needed for the largest container to be protected, which is about 483 m^2, would be about 1980 l/min as can be seen from Table 2. Same methods are used for the gasoline foam system and the foam availability there would be around 45 minutes.

The systems are activated manually, and only by the supervisors in charge each time. Others don't have permission to turn the systems on because of the possibility of human error. The cost of turning them on is considered too high for a false alarm.

	Diesel foam system		***Gasoline foam system***	
	Max flow	***Real flow***	***Max flow***	***Real flow***
l/min/m^2	4,9	4,1	4,9	4,1
Total flow (l/min)	2367	1980	3146	2632
Foam needed (l/min)	71,0	59,4	94,4	79,0
Foam availability (min)	81,7	97,6	38,1	45,6
Area of tank (m^2)	483		642	
Foam concentration	3%		3%	
Foam availability (l)	5800		3600	

Table 2. Water and foam needed for the foam systems.

The numbers quoted in Table 2 are only valid for one tank in the depot, one for each system. If more than one tank would be in danger and the system would have to protect or extinguish in more than one tank, the foam would be exhausted after a short period of time and the system would not be able to function as it is supposed to do. Therefore is it extremely important that the foam systems do function as they should do by extinguishing the fire in its early stages. If the systems do not function as planned, extra foam is needed on site and quickly, as would extra reinforcement in the form of firefighters and other equipment.

In cases where one or more tanks need to be protected, the foam and water needed is shown in Table 3. In relation to the diesel area the foam system is now shown protecting Shell 1, Shell 2 and Shell 3 or an area of total 1449 m^2. In relation to the gasoline area the system is now protecting ODR 11, ODR 12, ODR 13 and ODR 15, a total of 1496 m^2. Figure 3 is a schematic drawing of the tank area.

	Diesel foam system		***Gasoline foam system***	
	Max flow	***Real flow***	***Max flow***	***Real flow***
l/min/m^2	4,9	4,1	4,9	4,1
Total flow (l/min)	7.100	5.941	7.330	6.134
Foam needed (l/min)	213,0	178,2	219,9	184,0
Foam availability (min)	27,2	32,5	16,4	19,6
Area of tanks (m^2)	1.449		1.496	
Foam concentration	3%		3%	
Foam availability (l)	5800		3600	

Table 3. Water and foam needed if more than one tank is on fire.

In cases like these it is obvious that the duration of the foam will be much less than in cases where only one tank is protected. The time for the diesel foam system has dropped from 97,6 minutes to 32,5 minutes. The same is seen for the gasoline foam system or a time dropped from 45,6 minutes to 19,6 minutes. This time would even be less if more tanks would be on fire as those tables demonstrate.

Total foam availability in Örfirisey is about 28.400 l, where all of the foam is not connected to the system at a time as can be seen in Table 2 and 3. Capital District Fire and Rescue Service (CDFRS) in Reykjavík has 3.000 l more foam available, if needed. Emergency supplies of 100.000 l are to be found at Angus ltd. in England. As expected it will take at least take six hours to transport the foam to the site in Iceland in case of emergency, if flown by plane.

2.3.2 The Swedish approach – SMC

Only one large scale fire in an oil tank has occurred in Sweden since the year 1956. That happened in Nynäshamn and the tank ruptured due to severe cold [2]. Even though the frequency of accidents like this are low the risk is still present.

Equipment used in depot fires is expensive and can certainly not be found all over the country. To keep the necessary resources available if such a fire should occur, the Swedish oil companies formed “Släckmedelscentralen” [a] or SMC AB in 1994. A total of seven oil companies, invested in mobile equipment that will be used if a tank fire occurs somewhere in Sweden. The intention is that the local fire brigade should attempt to stop the fire from spreading out to other tanks by cooling adjacent tanks or objects until SMC response unit arrives and extinguishes the fire.

SMC reached an agreement with the fire brigades in Stockholm, Gothenburg, Malmö and Sundsvall regarding operations of SMC and emergency preparedness. The equipment is divided into four equal units all kept in those previously mentioned cities, where daily operation is based on agreement with the fire brigades. In case of fire the equipment is flown by the Swedish Air Force to the place needed with specially trained individuals for cases like this.

The equipment for each region consists of two modules where each module includes:

- A specially designed pump with a capacity of 10.000 liters per minute at 8 bars
- A foam monitor which has a capacity of 8.000 liters per minute
- 20 tons of alcohol resistant foam liquid
- A foam proportioning system
- 800 meters of 150 mm diameter hoses fitted with Storz couplings and a mobile hose recovery unit to handle the hoses

In Sweden there are a total of 200 specially trained firemen and about 30 leaders for these kinds of fires. In a case of emergency an operational SMC team is usually sent to the scene, which consists of one team leader and five firemen that will cooperate with the local fire brigade.

CDFRS has had discussions with SMC and an informal agreement assumes that SMC can assist in case of a large scale fire at Örfirisey. Formal agreement for assistance with Angus ltd. is in effect.

2.3.3 Compartments in the depot

In an attempt to minimize potential damage caused by leakage somewhere in the depot, the tank area is divided into a number of smaller areas or compartment that set certain boundaries between bundles of tanks. Those boundaries are made of 1 meter high concrete walls that prevent the petroleum from flowing freely from one compartment to another. All the gasoline found in the peninsula is located in an area named after its product or the gasoline compartment. The diesel found in the area is also located in an area called the diesel compartment. An overview of the compartments is given in Table 4.

Compartment	***Volume (m^3)***	***Tank area (m^2)***	***Boundary area (m^2)***	***Total area (m^2)***
Gasoline compartment	48.251	3.259	8.348	11.607
West compartment	17.079	1.308	4.650	5.958
East compartment	8.176	508	1.672	2.180
Shell diesel compartment	42.570	2.666	2.041	4.707
ODR/Shell diesel compartment	26.625	1.961	5.416	7.377

Table 4. Different compartments within the tank area.

More detailed information about the compartments can be found in Appendix B.

2.3.4 Water availability

The foam is diluted with water to make it functional as an extinguisher. The water needed for an operation like the one in Örfirisey is provided to the operation by Reykjavík city water system, which can pump 3.000 l/min. Three diesel pumps capable of pumping totally 20.000 l/min of seawater at 10 bars are stationed at the depot in case of emergency and as a reserve if the water system is not functional.

Estimates of the water needs can be hard to determine and it all depends on the number of tanks burning and their location. A consideration regarding how many tanks have to be protected by cooling has its effect on the water needed. In a review of tank fire incidents from 1951 to 2003 [2] the water used for the fires considered there where from 2,2 $l/min/m^2$ to 30 $l/min/m^2$, with the most common value of about 7 $l/min/m^2$. This value might be used as a benchmark for a large scale fire in Örfirisey.

The largest tank demands about 2.600 l/min. which is below the capacity of the Reykjavík city water system. In Table 3 an estimation of about 14.400 l/min was needed for only a handful of tanks found in the area. In case of extreme fire a rough estimation of 1500 l/min would be needed for cooling each tank that would possibly be in danger. The total water availability at the island is 23.000 l/min which would probably not be enough in those severe cases. On the other hand it should not be forgotten that CDFRS is nearby and they have extra pumps capable of fetching coolant in the form of seawater from nearby seashore, which is very close by.

Figure 3. Water hydrants in Örifisey.

Water availability will probably not be the limiting factor in those extreme cases. The foam would most likely be exhausted before any problems with water availability would occur.

Figure 3 demonstrates the location of the water hydrants in Örfirisey. Larger overview of the depot area can be seen in Appendix I.

2.3.5 Response plan

Fire is always considered a high risk for an oil depot operation and it is not certain that the foam system found at site will extinguish all possible fires. According to the response plan in the compulsory declaration, CDFRS shall be notified through 112 and react to the threat. In those cases CDFRS shall take command over the scene, while the safety committee of ODR and Shell shall be of assistance to CDFRS.

It has been emphasized by CDFRS that the site employees must be specially trained to respond to fire threats. They are the first link in the response since it is very important to react as soon as possible because of the growth rate of fires in depot fires.

According to Birgir Finnsson asst. fire chief at CDFRS [4], the fire brigade has unfortunately no special response plan in case of a large fire at the depot but uses instead a common plan for such fires. Large scale fires are categorized as F1, or priority one according to their working guidelines. In those cases all available firefighters at work would be summoned to the site when the threat has been confirmed and defined. Firefighters on duty are at least 22 at any time but 120 more are available when needed. Those 120 can be reached within a few minutes and the first one at site is estimated to be there 10 minutes after they get the call.

CDFRS are equipped with 8 pumping vehicles containing pumps capable of pumping 4000 l/min each. Two platform ladder vehicles are in their property, special water supply container with about 4 km of hoses and numerous smaller movable pumps. If additional units are required good cooperation is between CDFRS and fire departments from nearby communities.

Three boats are in their custody which can be used for an assault from the sea. Other boats from rescue teams in Reykjavík area are also available if needed. Some boats are sufficiently equipped but others would need to be installed with movable pumps and monitors.

Regarding the foam availability, the Swedish approach (chapter 2.3.2) is something that CDFRS is developing with the Icelandic petroleum companies and others in high risk operations.

In case of evacuation the population within a radius of 800 meters would be relocated, but only in worst case scenarios. That is because of possible threats from heat and explosion. Because of the smoke coming from the fire a wider area would possibly be evacuated, but that would be decided on scene. The evacuation would be done according to guidelines for that kind of work [4].

According to CDFRS only one 3.000 l/min pipeline is found on the island and water is certainly not sufficient in cases of large fire. Water availability from the sea can be a problem as well because of the distance at some places.

In a storage depot fire that took place 3-4th of May 2003 in Gdansk Poland where a tank storing 19.100 m^3 of gasoline was burning, the total number of firefighters used to control the fire was 429. They used almost 30 $l/min/m^2$ of water and 120 tons of foam. The area of the tank was 1253 m^2 [5].

2.4 Transportation of the fuel

The fuel is transported to Iceland by fuel vessels and they can be up to 45.000 DWT (Dead Weight Tonnage – refers to total lifting capacity of a ship) to enter and dock at the harbor in Örfirisey. Then the fuel is pumped to the depot and from there distributed further on.

As mentioned earlier this depot is petroleum storage for the largest part of the south-west corner of Iceland, where most of the population lives. The products are driven from Örfirisey to different service stations around Reykjavík city and further on through the city to communities and towns further away. This is done by transportation trucks, which are run by ODR. The drivers are all ODR employees and they have to know and follow strict procedures [6] regarding safety and response to accidents. Those drivers follow certain routes through the city when driving to other communities which have been predefined by ODR as the safest ones to their destinations.

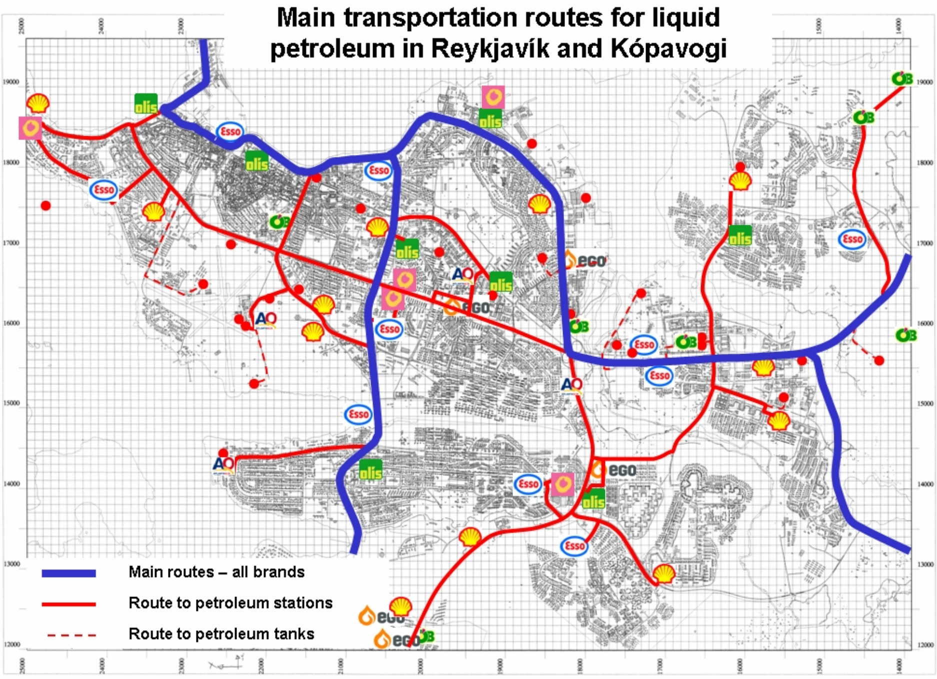


Figure 4. Main transportation routes for the petroleum in and through the capital.

Transportation of petroleum to the shipping fleet in Reykjavík is to some degree done by a petroleum transportation vessel. Communities farther away from the city get their petroleum driven to them by trucks, where the whole load is left behind in smaller petroleum tanks to minimize the trips of the trucks.

ODR has 50 petroleum trucks which are used for this transportation. The capacity of the trucks is from 24 m^3 to 40 m^3. The number of trips over the year varies depending on their capacity.

Petroleum	**Volume (m^3)**	**24 m^3**	**30 m^3**	**35 m^3**	**40 m^3**
Gasoline	111.453	4.644	3.715	3.184	2.786
Diesel oil	194.385	8.099	6.480	5.554	4.860
Fuel oil	38.625	1.609	1.288	1.104	966
JET A-1	63.000	2.625	2.100	1.800	1.575
AVGAS 100 LL	5.700	238	190	163	143
White spirit	3.900	163	130	111	98
Waste oil	11.040	460	368	315	276
Total	428.103	17.838	14.270	12.232	10.703

Table 5. Number of loading trips needed depending on the capacity of the truck.

Table 5 gives an estimation of the total number of transportation trips over the whole year 2005 depending on the capacity of the trucks and it is assumed that those trips will increase for about 5% the year 2006, since that has been the trend for the last few years [7].

2.5 Activity and population near the depot

The activity closest to the oil depot is mostly light industry. The usual activity around a harbor is there, since Reykjavík harbor is in the surroundings. The industries found there are fish processing, net shops and maintenance to that kind of activity. Other activities found there are a few offices, grocery store and different kinds of shops. The activity there is mainly during the daytime and therefore that area is more vulnerable to a catastrophic event during the daytime.

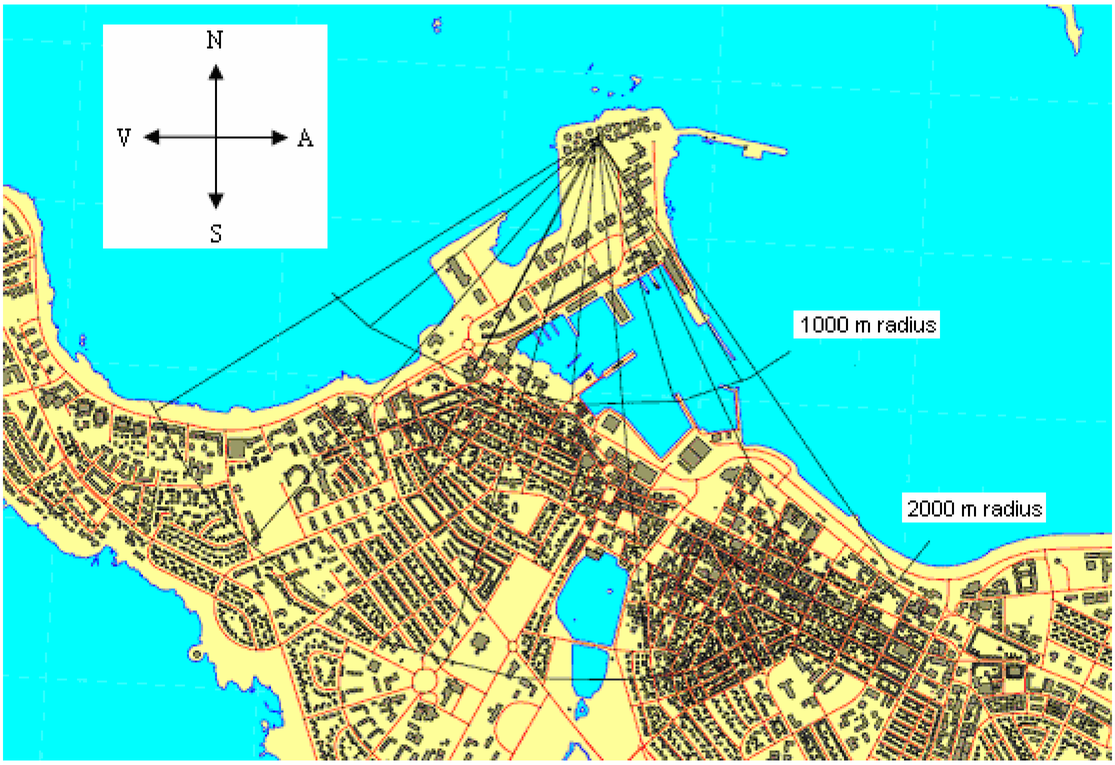


Figure 5. Distance from the peninsula to different populated sites in Reykjavík.

About 125.000 m^2 of industrial housing is found within a 1000 meter radius from the operation in Örfirisey. Estimation from the city of Reykjavík [8] states that one person is found for each 40 m^2 of area. This means that approximately 3.125 individuals are working there over the daytime. Within that radius 100 residential homes are located today and the city plans to build 500-700 more homes over the next few years. According to the Icelandic statistical bureau, 2,6 individuals live in each home. On the other hand this area in Reykjavík is not considered a family neighborhood and therefore two residents per home is more realistic, according to the city of Reykjavík. This will be used for estimation of the total number of individuals within each radius.

Radius	***Size of industry housing (m^2)***	***Working individuals***	***Number of residential homes***	***Residents***	***Total number of individuals***
1000 (m)	125.000	3.125	600	1.200	4.325
1500 (m)	400.000	10.000	2.100	4.200	14.200
2000 (m)	580.000	14.500	6.900	13.800	28.300

Table 6. Number of individuals, depending on the distance from the depot.

Residential homes start to condense considerably 900 meters from the depot and therefore the number of persons after that increase very rapidly. The number triples if the radius goes from 1000 to 1500 meters.

It should be mentioned that the distance in a direct line from the depot to the old town in Reykjavík is about 1400 meters.

Residential home areas are more vulnerable to hazards during the night time since it is more probable that people are found home during that time and might be sleeping.

2.6 Other preventive activities

Several different measures are taken to prevent a disastrous fire at Örfirisey. The most important measures are providing well trained and disciplined employees. Also, a foam system is made available for the operation and response plans with sufficient foam available.

When importing petroleum, safety regulation from the International Safety Guide for Oil Tankers and Terminals (ISGOTT) are followed. Those safety guides cover for example unloading the fuel from ships, among other things [3].

Hot work permit is needed when working with open fire, or devices that sparkle and might start fire within the area. This is based on a system that was created by Exxon Mobil in relation to hot work permits [3].

Systematic control of conditions and effectiveness of the devices used in the operation is an important factor in preventive activities. The same is done for all the buildings within the area. Daily inspection is carried out in an attempt to regulate leaks that might accumulate in the tank compartments and buildings checked. Besides this larger inspections are carried out on a weekly basis and a monthly basis. All pipes are pressure tested every five years according to Icelandic regulation no. 35/1994.

3 The risk analysis process

What is risk? This is a question many people have asked and there exist numerous different definitions of risk! According to Norme International [9] risk is the combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event. Then we must ask, what is hazard? Hazard has been defined as a source of potential harm or situation with a potential for harm.

The above definitions are not the only ones available and some say that risk can both have negative outcome like described here above or positive outcome like in the cases when stocks are bought. They can give the buyer value in form of money - positive results, or money can be lost and then the results are considered negative.

In this thesis the term risk will be considered a negative one, since it is assumed that the depot is on fire and values are lost for ODR and Shell as well. The society as a whole would probably also suffer certain loss because of the damages.

Risk analysis is the systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment [9].

In this chapter the methods and processes used in the thesis will be described, among a few concepts that need clarification before proceeding any further.

3.1 Method used for the analysis

A Quantitative Risk Analysis (QRA) method was chosen to estimate the risk from the oil depot in Örfirisey to its nearby surroundings and population. To be more precise a special QRA method will be used called CPQRA [10] or Chemical Process Quantitative Risk Analysis method. By using quantitative methods consequence is estimated by predicting the size, shape or orientation of the risk that could be created by release of hazardous material. The hazard can be toxic vapor clouds, fire or its radiation etc. By using frequency and probability calculations the risk can be quantified to a certain degree. This method is chosen because it is believed that it gives the most accurate results. It quantifies the problem and minimizes the uncertainties. It must be stated that the method has its uncertainties even though it aims at the modeling of stochastic uncertainties associated with occurrence and circumstances of major accident.

A quantitative risk analysis usually consists of at least four tasks [11] after defining the system; identification of the risk, calculation of frequencies and probabilities, calculation of consequence and evaluation of the risk. Figure 6 shows a schematic structure of the CPQRA model.

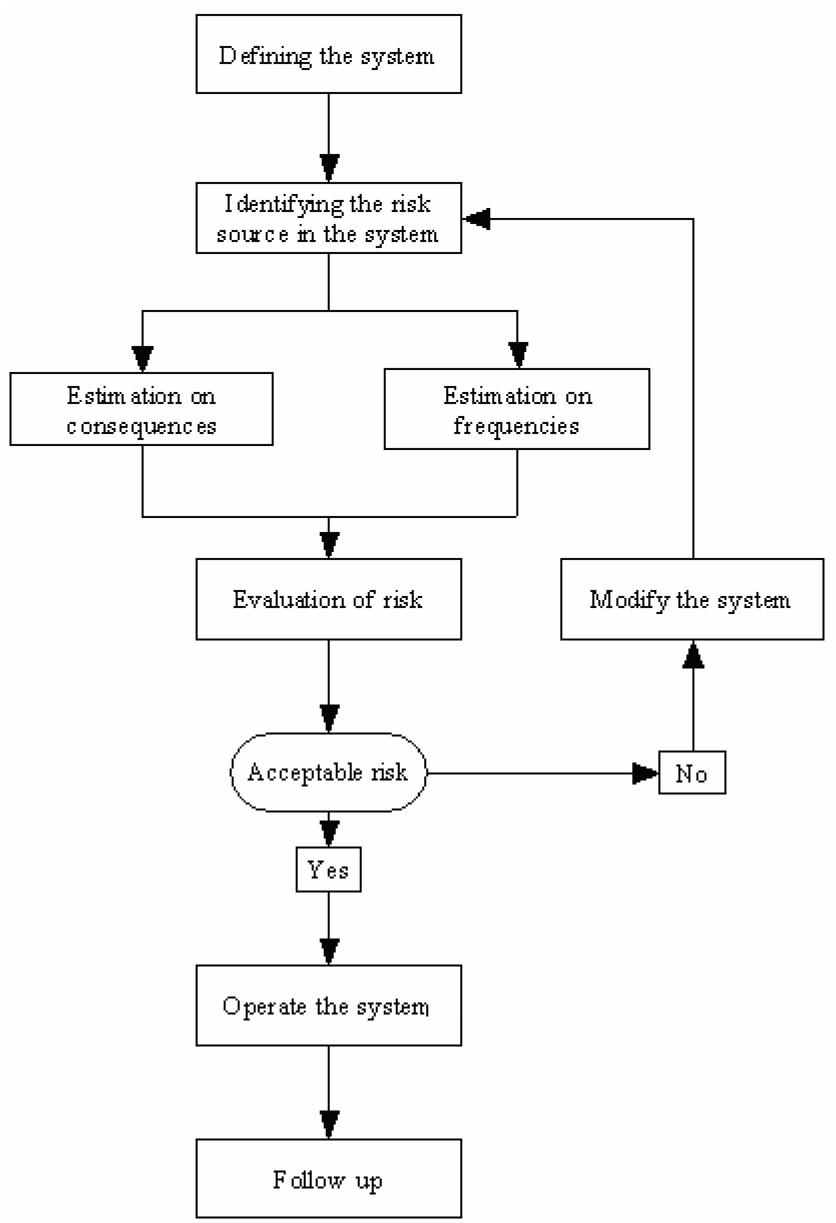


Figure 6. Structure of the CPQRA model.

3.2 Evaluation of the risk

Risk evaluation is the process in which judgments are made on the tolerability of the risk on the basis of risk analysis and taking into account factors that can be measured against some known criteria [9]. The tolerability criteria in this thesis are the criteria determined by the Icelandic Environmental Ministry for deaths related to avalanches in Iceland [12].

3.2.1 Tolerable risk

How many deaths can we accept in traffic every year or at sea? Most people probably say none. That answer is logical from an ethical point of view but impossible to implement in reality because of the cost involved. Some people say that lives can never be measured in economic terms and everything should be done to avoid death or injury. That is of course not logical either because of limited resources. Rune Elvik [13] wrote about the Swedish vision zero in relation to traffic safety. There he says that the amount of money spent on this program in an attempt to complete it would probably result in a negative total number of lives saved. Saving each life beyond certain number of individuals would be more and more expensive, and the money spent there would be better spent in other areas, that would instead be starved and by that causing a higher total number of deaths.

We can't save everyone at all times and therefore the term tolerable risk is something people are getting used to. We accept that people die in traffic accidents and in Iceland; we also accept that people die in avalanches. It is considered tolerable that the probability for each person to die, located on a known avalanche zone is $3{,}0*10^{-5}$ every year or about 1 person for every 33.000 individuals staying there each year [12]. That criterion will be used for the population in and around the depot. For comparison then it is assumed that 1 person for every 13.000 individuals dies in Icelandic traffic every year.

3.2.2 Risk perception

When speaking of tolerable risk the context risk perception can't be left out. According to the course in MTOR [14], perception is controlled partly by received information from the surroundings and partly from expectations. Prior knowledge is in this relation important since it makes the basis for the perception. Risk perception is how an individual interprets his/her senses of a certain risk. It must be clear that this event might not at all be dangerous or in any way negative for that individual, but he/she can possibly sense it that way. Risks that people consider "acceptable" are those that involve free-will, known risks for the individual, immediate, controllable, old ones that have been around for a long time and those that are natural. Most people prefer a risk that will kill a few people at a time and evenly distributed, rather than a risk that kills many people at once and is occurring seldom, even though the total number of deaths in the first one is often higher.

Before 1995, avalanches where not perceived as catastrophic events in Iceland, even though a few people died due to avalanches. That year two avalanches fell in small villages with the total fatality of 34 individuals. After that tragedy, avalanches were perceived as something much worse than statistical numbers gave reason to believe. The same year 24 persons died in traffic accidents, but that was just about the average number every year, so it was "accepted" in society.

The oil depot in Örfirisey is perceived by many people as something exceptionally dangerous. Nothing catastrophic has happened there over the years and other accidents in relation to the depot are well under average compared to other industries [7]. Why it is perceived that way is hard to say, but possibly because of the possibility of a catastrophic event, that is "if" something severe will happen there.

3.2.3 Individual risk

Individual risk is the risk experienced by a single individual in a given time period. It reflects the severity of the hazards and the time that the individual is in proximity to it. The number of people present does not significantly affect that concept.

Individual risk is defined formally [b] as the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards. It is usually taken to be the risk of death, and usually expressed as a risk per year.

Individual risks are often expressed as risk contours that show the geographical distribution of the risk. Those contours show expected frequency of a certain event capable of causing a specified level of harm at specified location, regardless of whether or not anyone is present at that location to suffer that harm.

Other ways are available to show and describe individual risk like maximum individual risk, average individual risk etc. Such methods will not be discussed any further in this thesis.

3.2.4 Societal risk

Societal risk is the risk experienced in a given time period by the whole group of persons exposed. It reflects the severity of the hazard and the number of people in proximity to it. It is usually taken to refer to the risk of death, and usually expressed as a risk per year.

Societal risk is defined [b] as the relationship between the frequency and the number of people suffering a given level of harm from the realization of specified hazards.

Societal risks are most often expressed in the form of so called FN curves, which show the relationship between cumulative frequency (F) and number (N) of fatalities or number of affected persons.

3.3 Uncertainty

Uncertainty is a term used in a number of fields including risk management. The uncertainty of some event happening can be great and the uncertainty does certainly affect the outcome of the decision making. When statistical data are rare or not available the uncertainty becomes greater for the user to come up with a solution that is reliable. A given fictitious value is estimated to range from 10 to 1000 where all numbers in between is possible. That gives the user great uncertainty if he is supposed to assume the most likely value there between because of the large value range. The user could use the worst case scenario which would lead to very conservative results. That would not give the most probable result for certain incident or event to happen since the actual value would more likely lie on a certain interval.

To avoid making those conservative decisions the previous values are given certain density or probability distribution to represents all their possible values and their likelihood. Widely used distributions include the normal distribution, uniform distribution and the triangular distribution etc. The distributions used in this thesis are:

- Normal distribution, with the median a and the standard deviation b.
- Uniform distribution, where all values between a and b are equally probable.
- Triangular distribution, where one is the smallest possible value, second is the most probable value and the third is largest possible value.

One of the most frequently used methods for handling uncertainty is Monte Carlo simulation or analysis. The program @RISK was used in this thesis and it uses Monte Carlo simulation to show the user many possible outcomes for a certain incident or an event. Many different variables can be used at a time, where the program calculates them according to their given distribution. Those numbers are calculated randomly for each variable according to their distributions. Because of that the number of iterations or how many times the program simulates the problem, is often set to 1000 or more iterations. The number iterations used in this thesis are 10.000. More iterations does decrease the uncertainty of decision making since the results are more probable than if only one simulation would have been done.

Of course, unless the distributions assigned to individual parameters capture their actual values, increasing the number of iterations will not improve performance.

4 Risk scenarios

A number of risk scenarios are possible in the depot. Many can be foreseen but not all will be accounted for. Only three actual fire scenarios will be considered in this thesis but with different possible approaches for ignition. Risks in transporting the fuel from the depot to different locations around the south-west corner of Iceland will be estimated as well in this chapter.

The main goal of this chapter is to find out how much energy will be released when fire occurs in different circumstances and to estimate the development of the fire, i.e. try and anticipate what will happen if fire does occur.

The scenarios are;

- fire starts at the gasoline loading rack
- fire starts at the fuel tank area it's self
- the whole depot is on fire

The fourth scenario considered is risks involved in transportation of the fuel.

4.1 *Possible causes for fire in Örfirisey*

A few potential causes for fires in the depot are possible but some are more probable than others, as is to be expected. It is considered that for the fuel to ignite, it first has to be exposed to oxygen and also to some kind of energy source for ignition to take place. Those possible causes that will be accounted for are:

- Leakage when loading the fuel truck
- Leakage from the storage tanks or pipelines attached
- Traffic accident within the perimeter of the depot
- Traffic accidents outside the operation (see chapter 4.5)
- Impacts from air traffic
- Vandalism or terrorism

This list could be made longer and as can be seen lightings have been left out, even though they are considered a major cause of many oil depot fires around the world. That is because that kind of phenomenon is seldom seen in Iceland and is therefore not considered a major threat.

As mentioned earlier, the goal is to find out how much the energy release is in case of fire and also to see how probable the specified scenarios are.

4.1.1 Leakage when loading the fuel truck

One possible cause for a fire could be a leakage when loading the fuel truck which is caused by a leaky connection between the fuel hose and the truck. Static electricity could ignite the gasoline fumes because the driver forgot the obligatory [6] ground connection or the connection failed. A minor spark could also ignite the fumes, possibly created by some panic reaction by the employee because of the leakage. The employee could drop a wrench or other tool found near by causing the spark.

Overfill of the truck could also cause fire similar to the one described here but with much more energy release, because of a larger spill.

4.1.2 Leakage from the storage tanks or the pipelines

There are totally 32 storage tanks of different sizes found in the operational area. Pipelines are found to the tanks, from them and also between them. Those pipes are used to transport the fuel from the vessel to the tanks for storage and from the tanks to the transportation trucks via the loading racks. As can be expected hundreds or thousands of connections are found between pipes and also connections between pipes and tanks that come with this kind of construction. Those connections have to be tight to avoid leakages but that is not the case all the time. Corrosion is a problem that has to be brought up since those tanks and pipelines are made of steel.

A possible cause in this relation is a scenario where fuel is leaking out due to corrosion, without being noticed. This leak is near some of the 32 tanks and contractors are fixing some of the pipelines in the area. Because of their work they need to weld some pipes together and a spark from the welding could easily set the fuel on fire.

4.1.3 Traffic accidents within the operation area

Heavy traffic is not found within the operation area since it is a restricted area. Employees do not have permission to drive their own vehicles inside the area. Only vehicles with certain known purpose are permitted to be driven there and only by employees with a valid access card. Primarily, these vehicles are fuel transportation trucks as well as a few other smaller vehicles needed for different kinds of work.

Vehicles can cause severe damage on the tanks or the pipes if a crash occurs. Since traffic is low and strict traffic rules apply within the area, the possibility of traffic accident because of speeding is ruled out. A more probable cause would be a sick driver that would faint because of some illness, like heart attack or stroke. If that would happen the vehicle could crash into anything at all and if it would be a fuel storage tank, the fuel could start leaking heavily, causing fire hazard.

The boundaries (chapter 2.3.3) around the tanks would probably stop the vehicle if it would hit them and by that diminishing the possibility of crashing directly into the tanks themselves. On the other hand if the speed would be more than permitted the vehicle could go over the boundaries and do more harm.

Another possibility is a collision between a gasoline truck and some other vehicle, perhaps another fuel truck. That could cause an eruption of the tank and by that possibly causing a huge immediate release of fuel, since a hole of unknown size would be on the tank. Ignition would also be possible in this situation since the impact its self could be enough to cause sparks to set the fuel on fire.

4.1.4 Impacts from air traffic

An impact from air traffic is a possibility worth looking at since the Reykjavík domestic airport is located not far from the center of Reykjavík. The airport is situated directly south of the operation, about 2,5 km away.

Flight traffic is slightly increasing again after taking a dive over the last years. One runway is located in a direct line with Örfirisey, or the north-south runway. This runway is also called BR01 and BR19, referring to the take off and the landing approach direction of the planes. If the wind is blowing from the south, runway BR01 is used and by that the approach is over the depot where the plane is heading directly into the wind. On the other hand if the wind is from north, runway BR19 is used for landing approach. This runway is even used when the wind direction is from east or west in cases where the visibility is bad and instrument meteorological conditions flight is needed (IMC-flight), because of good technical devices for that kind of situations [15].

Only 6% of all accidents [c] in the flight phase happen during the flight cruise. The other 94% happen during takeoff and in the landing phase. A pilot error is causing more than half of all accidents world wide.

A problem when taking the plane off or in the landing phase could cause a plane to crash into one of the tanks in the island, which would most likely cause fire. The tanks could easily erupt by such an impact and by that very much fuel would flow over a large area in a short time and the plane it self would probably be on fire, which would ignite the fuel.

Figure 7. Picture of Reykjavík international airport and Örfirisey in the north.

4.1.5 Vandalism or terrorism

Vandalism or terrorism is a factor that must be accounted for, even in Iceland. The world has become more aware of this threat over the past years or since the attack on the twin towers in New York in 2001. Oil depots are popular targets in “the art of war” because of their importance in fuel storage. Fortunately, Iceland has not been known for many wars nor terrorist attacks in the past and hopefully that will not change in near future.

Everyone entering the operation area at Örfirisey has to have a certain access card or sign in as a guest. All employees in the depot have those cards. High fences are all around the operation prohibiting unauthorized persons to enter. There are two entrances on land guarded by cameras and a security guard. The operation area is divided into four security camera sections depending on the resolution quality. Those sections are:

- Section 1 : The ability to see faces on people and car plates in that area.
- Section 2 : The ability to see what is being done in that area.
- Section 3 : The ability to see if there is any movement in that area.
- Section 4 : No special security alert.

Even though the operation is mostly during the daytime, some employees work on divided shifts. The security guards are always present at the depot with their routine checks.

A possible way for vandalism or terrorism to occur at the operation would be to get an individual hired by ODR, Shell or the security company and then that person would be able to go freely around the island. That individual could do practically anything he/she wanted to do to cause damages, since he could maneuver around the area freely. Explosion, leakage or fire is something that is not hard to implement if intended.

People’s bad intentions are often hard to avoid. Increased security can reduce that kind of threat but unfortunately it is always possible circumvent security measures.

4.2 Fire at the gasoline loading rack – scenario 1

There are two loading racks in the area. One is the gasoline loading rack and the other is for all the other petroleum products. Calculation for the gasoline loading rack will be done since gasoline is much easier to be set on fire than the other products found at the operation. The flashpoint for gasoline [d] is -40°C which is much lower than for the other products. White spirit has the same flashpoint but it is found there in much less volume so it will be ignored in this scenario.

The loading rack can be divided into two smaller areas of 82 m^2 and the probability of fire would be greatest there according to ODR [3]. The loading rack is protected with a foam system that has to be activated manually. The foam is ejected by the system both from above the truck and also below it, by that increasing the possibility to extinguish the fire.

In this scenario a leakage or overfill occurs creating a pool of 400 L of gasoline on the concrete floor underneath the truck. The pool is estimated to spread over an area of 50-150 m^2 right beneath the gasoline tanker. Since overfill is one of the options the tank is also assumed to be full of fuel. The outside temperature is 7°C which is realistic for Icelandic climate.

4.2.1 Frequency for fire at the loading rack

Leakages at loading racks are rare but do happen. According to OK-Q8 AB [16] leakages because of overfill happened about three times per year at their organization which leads to the probability of $4,6 * 10^{-5}$ for each loaded truck. This does not mean that fire breaks out on all occasions a leakage occurs.

Leakages at ODR each year are 15 where 10 are due to overfilling of the tanks and 5 because of other leakages at the loading racks [7]. One fourth of the fuel that is transported to the depot is loaded on trucks through the gasoline rack. Therefore is it estimated that 3,75 of those incidents happen on the gasoline loading rack and the rest on the other one for all the other petroleum products. The total volume of gasoline going through the depot every year is about 111.000 tons. That gives us between 2.786 to 4.644 trips of gasoline trucks each year, depending on their size. The most probable value for a leakage to happen is $1,08*10^{-3}$ for each loading at the rack over one year, according to @RISK and that is also the mean value as can be seen in Figure 8. Number of iterations are 10.000 and that will be the case whenever the program is run. Further details about the program @RISK and its distribution function, can be seen in Section 3.3, "Uncertainty".

Description	Distribution	Value
Size of the tank	RiskTriang(min;most likely;max)	24;32,5;40
Number of leakages per year	RiskNormal(median, std.deviation)	3,75;1
Total volume of gasoline	-	111.453

Table 7. Indata for @RISK.

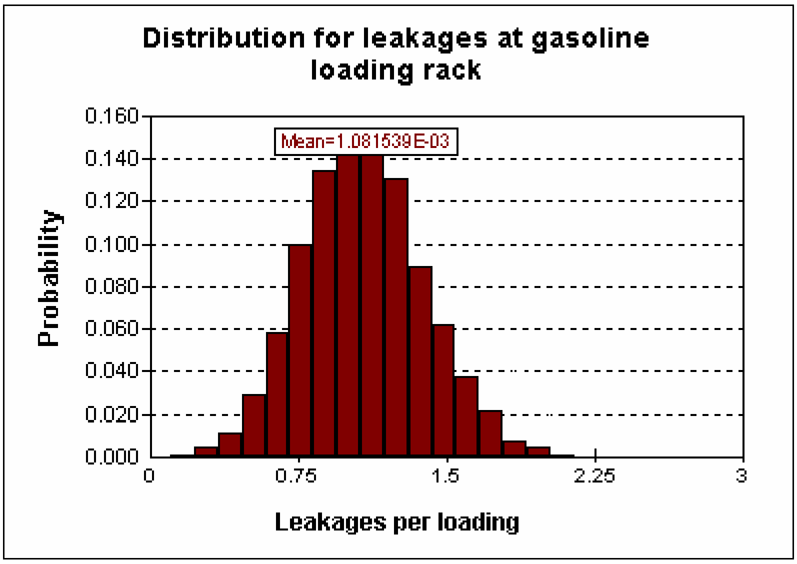


Figure 8. Leakages at the gasoline loading rack.

An event tree for the leakages was then constructed from all known information. The probability for ignition is hard to estimate but in the climate found in Iceland, this author has assumed that 2,5% is reasonable estimate. The foam system at the depot should be turned on in almost every case a fire occurs [3]. The value of 15% for the system not to extinguish the fire or for the system not to be activated manually is assumed by the author to make the outcome more conservative.

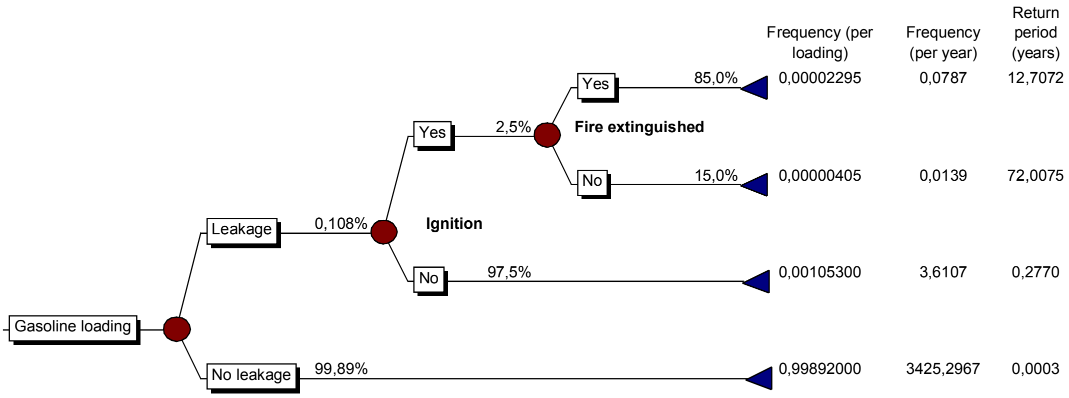


Figure 9. Event tree for leakage at the gasoline loading place.

The outcome of a fire because of leakage that would not be extinguished is estimated to have the return period of about seventy years if the probability for original leakage is $1,08*10^{-3}$ (0,108%) for each loading as the simulations run in @RISK suggest.

4.2.2 Heat release rate of fire at the loading rack

The heat release rate (HRR) is very dependent on the area that the fuel is estimated to spread over and of course the fuel type. The total area is assumed to be from 50 to 150 square meters. To account for uncertainty a uniform density distribution was used for the area since all the values between 50 and 150 are considered to have the same probability. The combustion efficiency has the normal distribution with the mean value of 0,7 and standard deviation of 0,1. Combustion efficiency for alcohols is close to unity but fuels like gasoline that produce sooty flames have a significantly lower one, typically around 60-70% [17] and therefore this distribution was chosen for this scenario. Mass burn rate and heat of combustion are constants in equation C-1 found in Appendix C, but that equation is used to calculate the heat release rate (HRR).

The mean value for the HRR is about 167 MW for this fire while the most probable one is somewhere around 130 MW as can be seen in Figure 10. That value will be used for this scenario even though most of the HRR values lie above that in the figure. It must be considered that the smallest area chosen was 50 m^2, and because of that the fire could spread over smaller area than that. That would make the HRR much less because it is very dependent on the area. Therefore is the chosen value considered a reasonable estimate!

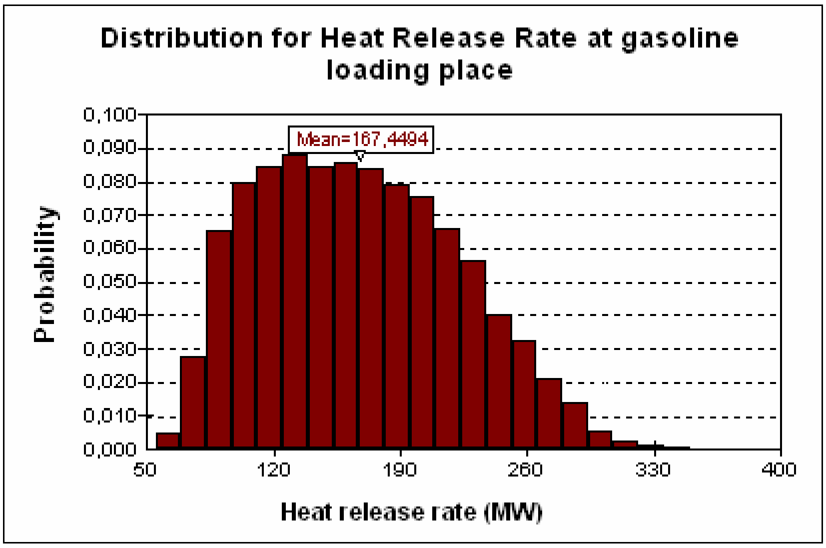


Figure 10. HRR at the gasoline loading place.

4.2.3 Possible consequences of the fire

In the beginning a pool fire would be the most likely result if the fumes from the fuel on the ground would ignite. The energy release is estimated to be around 130 MW, depending mostly on the fuel area.

Certain flame heights would be reached and possibly the fire would set the whole truck on fire, with the remaining gasoline. The aluminum starts melting when it reaches the temperature of 640°C and once that occurs, more fuel would flow from the tank. That would create further danger for nearby storage tanks and possibly set them on fire, which would be the worst case scenario for this particular incident.

If the flames from the fire could warm up the gasoline fumes within the tank to the critical auto ignition temperature of 420°C [18], the fumes within the tank could start burning or expanding so severely that the tank could explode. Explosions are considered further in Chapter 4.5, “Risks in transportation”.

Duration of the fire depends on the amount of gasoline leaking from the truck. If the leakage can not be stopped the fire will last for some time if not extinguished in its early stages. Actual consequences of the fire depend on this duration time; the calculations are given in Appendix C.

4.2.4 Results

The frequency for a leakage/overfill at the gasoline rack is extremely high compared to the overfill value at OK-Q8, or $1,08*10^{-3}$ to $4,6*10^{-5}$ respectively. The difference can partly be explained by the way the trucks are designed in Iceland. In Europe, the common way of loading a truck is that every compartment of the truck is loaded individually; hence the loading system of the terminal can control the amount that is loaded into every compartment accordingly and avoid overfilling. In the Icelandic system all compartments are loaded at once, hence the filling of the individual compartments of the truck is not as controlled as in Europe. The overfill protection systems of the trucks are therefore used to close the compartments as they are full until the whole truck is full. The overfill system in use is sensitive and fail once in a while, and hence this increased frequency [7]. That is something ODR should investigate further to minimize those leakages in near future.

Duration of a fire releasing 130 MW of energy with an area of about 77 m^2 (area needed for this HRR) is estimated to be around 70 seconds if the volume is exactly 400 L. That means that the mass burn rate in this fire is 4,25 kg/s.

To calculate if that pool fire could set the gasoline tanker it self on fire, the method of “lumped heat capacity” was used. The method assumes the total mass of the tank consists only of aluminum. The temperature used as the critical point was the auto ignition temperature for gasoline which is 420°C. The time needed to warm the aluminum to 420°C was 89,2 seconds assuming the flame temperature was 800°C. The fire would have to last at least 19 seconds longer to be able to warm the tank enough to set it on fire. Therefore this volume of fuel is <u>not sufficient</u> to cause any more damage than has occurred already.

According to this chapter and the calculations in Appendix C it must be considered unlikely that a fire at the loading place could cause fire at nearby storage tanks. If the volume of the leakage is about 400 L, then the fuel is fully burned up after about 70 seconds which is not even enough to warm up the tank on the petroleum tanker it self to a critical level. As has been stated, the cooling of the tank from the fuel inside or because of the wind has not been taken under consideration in those calculations. That was not necessary since the fire lasted for so short period of time.

If the leakage from the tank is continuous then the fire would exist for some time longer, i.e. for as long as the fuel is available or the fire would be extinguished by someone or something. If this was the case the fire would probably warm up the gasoline tanker sufficiently to set it on fire. The heat release from that kind of scenario has been estimated to be as much as 300 MW [19], but can vary. As was demonstrated in Table 20 in Appendix C, a larger fire would cause more heat flux to nearby tanks, by that causing more heat at the fire side of the storage tank. This energy on the other hand is not sufficient to warm up the fuel inside the tanks to reach the auto ignition temperature of 420°C.

By using the lumped heat capacity method in those calculations the worst case scenario has been established. The method only accounts for the shell of the tank which is made of aluminium. It does not take into consideration the fact that the tank is filled with fuel, which cools it from the inside. If the calculated energy from the fire is not enough to warm up 5 mm thick aluminium tank to a certain degree of temperature at a certain time, then it can certainly not warm the same tank up to the same degree if it is filled with liquid, unless the liquid or the fuel is streaming out continuously. By that the leakage could withstand the fire for some time and the warming of the tank would last longer

If a fire is loose at the gasoline loading rack it will only damage to gasoline tanker and the loading place itself. It is unable to spread to nearby tanks and thus a disaster is most likely avoided.

4.3 Fire in fuel storage tanks – scenario 2

The storage tank area is divided into five boundaries or compartments which are supposed to prevent a possible leakage from spreading from one compartment to the next. Fuel type is the main factor in determining what is found in each compartment. For example one compartment is named the gasoline compartment and as expected the fuel stored there is gasoline. Those compartments vary from 2.180 m^2 to 11.607 m^2, where the east one is the smallest and the gasoline area the largest. Total amount of fuel at the depot when it is at its maximum is about 143.000 m^3.

Because of the reasons described in scenario 1, the tanks storing gasoline will be used for scenario 2. Calculations will be carried out to see if a fire in one tank can set an adjacent tank on fire.

A major leakage is assumed to occur at tank Shell 12 (Figure 3). It is assumed that a contractor doing hot work nearby does not respect ODR safety precautions for a work like that resulting in the ignition. The leak is continuous and is at a low point on the tank, providing enough fuel for the fire to last for a long time. The outside temperature is assumed to be 7°C.

4.3.1 Frequency of fires in storage tanks

It is difficult to find frequencies for fires in storage tanks in the literature and therefore the estimation will be made based on a number of known leakages at the depot.

According to ODR [7], 10 leakages occur every year on several locations and that gives us the probability of 31,5% for each tank or adjacent piping to leak over the year. That means that a leakage is found in almost one third of the tanks or in pipes somewhere near them. They occur both when fuel is being pumped to shore from the vessels and also from hoses or junctions which are found all over the tank or boundary area. Those leaks range all from a small one to a large one like overfill of the storage tanks and then a large volume of fuel is out. It is estimated by ODR that only 1% of the leakage incidents are of any concern and 90% of them are not of any matter because of low volume. The last 9% are considered a medium leakage.

The probability for ignition is assumed to be related to nature of the leakage and diminishes as the volume of the leakage gets smaller. Whether the fire is extinguished or not is also assumed to be related to the amount of leakage since it is much harder to handle a larger pool fire than a fire in smaller pool. Therefore is it assumed by author that if there is a major leakage and it is ignited, the probability for this fire to be extinguished is only 10% etc.

The calculated frequency shown in Figure 11 will be used for the gasoline compartment, even though the frequency is valid for all the tanks in the depot.

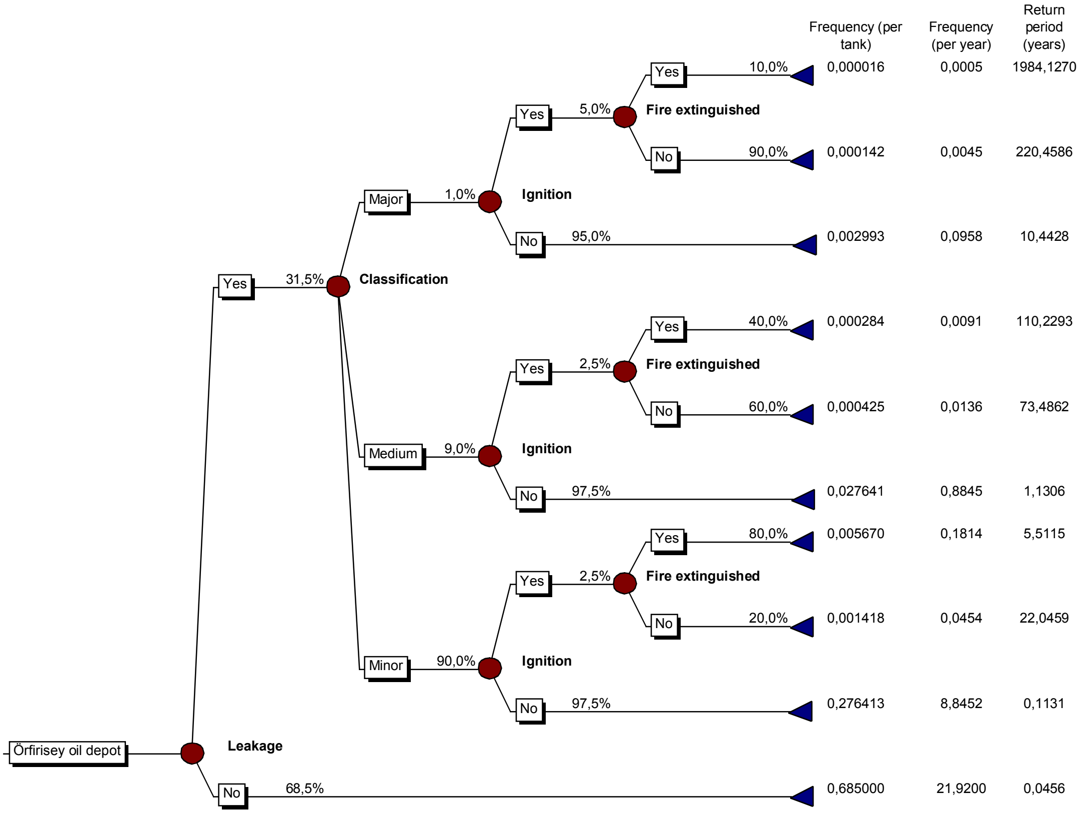


Figure 11. Event tree for leakage at the gasoline compartment.

4.3.2 HRR of fire at the gasoline compartment

The heat release is always dependent on the area of the pool. As is to be expected for a fire like this, it can be extremely large since much fuel is available. To estimate the most probable value for the HRR a Monte Carlo simulation was run for this scenario. To account for the uncertainty a triangular distribution density was used for the area where the minimum value was 100 m^2, most probable one 1.000 m^2 and the maximum value was 2.000m^2 since a rough estimate indicates that a leakage from Shell 12 alone could not spread over a larger area. The burning rate would be 110 kg/s if the area is at its maximum size. A normal distribution was used for the combustion efficiency with the mean value of 0,7 and standard deviation of 0,1 since this is a sooty burn.

These considerations resulted in a mean value for the heat release rate of 1,73 GW, but the most probable HRR is about 1,68 GW with an area of about 1000 m^2. That value is used as a benchmark to see if any further danger is to be considered for the surrounding tanks. Further details regarding these calculations can be found in Appendix D.

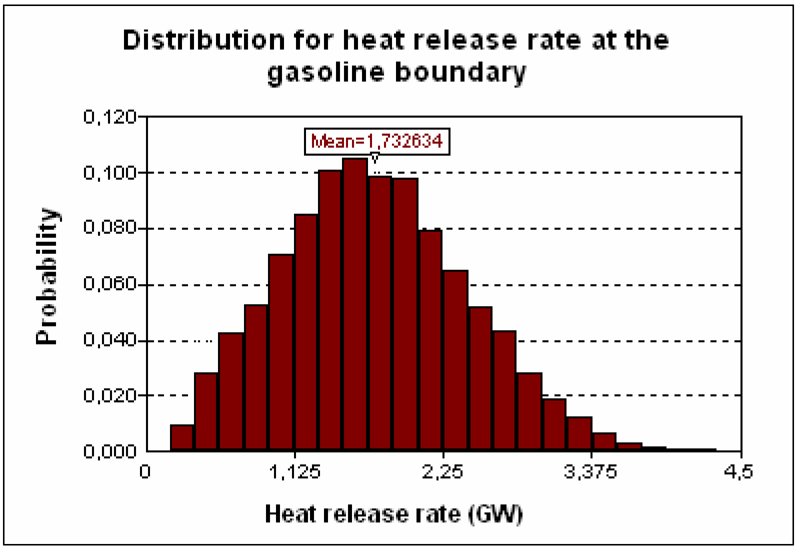


Figure 12. HRR at the gasoline boundary.

4.3.3 Possible consequences of the fire

Consequences of such a fire scenario can vary, from small fire to extremely large fire with the possibility of explosions. If the fuel is leaking continuously from the tank the fire is well fed and can last for a long time. In such cases a continuous radiation from the fire can cause the surroundings, in this case the nearby tanks, to warm up to a dangerous temperature, causing them to ignite as well. If that happens, the energy from the fire will be so great that it will be very hard to control. That kind of fire will most likely threaten its surroundings by possibly igniting other tanks.

If on the other hand the foam system does function as it should, the fire would probably be extinguished in its early stages. However if the leak is continuous the fire could grow too fast in its early stages, by that outranging the foam systems capability to extinguish it.

The frequency assumed in Chapter 4.3.1 for fires at the depot that could not be extinguished by the system, had the return period of 22-220 years. That frequency is rather high and is a result of far too common leakages in the depot compared to the number of tanks. As was mentioned earlier, 10 leaking incidents are assumed every year according to ODR. That high frequency strengthens the probability of an unwanted event, like fire that can’t be extinguished. The return period of 22 years is however for a minor fire to occur. That kind of fire should be easily controlled and extinguished by CDFRS or even by ODR employees.

4.3.4 Results

It can be seen in Table 24, Appendix D that all pool fires larger than 200 m^2 or with heat release rate of more than 0,34 GW are capable of igniting gasoline tanks within 20 meters from the fire if no cooling will occur. If one tank is burning or a fuel pool is on fire and it sets another tank on fire, more energy is available and the probability escalates for the third tank to ignite also. Soon the whole area could be on fire if insufficient action is taken to prevent it. As has been stated before, factors regarding the cooling of the flames and/or the heat have not been taken under consideration. What has been done should on the other hand give certain information about the minimum time or the worst case scenario for ignition of nearby tanks.

When heat release rate from the pool fire was investigated regarding the specific heat for the gasoline in tank ODR 12 (Appendix D.2), the outcome was that it could withstand the heat for at least 14,55 minutes if the tank was full. It must be stressed that this tank was assumed to be totally submerged in the flames and no gasoline fumes igniting inside the tank. The method used in Appendix D estimates the time needed to warm the gasoline to the critical temperature of 420°C and assumes that the tank has no outer shell. The only material properties considered where those of gasoline.

The most probable size for the fire was 1000 m^2 and that kind of pool fire is very well capable of igniting nearby tanks according to the calculations. If Shell 12 is on fire and it sets ODR 12 also on fire after a few minutes, the energy release increases substantially. Different sized pool fires and some of their properties can be found in Table 21 in Appendix D.

When the lumped heat capacity method was used for Shell 10, ODR 13 and 14 since the fire would probably reach them, the time to ignition was estimated to be 7,63 minutes. That is the time it takes for the steel in the tank it self to warm up to the critical temperature of 420°C. It does not take into consideration the fact that the tank is filled with fuel, which cools it from the inside. Also it does not take into consideration the fact that Shell 10 and ODR 14 do not contain the same volume of gasoline, which does matter when a liquid is warmed up. This method on the other hand shows that it is possible for the fire to warm the tank up to this degree and after a certain period of time, the fuel will ignite if nothing is done to prevent it. The lumped heat capacity method would give ODR 12 which is estimated to be surrounded by flames (800°C), about 4,4 minutes extra lifetime to the previous time of 14,55 minutes. First the fire has to warm up the steel shell of the tank by conduction to be able to start warming up the fuel mass inside it.

The exact size of the leakage is hard to estimate but an estimation of 55 kg/s can be made since that is the minimum amount of fuel needed to maintain a 1000 m^2 pool fire. However if a leakage occurs, it is quite possible that it spreads over at least 200 m^2 since there is extremely much fuel available at the depot. A leakage by it self is not enough to cause a major crisis, an ignition has to occur also. That lowers the frequency for this scenario.

The average pool of 1000 m^2 can start a chain reaction in the depot that will be hard or almost impossible to handle if it is ignited. The minimum time for the nearest tank to the one burning, to ignite is about 19 minutes. That tank is ODR 12 and that time gives CDFRS time to get there and start the cooling process or for ODR employees to start similar work. Because of that it must be considered unlikely that this fire would spread any further. It would probably be confined to Shell 12 for as long as there would be fuel or the fire would be extinguished by some means.

4.4 Fire in the whole depot – scenario 3

A fire in the whole depot is certainly a scenario no one wants to see, at least not the ones who have to deal with it. In this fire all fuel types are burning and in all boundaries. The maximum volume of fuel found at the depot each time is about 143.000 m^3 but it can be estimated to be little under that since constant distribution of the fuel is ongoing at all times.

4.4.1 Frequency for a fire in the whole depot

It is hard to estimate a frequency for such a scenario because of limited data. Nevertheless, such fires have occurred, in spite of considerable prevention efforts, and the latest example is the fire in Buncefield U.K. [20]. The frequency for this scenario will be based on the frequency for a fire at the gasoline boundary, see Figure 11. There it was stated that for a fire where a major leakage occurred, the gasoline was ignited and the fire was not extinguished by the fire protection system, the yearly frequency was 0,004536 which is equivalent to one such fire occurring every 220 years. It is assumed that the whole depot will not burn if the leakage is not a major one. The probability for that kind of fire to spread out and set the whole depot on fire will be assumed to be 20% by author and therefore the frequency for that kind of scenario will be 0,004536 x 0,2 = 0,0009072. That is equivalent to one large scale fire in the depot every 1100 years.

The main goal of this section is to estimate the energy release from such a fire scenario and its effect on the nearby population. The frequency of such fire is only approximated in order to give the reader an idea of the return period but as has been said, the statistical information on the frequency of such fires regarding this scenario are very limited.

4.4.2 Heat release rate of a fire in the whole depot

The goal of this section is to estimate the possible heat release rate if the whole depot is burning. The frequency calculated in section 4.3.1 for a major leakage will be used for this scenario as well, since statistical information are lacking.

To estimate the total heat release rate from the depot it must be taken into consideration that there are different types of fuel found at the depot. To account for uncertainty a uniform distribution was used for the mass burn rate where it was from 0,039 to 0,055 kg/m^2s, see Appendix E Table 24. The area was the total area of the boundaries or 31.829 m^2. The heat of combustion was also assumed to be uniformly distributed with the value of 43,7 to 44,4 MJ/kg. Combustion efficiency was taken to have a normal distribution of 0,7 and a standard deviation of 0,1. Using these values gave a mean value of 46,1 GW and that value is the most probable one as can be seen in Figure 13.

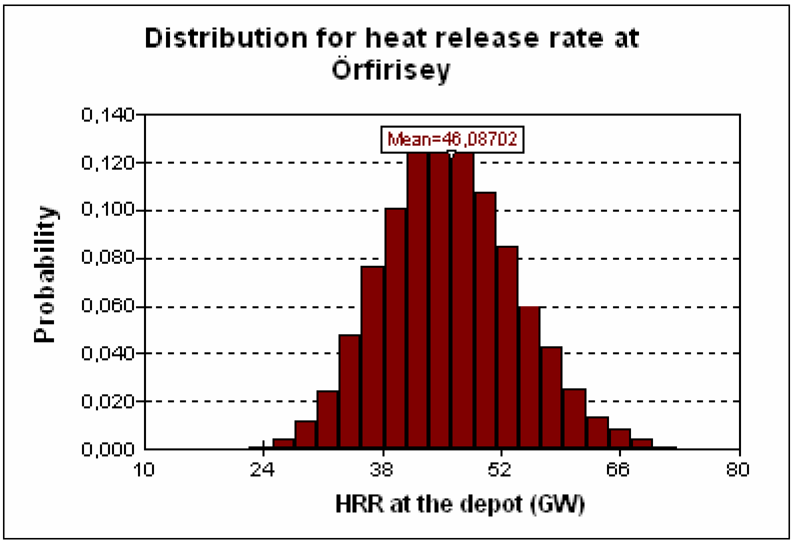


Figure 13. HRR if the whole depot is on fire.

The minimum value calculated with @RISK was 19,7 GW and the maximum one about 73 GW.

4.4.3 Possible consequences of the fire

Consequences of such fire would be very severe. First of all the people within the depot would be in great danger because of both direct flames and radiation from the flames. Explosions would be possible which would make it hard for the people within the perimeter to get away in time. Nearby buildings would be in danger because of radiation, smoke and possibly a pressure wave created by an explosion, which can damage buildings severely.

Secondly the burning fuel would create a large smoke cloud that would probably spread over Reykjavík, depending on the wind direction, the most probable wind direction being from south, east or anything there between. Fortunately that is exactly the direction that would take the concentrated smoke away from the city. This smoke cloud would have a high concentration of toxic chemical substances that could harm living creatures and the environment, as well as property in the form of buildings and their content.

The environment would suffer from such scenario since it would be very likely for this volume of fuel to escape the fuel compartments, through holes on the boundary walls or because of explosions or if the fuel starts to boil over the boundary walls. A great amount of contaminated water would flow in the area when the fire department would start cooling the tanks or trying to extinguish the fires. The major incident at the Buncefield oil depot demanded 600.000 liters of foam and 40 million liters of water [20]. At that fire it was decided to use high-volume pumps to move water runoff around the site to minimize infiltration of contaminated water getting into the chalk substrata, which acted as a water collecting area for London drinking water supplies.

Fire in the whole depot would also create a great disturbance in fuel transportation and might inflate the fuel price. In this way the fire could affect the entire Icelandic nation in one way or another.

4.4.4 Results

It is clear that a major crisis has occurred if the whole depot is on fire. The heat release rate of almost 46 GW is an enormous energy release rate and by comparison, the new hydro-electric power station at Kárahnjúkar in Iceland is designed to produce roughly 0,75 GW [e].

Whether the people located near the depot are in direct danger or not is a different story. According to Table 28 in Appendix E the heat flux has very little effect if the distance is further away than 700 meters from the depot. The calculations show that it is theoretically not safe to be within 500 meter from the fire. The highest radiation that a person can endure for a long time without feeling pain is 1 kW/m^2. If the radiation is 2 kW/m^2 then the skin can't withstand it more than a minute [21]. Those values are for naked skin and for humans wearing clothes, the time would be longer. A fire fighter in full protective clothing would tolerate the radiation for a much longer time.

It can be assumed from the calculations in Appendix E that radiation on the population about 900 meters away from the depot is not of any concern. As before no account has been taken of the possible cooling factors which give reason to believe that the actual values would be much lower. Therefore danger due to radiation for the population living outside 900 meters from the depot is not considered to be of any concern.

Other factors regarding this scenario are more interesting, like the smoke distribution and its concentration. Further analysis regarding that will be presented in Chapter 5 in this report.

It is clear from the fire in Buncefield [20] that much water will be needed to suppress this fire and extinguish it. The fire fighting plan there required 32.000 litres of water per minute. The capacity in Örfirisey is currently 23.000 l/min. The water supply in a scenario like this has to be ensured before something happens and also how to handle contaminated water streaming from the depot.

4.5 Risks in transportation

As was previously mentioned the Örfirisey depot does not solely service the capital area, but also large parts of western and southern Iceland, as well as the international airport in Keflavik. This fuel is stored in the depot and transported by trucks to the final destinations. Due to the location of the depot all this fuel has to be transported on the roads of Reykjavik for several kilometers, through the city center and its urban areas. This issue has been a focus of local debate for some years, but to fully analyze the risks involved the alternative must also be analyzed, i.e. the risks involved in utilizing one or more smaller depots at other locations on western and/or southern Iceland, as well as in the vicinity of Keflavik. A detailed study of that type falls outside the scope of this study, as well as all economical aspects.

The road transports are nevertheless an integral component of the depot's activities and must be addressed here. Traffic accidents are relatively common in Iceland, as it is a scarcely populated country with relatively long distances between towns, no railroad system and a high ratio of car ownership per capita. Lately the heavy transports on the road system have intensified distinctly as the traditional transports along the shores by ships have ceased. Therefore an attempt is made in this chapter to estimate roughly the risks involved in said road transports of fuel.

The available data is scarce though, ODR has been operating for merely ten years and a lot has changed even during that time, both with regard to the internal transport strategies of ODR as well as on a national level, as stated above.

The risk estimation performed in this chapter is not specific for the roads of Reykjavik, that would be to narrow an approach for the purpose of this thesis. That would be a worthy field though for further studies, as an important contribution to the debate mentioned above.

Another delimitation here is that focus will be on ignition following an accident. Leakage and consequences following such an event are not addressed. Actually consequences of a fire are merely addressed in a general fashion, as they would be very site-specific. Therefore the focus below is on frequency.

4.5.1 Traffic accidents in Iceland

Traffic accidents leading to death have been calculated to be 22,76 [22] every year with the standard deviation of 6,18. Those calculations where done for all known traffic accidents from 1987 to 2003.

The total number of registered vehicles in Iceland 2004 was 200.224 and that number contains all passenger vehicles, trucks, transportation vehicles, busses and motorcycles. All trucks are 8.596, where 4.533 of them are trucks above 5 tons. Fifty of those trucks above 5 tons are in the property of Olíudreifing ehf. (ODR).

Those vehicles on Icelandic roads or their drivers cause on average 8.070 accidents each year that can be divided into three categories:

- Category 1: Major accidents where people are killed and/or seriously injured.
- Category 2: Minor accidents where people have minor injuries.
- Category 3: Only property damage and no people injured.

Accidents in category one and two are of special interest since those are the ones that could create enough impact to open the fuel tank and a fire scenario could be possible. The third category is not assumed to be of any real danger, but the tank could still tear apart in an accident and is therefore accounted for as well.

4.5.2 Frequency of collision

Trucks above five tons are 2,26% of the total number of vehicles in Iceland the year 2004. ODR trucks are about 0,025% of the total number of vehicles in the country and 1,1% of all the trucks above five tons. The probability for any vehicle to have some kind of an accident is 4,03% over the year, see Appendix F.

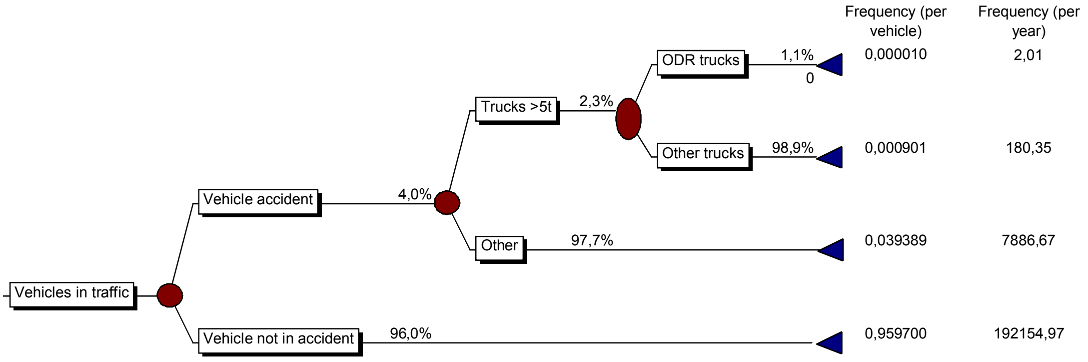


Figure 14. Event tree for traffic accidents on Iceland.

The frequencies in Figure 14 show that it is estimated that an ODR vehicle can expect 2,01 accidents each year if the probability for each event is multiplied by each other. This tree was based on national traffic accident numbers, but not accidents directly involving ODR trucks. Yearly accidents according to ODR for their trucks for the last ten years have been one per year [7]. Frequencies of accidents involving vehicles are often discussed as parts per million driven kilometers. The above information will be used to upgrade the frequency in relation to accidents per million driven kilometers. A second factor needing an upgrade is the fact that all accidents caused by trucks over 5 tons are 5,98% of the total national accident number or 483 accidents. That is based on a research [23] done in co-operation with the Icelandic Road Administration, over the years 2001-2004. ODR trucks are only causing 1 accident each year out of those 483 or 0,207%.

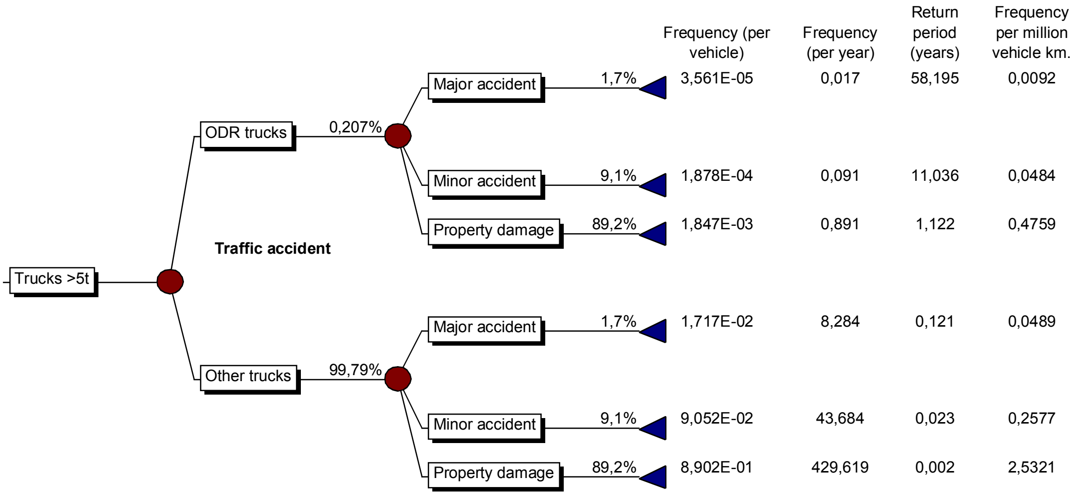


Figure 15. Event tree for ODR traffic accidents compared to trucks above 5 tons.

In Figure 15 the distribution of different accidents can be summed up and the outcome is one accident over the year, as was expected for ODR trucks. The sum of the frequency per million vehicle kilometers is 0,5335 and since ODR trucks are driven 1.874.250 km yearly the accident rate is 1 per year. More detailed calculations are given in Appendix F.

Figure 16 demonstrates the return period for a fire to occur in any traffic accident for ODR vehicles. The value for ignition is assumed by author to make the outcome more conservative.

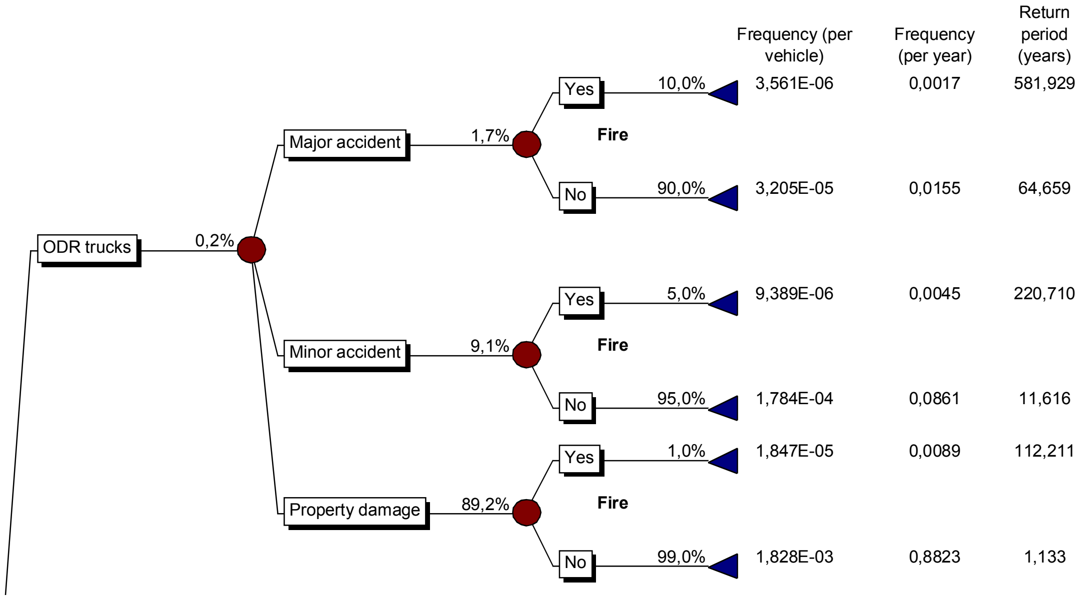


Figure 16. Event tree for ODR traffic accidents where fire occurs.

Combining the frequencies for the three scenarios where fire occurs, the total annual frequency is 0.0151 and the return period would hence be 66 years. This result is based on the company specific data, which consists of merely 10 observations. If instead an oil-truck is assumed to be as accident prone as any other heavy vehicle on the road, the national data illustrated in the lower part of figure 15 would imply a roughly fivefold increase in the frequency and hence a return period of 12-13 years.

4.5.3 Possible consequences of an accident

An accident where a petroleum truck is involved always presents danger to people and surroundings. Such trucks are massive and can cause tremendous harm to other vehicles in traffic and their occupants, as well as possible harm to the drivers themselves.

If a fuel truck hits another vehicle or has a single vehicle accident, there is a possibility that the truck will start leaking and the fuel could ignite. If that would happen in the city or within the perimeter of some other community, a great danger would be created for people near the accident scene in the form of fire or explosion. Areas would need to be evacuated and secured, fire fighters would have to either fight the fire or clean up the spill that could possibly spread to groundwater etc.

The possible heat release from such fire has been demonstrated in section 4.2 where it was estimated that the most probable value for the HRR would be around 130 MW, if the gasoline pool area would be between 50 and 150 m^2.

4.5.4 Explosion of fuel truck

If a fuel truck has a traffic accident, there is always certain danger involved. Accidents causing the tank to rupture are of concern, especially if there is any energy source nearby capable of igniting the fuel. All sorts of energy factors that are capable of heating up the tank, like a burning car in the proximity, are a major threat too.

Under right conditions the fuel fumes can start burning if they get in contact with the atmosphere and cause powerful explosions, creating danger to people’s lives and the surroundings. If the tank warms up enough, possibly because of fire, the pressure inside could increase to a point where the tank bursts and much volume of fuel gets out. Large pool fire would be the case, where it would ignite almost instantaneously.

If the pressure inside the tank increases fast and/or the tank has a weak spot and has not burst yet, there is a possibility of an explosion where parts of the tank could be thrown at people.

It is hard to estimate the number of people near an accident like this. If the truck would not start burning in the accident, it is most likely that number of spectators would gather around the truck in an attempt to help or just to watch. That would increase the probability of a number of people to die or get seriously hurt if the truck would start burning or explode.

4.5.4.1. BLEVE

BLEVE is the acronym for Boiling Liquid Expanding Vapor Explosion and can happen if the tank is exposed to heat. The fuel inside might start to boil resulting in increased pressure and the fuel could instantaneously burst out from the ruptured tank and explode. A fire ball can be seen when this phenomenon occurs, where the fuel burns very quickly as the intensity of the radiation is very large [24].

If a gasoline truck carrying 30 tons of gasoline would start burning on its route through the city, the maximum size of the fire ball would be about 185 meters. That diameter could be used to evaluate the minimum distance for bystanders near the accident scene. Calculations are given in Appendix F.4.

It can be assumed that an individual standing within that fire ball diameter, will most likely die because of burn wounds created by the phenomenon. How many people are found within that diameter each time is hard to estimate? It is however clear that if a gasoline truck would have an accident within the city perimeter leading to explosion; people within 185 m from the accident site are in severe danger because of the fire ball.

4.5.5 Results

The statement that the trucks transporting fuel from the depot, have or cause only one accident per year gives the activity a certain comfort regarding safety. One accident for every fifty trucks is 2%, compared to about 11% for other trucks above five tons. That could be interpreted as good results for the depot activity or simply a fluke since data for the activity is scarce. This year there have been two accidents for ODR trucks where some spilling was related to one of the accident, but without any fire though. Because of this is it hard to assume that those numbers of accidents are exactly one per year for those trucks. It should be more realistic to assume that the real value lies between 2-11% per truck.

The return period for any accident to happen and a fire to occur was calculated to be 66 years. That return period is probably the best case scenario since it easily changes if the accident frequency increases from one accident to some other higher number. It must be assumed that the real value for this return period is somewhere between 12-66 years, if national accidents numbers are taken under consideration.

The fact that fuel transportation is increasing every year [7] does not benefit the risk related to those transportations, because of increased exposure in traffic. ODR drivers are often driving long distances to nearby towns and communities.

The international airport in Keflavík which is about 50 kilometers away from Örfirisey, is demanding around 20% of all the fuel from the island. To maintain a smaller depot near the airport that could also be used to serve the communities around it could be an option worth considering. A thorough cost-benefit analysis would have to be implemented and then the decision making should be easier.

Those transportations are causing a certain threat to the people living in the route area. It is of consideration that the fuel needed for the south-west part of Iceland and other locations further away from the capital area, is driven through the city and therefore causing a threat for those residents living there. Each transportation trip does increase the frequency of an accident to happen; therefore those trips should be minimized as much as possible. More details are found in Appendix F.

5 Smoke distribution over Reykjavík

According to the Fire Protection Handbook [18], smoke is most often defined as the airborne solid and liquid particulates and fire gases evolved when a material undergoes pyrolysis or combustion.

If an oil depot burns large amount of gaseous products will rise into the air. The conservation law for mass dictates that mass can not be destroyed nor created and therefore it is assumed that the burning rate is directly related to the amount of gaseous products in this particular fire.

The toxicological particles formed in fires are the ones that are responsible for most deaths related to fires, not the flames or the radiation. When deaths are involved the victims usually die because of suffocation from breathing in poisonous gases. Only one quarter of home victims die from burn wounds [f].

In this chapter the particles in the smoke will be accounted for and their possible effects on people. The distribution over the city will also be studied with the help of the program ALOFT.

5.1 Petroleum fire products

When petroleum products burn toxicological compounds are released to the atmosphere. They vary depending on the substance burning and outdoor conditions. It must be stated that compounds in fires like that are numerous but only the most common will be accounted for in the following sections.

5.1.1 Acetic acid (CH_3COOH)

Acetic acid, also known as ethanoic acid, is an organic chemical compound best recognized for giving vinegar its sour taste and pungent smell. Acetic acid is a weak acid but is corrosive and must therefore be handled with appropriate care. It can burn skin, cause permanent eye damages, and irritation to the mucous membranes. Those burns or blisters may not appear until several hours after exposure. Known symptoms when in contact with the acid are; burning sensation, coughing, dizziness, headache, labored breathing, shortness of breath, and sore throat [g].

5.1.2 Acrolein (C_3H_4O)

Acrolein is used as a microbiocide in oil wells and liquid hydrocarbon fuels. Acrolein is a byproduct of fires and is one of several acute toxicants which firefighters must face. It has been demonstrated to be both sensory and pulmonary irritating, at as low concentration as a few parts per million. It is assumed to be carcinogenic and skin exposure causes serious damage. It was used in world war one as a chemical weapon, but has however not been banned so far by the Chemical Weapons Convention [h].

5.1.3 Carbon dioxide (CO_2)

This compound is usually evolved in large quantities during fires. It is not particularly toxic but it can increase both the rate and depth of breathing, thereby increasing the respiratory minute volume. By that the exposure to other chemicals present in air increases also. A possible victim starts breathing faster and deeper to an extent which is not acceptable. The amount of 2% carbon dioxide concentration can cause up to 50% increased breathing rate and depth. At 10% the rate and depth may be up to 8-10 times compared to normal. The earth's atmosphere contains roughly 0,04% of carbon dioxide.

This compound is also odorless and colorless, and therefore the victim has problems knowing if he or she is being exposed to it. The symptoms are dizziness, faintness and headache [i].

5.1.4 Carbon monoxide (CO)

Carbon monoxide (CO) is one of the most abundant compounds formed in fires, and that is no exception for petroleum fires. The toxicity of the compound is largely due to the fact that it forms a strong bond with the hemoglobin molecule, forming carboxyhemoglobin (COHb), which impairs the oxygen carrying capacity of the blood. The affinity of human hemoglobin for carbon monoxide is roughly 240 times the affinity for oxygen. There is no special saturation for COHb blood associated with death. Persons with some pre-existing functional impairments, low COHb saturation can be lethal. Factors increasing susceptibility are if people are over 65, under 5 years of age, physically disabled, under the influence of alcohol, drugs, or medication, and those with heart disease.

As a rule of thumb the exposure in which the product of concentration (ppm) x time (minutes) exceeds approximately 35.000 is likely to be dangerous. Studies involving rats and none-humans primates, showed that a saturation of 49,5% COHb in blood with the standard deviation of 14,0 is lethal.

The compound is colorless and odorless, and it is therefore hard to notice when exposed to it [j].

5.1.5 Nitrogen oxides (NO_x)

Nitrogen in the atmosphere can react with oxygen at high temperature and form nitrogen dioxide (NO_2) or nitric oxide (NO). Nitrogen dioxide is considered to have high toxic levels for mammals, but nitric oxide is about one fifth in toxicity compared to the nitrogen dioxide.

Nitrogen oxides are mostly pulmonary irritant and in that relation aggravate asthmatic conditions. It can react with oxygen again to produce ozone (O_3) and if dissolved in water form acid rain [k].

5.1.6 Sulfur dioxide (SO_2)

Sulfur dioxide can be produced by combustion of fuel oil and gasoline, since these fuels contain sulfur. It is a colorless gas with a strong suffocating and pungent odor. It is corrosive to organic materials and dissolves in water to form sulfurous acid, H_2SO_3. That means it can be formed when the cooling process of the tanks begins or it is raining the day of the scenario. Sulfurous acid may again combine with air, forming the even more irritating and corrosive sulfuric acid (H_2SO_4).

Contact can irritate and burn the skin and eyes with possible eye damages. Inhalation can irritate the nose and the throat. Exposure to high concentration for short periods of time can constrict the bronchi and increase mucous flow, making breathing difficult. Exposure can cause fluid to be built up in the lungs or pulmonary edema, which needs to be treated by medical staff. Headache, nausea and dizziness are all known side effects of sulfur dioxide inhalation. Elderly people, children, those with chronic lung disease and asthmatics are especially susceptible to the effects described above [l].

5.1.7 Volatile Organic Compounds (VOC)

Organic compounds that have enough vapor pressure under normal conditions (1 atm., 25°C) to vaporize and enter the atmosphere are so called volatile organic compounds. Aldehydes, hydrocarbons and ketones are all carbon based molecules and are VOC's. Petroleum fuels like gasoline are known sources of VOC's. Those compounds are efficient in greenhouse gas contribution and some are considered carcinogenic and may even lead to leukemia. Some react with nitrogen oxides in the air and form ozone that is found in the lower atmosphere, which can cause respiratory problems [m].

5.1.8 Particulate PM 10 and PM 2,5

Particulate matter (PM) is the general term used for a mixture of solid particles and liquid droplets found in air. PM 10 is the particulate combustion product with diameters less than 10 micrometers in units of micrograms/m^3. PM 2.5 is the particulate combustion product with diameters less than 2.5 micrometers in units of micrograms/m^3.

These airborne particulates consist of many different substances, like the one mentioned above, that's vary widely in size. Some particles are emitted directly from their sources, such as chimneys and exhaust pipes. In other cases, gases such as sulfur oxide and SO_2, NO_x and VOC interact with other compounds in the air to form fine particles.

Inhaleable PM includes both fine and coarse particles (PM 10). These particles can accumulate in the respiratory system and are associated with numerous health effects like respiratory conditions such as asthma. The fine particles are associated with increased heart and lung diseases, increased respiratory symptoms and disease, decreasing lung function, and even direct death [n].

5.1.9 Chemical concentration in the smoke

In order to estimate the risk of the substances found in the smoke threatening life in the nearby areas, we must compare the concentration for those substances to other estimated limits. The concentration is probably not threatening to life since there will be great mixing in air because of its long travel distance, before hitting any dense population. Table 8 shows different values for different criteria limits which are considered to threaten life in some way.

Compound	IDLH (mg/m^3)	LC_{50} (mg/m^3)	AOSH (mg/m^3)
Acetic acid, CH_3COOH	123	17.274	25
Acrolein, C_3H_4O	4,6	344	0,2
Carbon dioxide, CO_2	72.131	89.262	9.000
Carbon monoxide, CO	1377	5975	29
Nitrogen oxide, NO_2	38	266	5,5
Sulfurdioxide, SO_2	262	7.868	1,3

Table 8. Values for IDLH, LC_{50} and AOSH

IDLH is an abbreviation for Immediately Dangerous to Life and Health, and is defined by the NIOSH [o] as the maximum concentration that a worker can be exposed to airborne chemicals for up to 30 minutes without loss of life or irreversible health effects or severe eye or respiratory irritation that would prevent his/her escape.

The Lethal Concentration or LC_{50} is the amount of a substance in air that, when given by inhalation over a specified period of time, is expected to cause the death in 50 percent of a defined animal population. The time used in the table is 30 minutes since it is assumed that people in reach of the smoke will not be exposed to it longer than this time. Most likely people would be evacuated if it would be considered necessary to a safe gathering point or a house.

The values from the Icelandic Administration of Occupational Safety and Health (AOSH) in Table 8 are used as a guideline for the highest allowable quantity of a substance in breathing air for Icelandic employees [25]. Those values are much lower than the ones for IDLH and LC_{50}, but the exposure for the AOSH numbers is estimated to be over a whole working day.

Values for IDLH and LC_{50} differ depending on research and methods, and therefore is it possible to find different values than the ones used in Table 8. All data used in the table are gathered and published by NIOSH [o].

Table 9 shows the estimated concentration values for the smoke, at different radius from the source. This estimation is made with the program ALOFT, see section 5.3.

Compound	Conc. 100 m from source (mg/m^3)	Conc. 1.000 m from source (mg/m^3)	Conc. 2.000 m from source (mg/m^3)
Acetic acid, CH_3COOH	90 (PM_{10})	11 (PM_{10})	4 (PM_{10})
Acrolein, C_3H_4O	90 (PM_{10})	11 (PM_{10})	4 (PM_{10})
Carbon dioxide, CO_2	4.052	184	124
Carbon monoxide, CO	5,2	0,5	0,2
Nitrogen oxide, NO_2	90 (PM_{10})	11 (PM_{10})	4 (PM_{10})
Sulfurdioxide, SO_2	0,8	0,4	0,2

Table 9. Estimated concentration at different radius away from the smoke source, for different substances in 6.000 m^2 gasoline fire.

The values for PM_{10} in Table 9 can indicate that the particulates in the air are threatening people since those values are well above some of the AOSH values and others in Table 8. As was said in section 5.1.8, PM_{10} is a term used for mixture of particles and liquid droplets found in air. This means that it is very unlikely that those substances, where the PM_{10} concentration exceeds the values in Table 8, are the only ones found in the smoke. More likely the contribution of each would be considerably lower than the whole.

5.2 Wind conditions

In case of fire the wind conditions are of significance when it comes to distribution and concentration of substances of the smoke. This can influence the firefighting greatly since the fire department may not be able to attack the source in the most convenient way if the wind directions are not favorable.

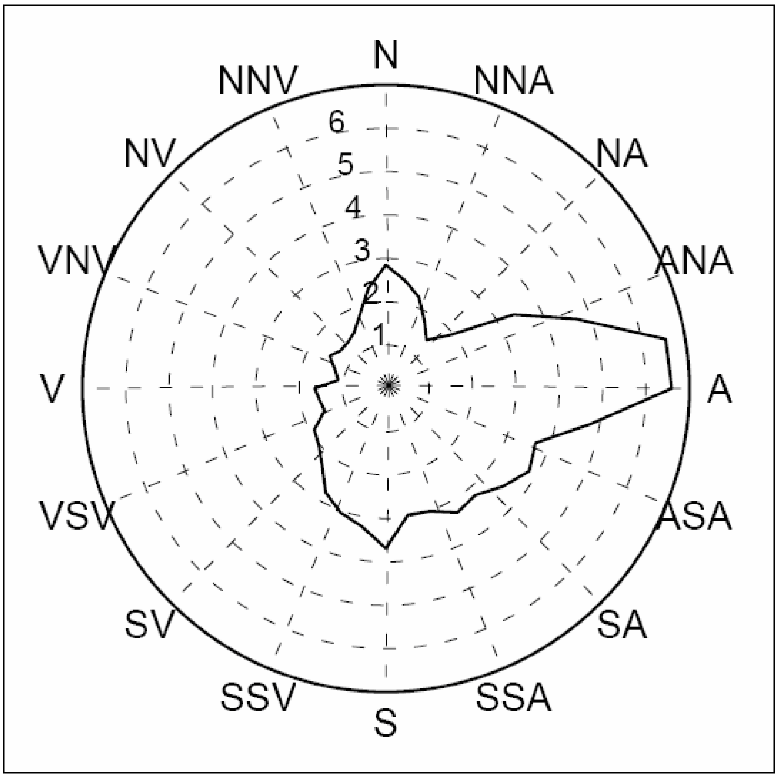


Figure 17. Frequency of wind directions in Reykjavík 1985-2004.

The average wind speed in Reykjavík over the years 1985-2004 is 4,1 m/s. The most frequent single direction is directly from east but the most probable wind direction is blowing from south and east, and everything there between. Those data are based on 58.431 measurements done by the Icelandic Meteorological Office [26].

5.3 ALOFT – a model for smoke distribution

Considerable progress has been made in the last decades with respect to simulating the movement of smoke and mixing with air. The program ALOFT [p] (A Large Outdoor Fire Plume Trajectory) is based on the fundamental conservation equations that govern the introduction of hot gases and particulate matter from a large fire into the atmosphere. The model predicts the downwind distribution of smoke particulate and combustion products from large outdoor fires. Measurements and observations at experimental fires have shown that the downwind distribution of smoke is a complex function of the fire parameters, meteorological conditions and topographic features. To incorporate these features, NIST has developed a smoke plume trajectory model that solves fundamental fluid dynamic equations for the smoke plume and its surroundings. The program contains a graphical user interface for input and output and a user modifiable database of fuel and smoke emission parameters.

5.3.1 ALOFT limitations

Even though the program can handle very large fires it has its limitations. It "only" allows the maximum of six separate fires each of up to 1000 m^2. That is much less than the total area of the depot of 31.829 m^2. The ratio between 31.829 and 6.000 is 5,33 and therefore the values from Table 9 should be multiplied by this ratio to estimate the maximum smoke concentration for the scenario where the whole depot is on fire. This maximum value was usually found at or within 100 meters away from the source of the smoke. That would change the outcome there since the smoke concentration would exceed the AOSH values in all cases and some of the others as well.

Compound	IDLH (mg/m^3)	LC_{50} (mg/m^3)	AOSH (mg/m^3)	Max. Smoke concentration (mg/m^3)
Acetic acid, CH_3COOH	123	17.274	25	480 (PM_{10})
Acrolein, C_3H_4O	4,6	344	0,2	480 (PM_{10})
Carbon dioxide, CO_2	72.131	89.262	9.000	21.597
Carbon monoxide, CO	1377	5975	29	27,7
Nitrogen oxide, NO_2	38	266	5,5	480 (PM_{10})
Sulfurdioxide, SO_2	262	7.868	1,3	4,26

Table 10. Values for IDLH, LC_{50}, AOSH and estimated concentration at the source of the smoke plume for different substances if the whole depot is on fire.

Another limitation is that the maximum downwind distance is 20 kilometers. That doesn't actually matter since the radius from the depot to the outer perimeter of the city is about 10-12 kilometers.

A third limitation is that the program assumes that the smoke is moving over a flat terrain. This assumption is not far from the reality when considering the surroundings of the peninsula. The land there is not very rocky or hilly, but on the other hand the buildings found in the smoke path can have an influence on the results presented below.

The fourth limitation is that the program defines only the PM_{10} and $PM_{2,5}$ concentration, Carbon Dioxide-, Carbon Monoxide-, Sulfur Dioxide- and Volatile Organic Compounds concentration. By that leaving out many substances found in fires like Acetic Acid and Acrolein etc. Therefore was it necessary to use the value for the PM_{10} in some cases in this thesis to assume concentration for some other compounds.

5.3.2 Smoke distribution according to ALOFT

To get the most realistic results from the calculations with respect to the nearest population, distance from the fire was set to 5 kilometers. The temperature is assumed to be 7°C, wind speed is 4,1 m/s and its direction is straight south from the island. Incoming solar radiation is moderate to slightly unstable and the selected lapse rate is slightly unstable meaning that the cooling is estimated to be -3°C for every 1 km upwards.

The fire is assumed to be a gasoline fire, burning at an area of 6000 m^2. The burning rate per area is taken to be 0,055 kg/m^2s. It is estimated that the heat release rate for the fire is 1,68 MW/m^2. That should give a massive pool fire and should give certain clue of how the smoke particles react.

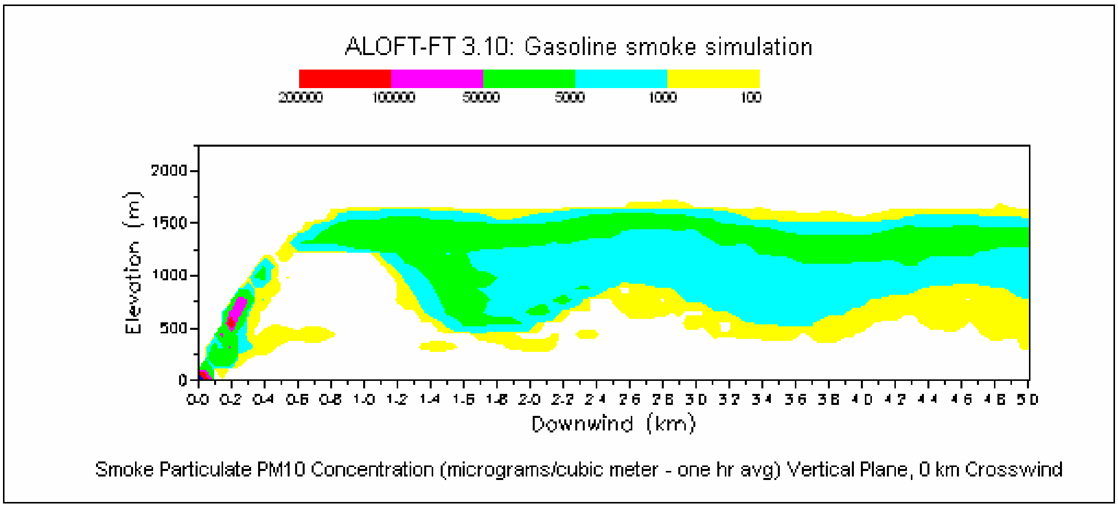


Figure 18. Distribution and concentration of PM_{10} 5 km downwind.

Figure 18 shows how the smoke particles distribute downwind from the fire or from the so called smoke source. Most of the particles never go close to the ground and their elevation is about 3-400 meters from the ground. Concentration of the substances found in the smoke decreases as the distance from the source increases due to dilution by air and also because the particles react with air and get neutralized. That can be seen in Figure 19 which demonstrates the smoke concentration up to 20 km downwind from the fire source.

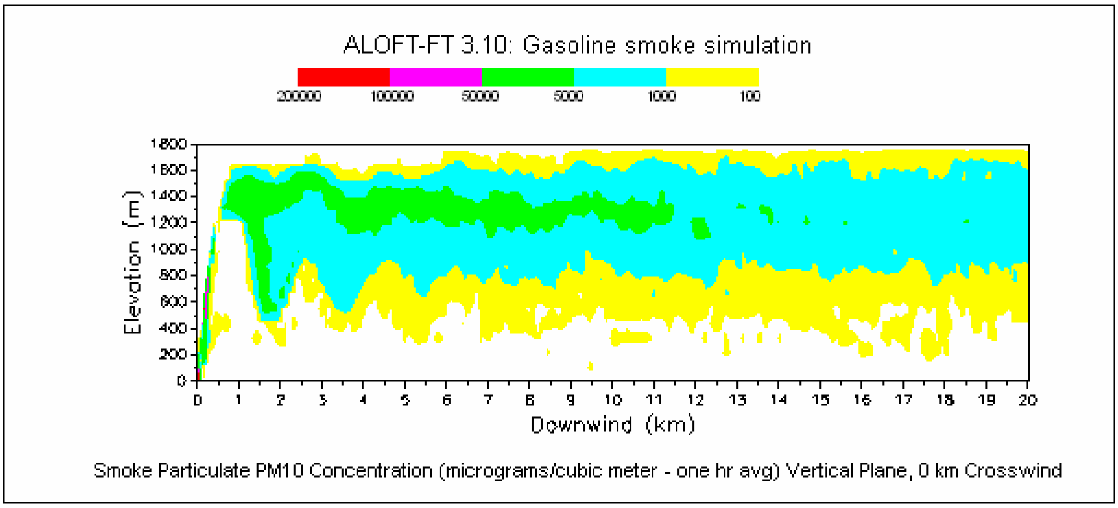


Figure 19. Distribution and concentration of PM_{10} 20 km downwind.

The concentration of carbon dioxide is much greater and sets itself much lower than other substances in the fire. The carbon dioxide is found somewhere between 100-200 meters from the ground at a distance of 5 km from the fire source.

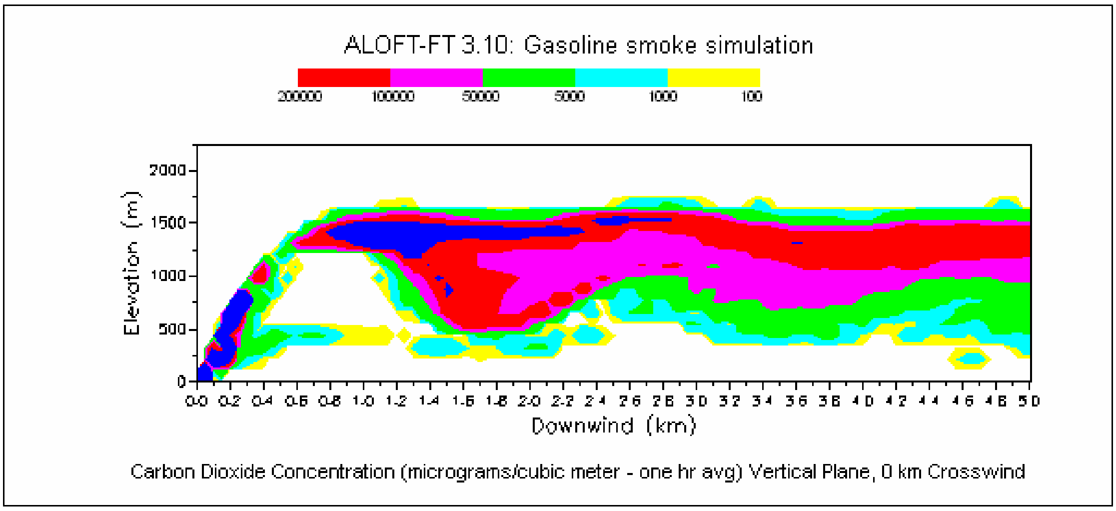


Figure 20. Distribution and concentration of carbon dioxide.

According to the ALOFT simulation model, the concentration of carbon dioxide was the strongest one of the compounds that where accounted for.

The horizontal profile for the concentration of PM_{10} is shown in Figure 21. There it can be seen that the width of the smoke plume is about 3 km when it has traveled 2 km downwind. It spreads even further to the sides as it travels further downwind, thereby covering more area than before. The concentration becomes less as the plume moves further and further downwind.

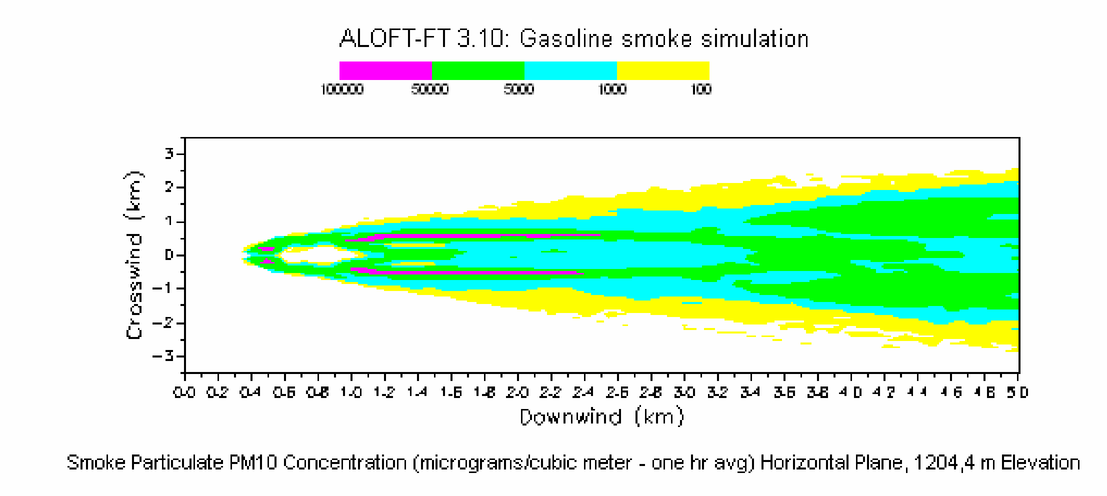


Figure 21. Horizontal profile of PM10 concentration at 1204 m elevation, 5 km downwind.

More detailed results of the distribution and concentration can be seen in Appendix G.

5.3.3 Results from ALOFT

According to ALOFT the main smoke concentration is well above the ground or between 100-500 meters. Also, for the assumed wind speed, it is seen that the smoke travels easily further than 20 km but at that distance the smoke is very diluted? If the smoke is blowing directly south then the distance over the city would only be about 2,5 km until it would reach the domestic airport and about 4,5 km to reach the sea. The width of the plume when it would reach the populated area 900 meters away would be about 1500 m wide. That width expands to at least 6 km as it distributes further away from the main source.

The smokes ability to travel a long distance in the air creates problems for other communities besides Reykjavík that are lying directly south of the island and are within the range of 20 kilometers. Even though they where further away they could also be exposed to some smoke but it will be very diluted.

If there is only gasoline burning like in this scenario, it seems that most of the concentrated gas will go over the populated area according to ALOFT. In a depot fire in Gdansk the year 2003 where gasoline was burning, the smoke height was much lower if judged from Figures 36 and 37 in Appendix G. The same was seen at Buncefield London.

It must be considered that the ALOFT simulation model assumes that the landscape is flat. That is the case near the activity in the island. The landscape further away is hillier and buildings nearby have not been taken under consideration. In the populated area near the depot, 5-6 floor high accommodation buildings are common. This increases the probability that the smoke actually does contact the buildings. That also increases the probability of some people getting in contact with the smoke particles.

Therefore it is clear that the population in the vicinity will be affected by the fire but mostly in an irritating way if the fire does not exceed the area of 6.000 m^2. The concentration of the particles mentioned in section 5.1.9 for that kind of fire is not sufficient to cause serious illness or casualties, if people notice the threat in time. People will most likely be notified and evacuated to a safer place. If however fire is ignited over the whole depot, the smoke concentration changes to a more threatening situation for people at or near the depot. More concentrated smoke is produced and will most likely be above the AOSH limits found in Table 10.

The values for the maximum smoke concentration are mostly based on the values for PM_{10}. The most common substances found in petroleum smoke are Carbon Dioxide, Carbon Monoxide, Nitrogen Oxides and water fumes. That gives reason to believe that the values for PM_{10} are lower for each and every substance found in Table 10. That table also gives us reason to worry about the Nitrogen Oxides because of a low IDLH value compared to a high PM_{10} value.

It must be stated that this work uses “Maximum Smoke Concentration” found in the whole smoke plume and not the average concentration. This value was always found near the source of the plume or within 100 meters from the source. That gives us reason to believe that this concentration will be diluted by air on its way to nearby surroundings and become much less than it is shown in previously mentioned tables.

By increasing the wind speed in the program the smoke tended to travel closer to the ground than if the speed was slower. Also by assuming more cooling effects in air, same happened – the smoke plume laid itself lower to the ground. This means that the wind speed and the temperature outside do affect the distribution of the smoke substantially. Therefore, the calculations using ALOFT must be seen to be approximative.

6 Risk evaluation

This chapter will discuss individual risk and societal risk in an attempt to come up with a risk evaluation for the people working at the depot. It has been assumed that the most probable cause for an individual or a group of people to die is at or near the depot itself. Casualties for nearby population are not considered probable because of the possibility to evacuate large groups of people from their homes and get them to a safer place and also the fact that the smoke will most likely be greatly diluted by air before it reaches the populated areas. Individual and societal risk will be evaluated based on the radiation from the flames in the three scenarios. This radiation can be a major threat to especially the people working in the island at the time of ignition and therefore is this criterion chosen. The tolerable risk for an individual is considered to be $3{,}0*10^{-5}$ as was stated before in relation to avalanches.

6.1 Individual risk

When the radiation from a fire in the whole depot was calculated, the threat for the population near by was insignificant since the radiation diminished as the distance from the fire increases. Therefore is the individual risk in our case only affecting the personnel working at the oil depot and because of that the calculations are a bit simpler. That is also the case for the other scenarios since they give much less energy release and therefore constitute a lesser threat.

To estimate who will survive and who will die in such situations, the percentages of those who will encounter a second degree burn were calculated, see Appendix H. It is estimated that 15% of these will not survive and die [21]. The results can be seen in Figure 22 below.

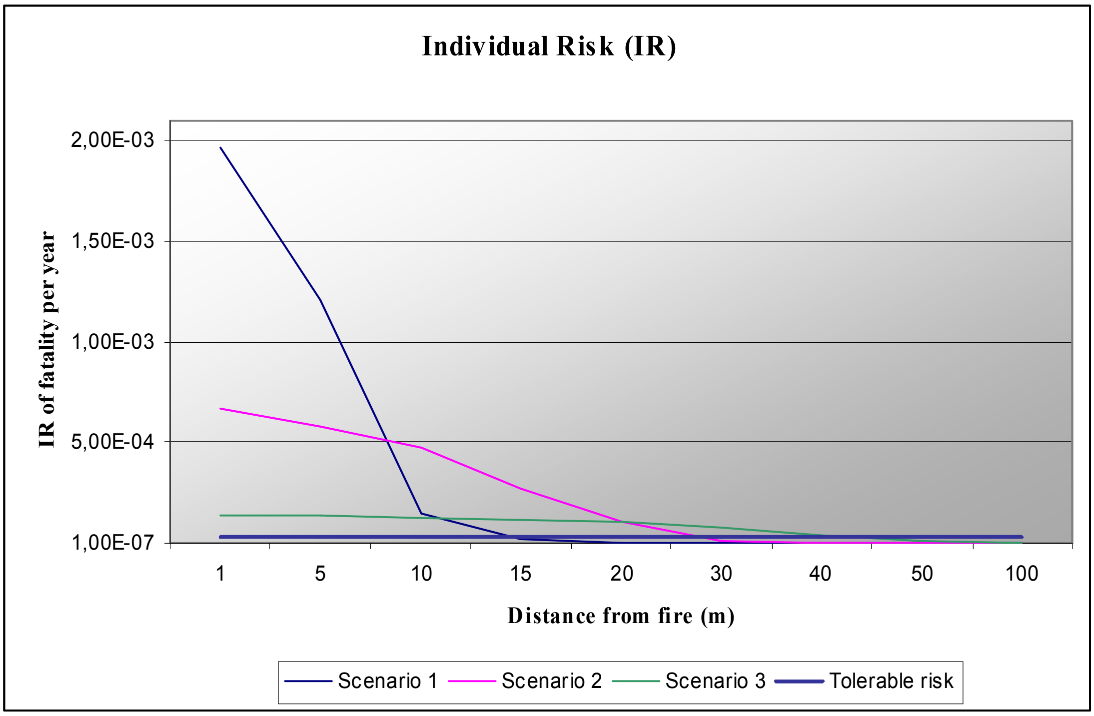


Figure 22. Individual risk at the oil depot caused by radiation

The individual risk is plotted as a function of distance from the risk source or the fire in this case. The source in this case is large and therefore the individual can be found in numerous different places around the depot.

The individual risk found in the figure is extremely high compared to the criteria but that can partly be explained by the fact that if someone is standing close to such fire as in the case where the whole depot burns (scenario 3), it is unlikely that he or she will get away unharmed.

The choice for tolerable risk might also be to low since working at an oil depot and living on an avalanche area is not actually comparable. Both choices are peoples own will, but working with dangerous chemicals like fuels, must be considered more risk orientated than living on an area where an avalanche might occur. An American Petroleum Institute (API) study reported a death rate of direct hire personnel of 14,3 deaths per 100.000 employees averaged over a five year period. That is an individual risk equal to $1,43*10^{-4}$ which fell in their criteria range of 10^{-4} to 10^{-5} per year. Most common suggestions for potentially fatalistic events fall in the range of 10^{-5} to 10^{-6} or 10^{-7}, like the ones from Volkschuisvesting Ruimtelijke Ordening en Milieubeheer (VROM or the Ministry of Housing, Spatial Planning and the Environment), Netherlands and the Environmental Protection Agency, Australia.

The criteria range for the Health and Safety Executive (HSE), U.K., is 10^{-3} to 10^{-6} if those individuals are considered workers, but 10^{-4} to 10^{-6} for the public [27].

6.2 Societal risk

When calculating societal risk for the fire in the depot the three scenarios where added to each other, since in the case where the whole depot is on fire it is certain that the loading place and the accounted tanks in scenario 2 are also burning. Therefore it is assumed that those in danger in scenario 1 and 2 should also be in danger in the case where everything is burning.

The employees working in the depot are considered to be the group (section 3.2.4) which is exposed to the risk. Most often calculations like this are done for a much larger group of people. The number of people here are only twenty since that is about the number of employees at the depot. Estimated numbers of people at the gasoline rack and near some of the storage tanks were five and ten respectively.

Since the calculated radiation in Appendix H from the fire scenarios is not considered to cause any major harm outside the depot perimeter, this way was chosen to show the societal risk instead. This does demonstrate a certain number of people dying related to fire in the depot which must be accounted for.

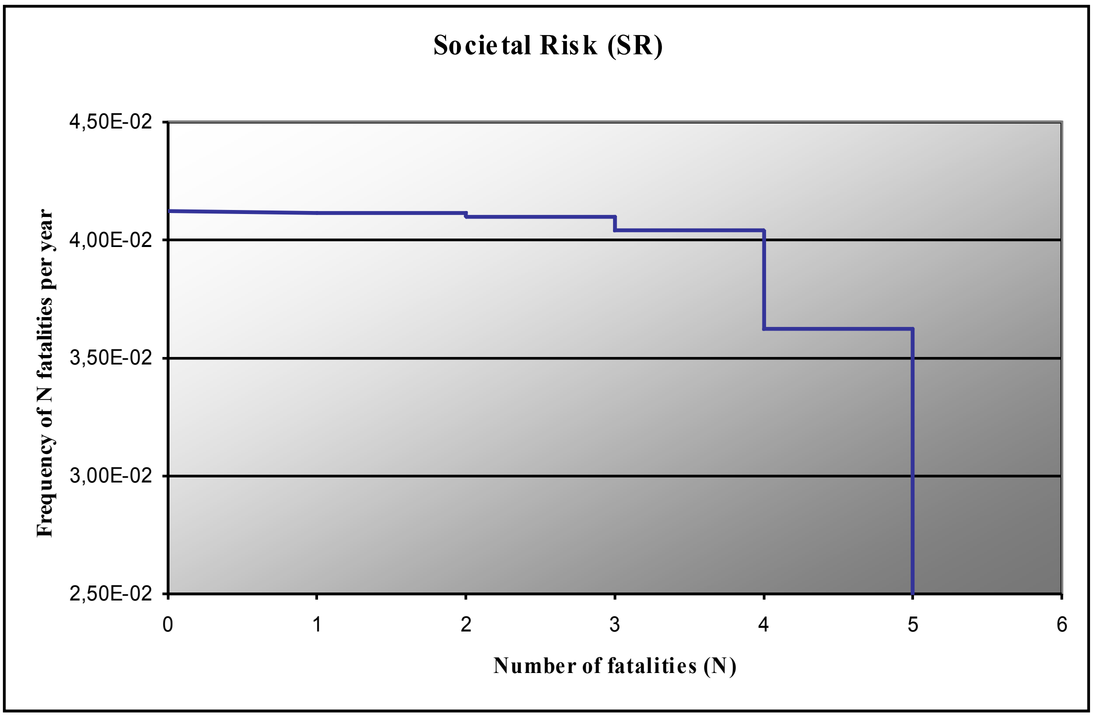


Figure 23. Societal risk at the oil depot caused by radiation.

Figure 23 demonstrates the frequency of a certain number of fatalities per year. Notice that the FN curve shows the relationship between the accumulated frequency for N or more fatalities. The curve shows that the frequency for a single accident where one or few individuals are dead is higher than the frequency of an accident that leads to the death of many people. In this case the single accident probably leads to the death of two individuals not one, as can be seen in the figure. It is more common that one person dies at a time than a group of persons at the same time. More details can be found in Appendix H.3

A known criterion for societal risk is the one from DNV (Det Norske Veritas). There it is stated that the tolerance for high risk or the frequency of it is 10^{-4} per year where N=1. The tolerance where the risk is considered small the frequency there is 10^{-6} per year where N=1. The slope factor in this relation is -1 (Figure 24).

Figure 24 states that the tolerance for a high risk situation is 10^{-4} per year for a one person to die. If the number of those persons increases, the tolerance becomes lower. The tolerance for a thousand people to die is much lower or 10^{-7} per year.

Other criteria's for the societal risk can be found like the one from VROM, Netherlands, where the frequency is 10^{-3} per year for N=1 [27]. The same can be seen from the Health and Safety Executive (HSE), U.K., where the ALARP region is ranging from 10^{-3} to 10^{-6} per year if workers are involved instead of the public [q].

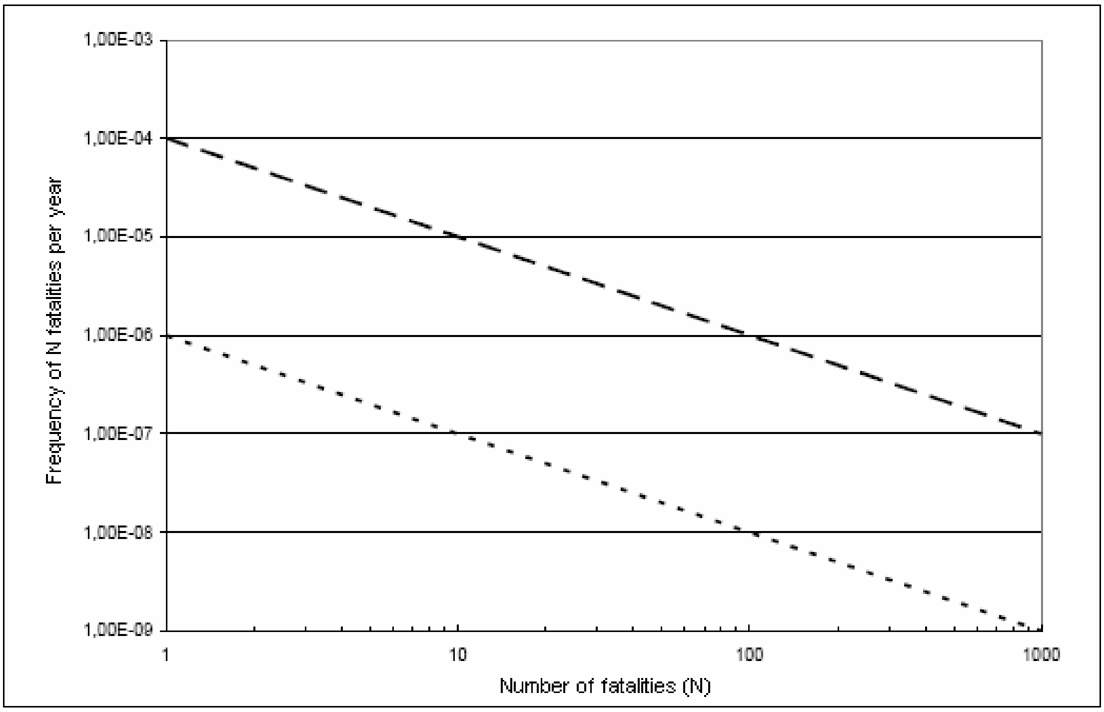


Figure 24. DNV societal risk criteria.

By comparing Figure 23 and 24 the societal risk calculated in the previous figure is much higher than criteria from Det Norske Veritas. That can be explained by the fact that the societal risk calculations where based on large fire scenario and the individuals harmed in the scenario where all standing close to the fire when it started. If the fire scenario would have occurred over a night it would be very possible that the number of fatalities would have been much less since there are much fewer employees over the nighttime.

Usually, the societal risk is calculated for much larger population which may explain some part of the difference between the calculated societal risk and the criteria from Det Norske Veritas. The uncertainty is more when the sample is smaller as in the case for the depot employees.

Societal risk will be accounted for in the next section using other approaches, since it is certain that such a fire will affect the nearby surroundings – maybe not by killing anyone, but rather due to mass evacuation of the nearby population.

6.3 Evacuating the nearby population

Fire smoke is always a threat to people and living creatures. An oil depot fire is no exception in that matter since hazardous chemicals are found in the smoke.

As was mentioned in the chapter regarding smoke distribution over Reykjavík, the concentration of particulate did not seem to be of immediate threat to life for fires not exceeding 6.000 m^2. The concentration needed to irritate people and/or cause some physical symptoms after half an hour is much lower than the IDLH and the AOSH values for most of the substances. Some substances in Table 10 give reason though to believe that the concentration can be critical at some point if the values for PM_{10} are assumed to be the values for Acrolein, Acetic acid and Nitrogen Oxide. Because of this there is a possibility that some areas would have to be evacuated near the operation.

That would certainly be the case if the whole depot is on fire even though it has been stated that the smoke concentration would probably be diluted by air on the way to nearby population. However that kind of concentration would most likely at least irritate people and cause much inconvenience, based on the possible particulate concentration.

Earlier it was stated that the smoke plume would probably not fall to ground level. Pictures both from the oil depot fire in Gdansk Poland and Buncefield U.K. show that the plume raises high from the ground but there is always some concentrated smoke moving along at ground level. Also, the ground is not flat and houses can be many floors high. Therefore the authorities in Iceland should have a response plan for evacuation of the affected population.

6.3.1 Evacuation plan

It is clear that in the case where the whole depot is on fire the fuel will last for at least 20 hours. The local wind conditions or directions can change much over a short period of time and therefore is it possible for the wind to even press the smoke plume further down to the ground making the situation more severe.

A population of about 30.000 individuals lives directly south of the peninsula in Reykjavík. The population in communities further away is not accounted for in these numbers since the smoke has diluted very much at those distances.

For safety reasons a large majority of this population would have to be moved to a secure area outside the smoke plume. That kind of action demands much manpower, facilities for the evacuated people and planning. The CDFRS could not spare their manpower in procedures like that since their job would be fighting the fire, so other options would have to be available. The Icelandic Civil Protection Department would have to declare a public emergency situation in cases like this and act according to that. During an emergency situation the Civil Protection authorities organizes the set-up of the following service if needed [r]:

- Temporary mortuaries
- Centre for casualties
- Centre for survivors
- Centre for evacuees
- Centre for relatives and friends
- Centre for the provision of food

Iceland is divided into 32 civil protection districts. Each civil protection district has a civil protection committee which is responsible for organization at the local level. The task of the committees is to organize and carry out rescue and protection activities, preventive measures as well as of an acute nature, caused by war, natural catastrophes or other similar incidents.

The operation of some of these services is often delegated to volunteer organizations, i.e. the Icelandic Association for Search and Rescue and the Icelandic Red Cross, which can provide qualified manpower.

If the smoke is traveling low and entering buildings and houses, the damages might be very extensive. Estimation of the cost will not be discussed in this work but it is obvious that there are other losses than lives to be considered in a fire. In the case where there is damage to properties the insurance companies need to be involved in the salvage of those properties.

7 Risk reduction

It is possible to reduce known risks or to completely eliminate them in a number of different ways. The best way is of course to totally prevent the risk, but that can be costly and sometimes even impossible. Three approaches will be discussed in this chapter and they are:

- Reducing frequency of incidents at the depot
- Reducing consequences of incidents
- Moving the activity

Some of the approaches are easier to implement than others, but they all have their benefits and drawbacks. The cost is always a factor that must be considered when risk reduction is mentioned. Sometimes the cost is unacceptable and other precautions have to be made. Sometimes is it necessary to even shut down the activity or a part of it.

7.1 Reducing frequency of incidents

The calculated frequency for a fire in the depot is high and that is directly related to the numbers of fuel leakages in the depot. For an activity like the one in Örfirisey, the number of pipes and connections found there make it hard to totally control that no leakages occur. Organized inspections by the employees at the depot on a daily basis could reduce the frequency of such incidents considerably. The numbers of overfill when loading is mostly related to a human errors as well as the overfill protection system on the trucks, and that is something that must be prevented instantly. It is not tolerable that the probability for a leakage to happen at the depot in Örfirisey is about 20 times greater than for a similar leakage to occur at OK-Q8 [16]

There are considerable safety precautions at the depot according to the Compulsory declaration for ODR oil depots [3], but sometimes things are taken for granted if not revised regularly. Safety behavior tends to diminish after some time if employees aren’t continuously reminded of its importance. Regular safety meetings help in that relation, where all individuals working in the island are taking part and do have the opportunity to bring forth suggestions regarding safety. Such meetings have been used now for several years at Alcan Iceland and are considered effective there. Employees who are safety oriented seem to notice the threat earlier and even before it does any harm. Preventive actions are always more beneficial than the reactive ones.

Regarding the transportation of the fuel from the depot to other communities, the frequency for ODR trucks to encounter an accident is 5 times less than for other similar trucks in traffic according to ODR [7]. It is difficult to decrease this frequency further if compared to national numbers. However, those numbers are only based on observation over the past ten years and this year there have been two rather severe accidents, where a rollover of the transportation trucks occurred in both of the accidents. It is hard to come up with a statement saying that this low frequency will be the case for the trucks in upcoming years. More likely, those accidents numbers are in an interval between 2-11%, since the later percentage is actually based on larger sample and therefore more reliable [23].

Therefore is it not considered effective to put effort in improving that category and rather emphasize on other aspects of the operation like the leakages.

Other measures might be installing fuel detectors that detect leaking fuel on the ground or in the air. That type of system would warn the employees and give them the opportunity to react much sooner to the leakage than currently is the case. It can be difficult to use only eye audits for leakage problems since the leak can start slowly and increase dramatically in later stages.

7.2 Reducing consequences of incidents

The consequences of the incidents affect people and their surroundings directly when an incident occurs. Some possible factors for reducing consequences are:

- Well equipped fire department with the expertise needed to fight fires like those assumed at the depot.
- Active fire protection systems connected to all tanks in the depot.
- A larger volume of foam in the country, the Buncefield fire demanded 600.000 liters of foam and the maximum amount of foam in Iceland is about 50.000 liters.
- Well organized emergency plan in case of fire that would include the fire fighting plan, evacuation plan and co-operation between all organizations involved in such an action.
- Continuing safety education of the depot employees so that they can respond correctly to all kind of threats inside the facility, as quickly as possible.
- Ensuring more water to the depot since the demand will be extremely high in case of fire. Buncefield demanded 32.000 liters per minute over a long period of time. Örfirisey has 23.000 liters per minute today which should be increased, since the worst case scenario will demand more water.
- Informing people in Reykjavík and especially those living close to the depot that an evacuation from their homes might become necessary in case of such a fire (directive 263/1998[1]).

7.3 Moving the activity

The possibility of moving the activity in Örfirisey to other locations has been regularly discussed in the media throughout the years.

To move a facility like this would demand very strong arguments for those in charge of the depot, simply because of the cost involved. The depot was built in the fifties and it has been there longer than the majority of the buildings found in the vicinity. Gasoline prices have been high for some time now and if the largest depot on Iceland would have to be moved to some other location further away from the city or the capital area, it would probably increase the transportation cost of the fuel and thereby increase the total domestic gasoline price. It might also be assumed that the cost of moving the activity would be added to the fuel price, distributed over a certain period of time. The customers themselves would probably pay for the transportation eventually.

Moving the activity would call for some other location, probably somewhere in the south-west part of Iceland because the location of the largest market area is in or around the capital area. One possibility is the location in Hvalfjörður, where there already is a small depot. That depot is much smaller than the one in Örfirisey and would have to be enlarged in order to store enough fuel for the area. Hvalfjörður is about 30 kilometers from Reykjavík, which would increase the transportation cost somewhat. Another option might be to build two or more smaller depots in different locations that would possibly divide the market area.

It might be possible to increase the number of smaller depots around the capital area, but ODR has recently closed many of them on the south-west corner since it is less costly to use the road transportation system than operating a number of smaller depots. But that is based on the fact that the main depot is in Örfirisey and not somewhere else. By increasing the number of depots the fuel cost could increase even further.

Moving the depot would not necessarily solve the problems completely or eliminate the consequences of an incident since the fuel would still be driven into the city and the probability for a petroleum truck to have a traffic accident would increase because of longer distances.

According to the program ALOFT which estimated the smoke distribution caused by large fire, it was assumed that the smoke could travel at least 20 kilometers from the fire but beyond that distance the smoke would be very diluted. This underlines the possibility of the smoke to reach the city of Reykjavík even if the depot would be moved to some other location on the south-west corner of Iceland, if the wind direction would be towards the city. Since the product concentration was not creating any major threat to life near the depot, it can be assumed that the smoke will not cause any problems at all if it has to travel over a long distance in air on its way to the city. By traveling in air the smoke dilutes in time and with distance and becomes harmless to living creatures.

By moving the activity the threat to the capital area, caused by smoke would be almost eliminated. Transporting the activity would on the other hand not eliminate the traffic risk but possibly increase it because the fuel would be driven to the city and then around it. That risk would however not be as much in the vicinity of dense populated area as it is now. Today the fuel is driven through the city whether it is for the use of the capital area or other communities further away. That means that a certain group of people in the capital area is more exposed to the threat than other groups, which might be considered unacceptable to that group.

8 Future alternatives

The result from this study does not warrant a move of the Örfirisey depot at present risk levels. The remaining question is if the transportation through the city center and urban areas of fuel intended for use outside the capital area could be reduced? And if so, would it lessen the risks involved?

There are areas around the capital area and other communities that are defined as water protection areas. Those areas are the water protection area for Reykjavík (Gvendarbrunnar) [28], the area at “Lágar” north of Grindavík and the one at Vogar that is used for the communities in Sudurnes [29]. Fuel is being transported across or past these areas on the way to different locations on the south-west corner of Iceland and to Keflavík international airport.

A future alternative for ODR is to put up one, two or even three smaller depots outside the capital area, beside the depot in Örfirisey. Fuel could be transported to those depots by ships and by that diminish the transportation on road. Those possible locations are Helguvík, Þorlákshöfn and Akranes.

Figure 25. View of future alternatives.

8.1 Helguvík port - Suðurnes

Today, 20% of all the transportations from the depot in Örfirisey are driven to the international airport in Keflavík. Those transportations are increasing every year and it is hard to estimate the extent of this increase in the near future.

The Helguvík port was originally developed for oil imports to the recently decommissioned NATO Base in Keflavík. An additional quay of 150 m with a depth of 10 m has been built in the Helguvík harbor, making it easily accessible for up to 200 m long vessels. A smaller depot is found there today which could be used for storage of fuel. Land for further development is also available if the depot would need to be enlarged or altered in some way.

Figure 26. View of the Helguvík port [s].

The transportation of fuel for air traffic, from Örfirisey through Reykjavík city center and a considered stretch of 50 km, about half of which is through urban areas, would lessen risks in fuel transportation. Part of that route is via water protection areas used for people living on Sudurnes, which causes certain environmental and health risks.

8.2 Þorlákshöfn – south coast of Iceland

Current transport to the south part of Iceland from Örfirisey does not only go through the city center and urban area but also closely passes the Reykjavík water protection area, where all tap water for the population of the capital area has its origin.

Figure 27. View of the Þorlákshöfn port.

Situating a small depot in Þorlákshöfn would lessen risks in transportation since the number of trips from the depot would diminish greatly.

8.3 Akranes

North side of Hvalfjörður tunnel would be the third option, e.g. Akranes. This location might be beneficial for an oil depot since the transport of fuel through the Hvalfjörður Tunnel is thought to be a considerable source of risk [30] and such transportation is limited to certain time interval.

Figure 28. View of the Akranes port.

All the alternatives discussed above would lessen transport through the city center and its urban areas and thereby reduce the risks due to transportation. The question now arises:

- What will the cost be?
- To which degree will the risk be reduced?
- Will new risks arise and if so, how do they compare to the previous ones?

We shall below briefly discuss how an analysis of the above fictive future alternatives could be studied.

8.4 Cost Effectiveness vs. Cost Benefit Analysis

To implement such an analysis one needs a tool or a method that would allow a meaningful comparison of the different options. Numbers of tools or procedures are available but two methods will be accounted for in this chapter.

The first method is the Cost Effectiveness Analysis (CEA), which is considered a feasible tool for this type of problems. This method is suitable to decide which alternative maximizes the benefits in physical terms (i.e. human lives saved etc.) for the same or fixed cost. It allows projects to be compared and ranked according to the cost necessary to achieve the established objectives. The method refers to the comparison of the relative expenditure (costs) and outcomes (effects) associated with two or more courses of action. Cost-effectiveness is typically expressed as an incremental cost-effectiveness ratio (ICER), the ratio in costs to change in effects [31]. Life Years (LY) and Quality Adjusted Life Years (QALY) are units that the changes in effects are often measured in. A unit of QALY is defined as a year of perfect health which equals to one, zero refers to death.

The second method spoken of is the Cost Benefit Analysis (CBA). This method is described as the process of weighing the total expected costs against the total expected benefits of one or more actions in order to choose the best or most profitable option [t]. This process involves monetary calculations of initial expense vs. expected return. The analysis attempts to put all relevant costs and benefits on a common temporal footing. A discount rate is chosen, which is then used to compute all relevant future costs and benefits in present value terms. Monetary values may also be assigned to less tangible effects such as risk, loss of reputation, goodwill, market penetration, long-term strategy alignment etc. This could be convenient when the objective is to build a new road or to increase the number of smaller depots for instance. The value in this case is put on human life or the environment.

CEA analysis accounts for life expectancy whereas CBA typically does not. It is complicated to determine how good perfect health is as in QALY and some argue that there are conditions worse than death. Because of what has been said here it is assumed that the CBA analysis is more convenient for this project if one of the two methods would have to be chosen. An analysis that involves moving the operation would most likely be conducted on a monetary basis and the CBA analysis is more proper for that than CEA. The CEA analysis is however useful for such a project but it would provide different information which is not as straightforward as when a monetary analysis is performed.

8.5 Implementation of CBA

To implement such an analysis one has to define the problem or the project thoroughly to minimize uncertainty. In this phase a number of question have to be answered, for example:

- The purpose of the project; what are the goals or intended benefits?
- Project description; what will be done?
- Purpose of the analysis; will it be used to determine if the project should be undertaken or to determine which alternative should be selected?
- Appropriate level of effort for the analysis; given the cost of the project, how much effort should be devoted to the analysis and which aspects should receive the most attention?
- Operation perspective; what is the operation constituency? For whom are benefits being sought? Who will incur the direct and indirect cost?
- Basis for the analysis:
  - Base case; what will happen if there is no project?
  - Alternatives to be considered; through what other means could the desired benefit be achieved?
- Project schedule; when will costs be incurred? When will benefits be realized?
- Type of CBA to be used; should the project be evaluated on the basis of its cost-benefit ratio, net present value, internal rate of return or some combination of these?
- Geographical scope of the analysis; what area will be affected by the project? By its alternatives?
- Time period of analysis; over what period of time should projects be evaluated?

Other questions directly related to the problem are mostly regarding the cost. Those questions are the cost of:

- the building land for possible depot or cost per year for renting a property or a land
- installing a new depot or upgrading a older one
- harbor constructions to make it appropriate for large vessels
- equipment for receiving fuel from vessels
- transportation of the fuel from those new locations compared to the older route
- running a number of depots compared to only one
- total number of employees

8.6 Evaluation of the alternatives

It is clear that setting up one, two or three extra depots will call for some expenditure for ODR. It is considered less costly to transport fuel by trucks, than the seaway by ships [7]. However, it can be assumed that the total transportation cost by trucks would be lower if a total number of four depots would be used instead of only one. Each depot could serve its area with minimum manpower and all distances would be shorter for the fuel to be transported.

Security would have to be maintained at all sites, independent of its location. Maintenance would probably be more expensive since it would be harder to use the same manpower to perform regular maintenance over the four depots. The number of employees would definitely increase, compared to the present situation.

Perhaps the most important benefits from this hypothetical situation are that transportation of fuel through water protection areas would almost be eliminated. If a severe accident would occur there, it would be possible for the drinking water to become unfit for consumption for decades. The probability for that to happen in those areas is low, but the consequences are devastating.

Transportation through the Hvalfjarðar tunnel would also eliminated by setting up a depot in e.g. Akranes. Risks due to fuel transportation through the tunnel are considered high [30] and in case of a fuel truck accident where a fire occurs, fatalities are very likely.

By diminishing the number of transportation through the capital area, the risk decreases in relation to the frequency. If a severe accident occurs in populated area, people will be in danger.

8.7 Discussions

The suggested locations are not the only ones that could be used as candidates for future smaller depots, but each addresses a specific problem related to road transport. A major analysis would have to be implemented to calculate all significant cost related factors as well as beneficial aspects.

Transportation of fuel by heavy trucks is wearing roads down as much as several thousand regular cars would. This is a part of a larger issue; transportation of goods by sea has been replaced by road transport in Iceland in recent years. That is costing the society large amounts of money every year in the form of road construction and repairs, besides increased accident risk. Fuel transportation by the sea is not causing any extra expenditure for the society as a whole, but the purpose of every company is doing its best to maximize its profits and that is the case for ODR as well. If they are following all laws and regulations for their business, why should this distribution system be changed?

If those transportations by trucks would be “banned” by some means and ODR would have to increase their number of depots around the country, it is very likely that operational cost would increase. If that would happen, it is also very likely that the fuel price would increase and the regular consumer might have to pay for those changes. Then it is a question of willingness to pay (WTP). Would the regular consumer be willing to pay a certain extra amount for every liter of fuel, if the water protection areas and people around the transportation routes would be safe or safer? That is a question that is hard to answer and would need thorough analysis as well.

Another question worth considering is who is liable for the damage caused to the water protection areas, if a fuel truck has an accident? Is ODR accountable if the water protection area of Reykjavík would be destroyed or damaged for some years or even decades? What alternatives for water are there to be found instead of present water sources? What is considered tolerable in this relation? Is the risk presently accepted or has it simply been overlooked so far? Is this solely the problem of ODR or should municipal or national government or agencies step in?

The last sentence is something that should also be considered. If all those alternatives will become a reality, the Icelandic society would probably be beneficial both in monetary form (less road wearing) and less risk because of transportation. Would it be possible for the government to step forward and lower taxes on fuel because of lower expenditure to road construction? Or should they at present in some way charge the transport industries for the increase in road repair costs and the decrease in safety due to their strategy shift from sea transports?

Thorough cost benefit analysis could answer most of those questions and should certainly be committed. It should be done by an independent organization and by a group of specialists that is as broad as possible, so all relevant factors will be considered. Homogenous groups are more likely to miss certain aspects of the analysis than a diverse one.

9 Discussion and conclusions

9.1 Discussion

This report discussed three possible fire scenarios at the oil depot in Örfirisey. To evaluate the possible risk from the operation to its nearby population, frequency and consequences of those scenarios were estimated with the help of the Chemical Process Quantitative Risk Analysis model (CPQRA).

It is clear that a fire is the largest threat for the oil depot in Örfirisey. A few possible ways for a fire to break out have been accounted for and some of them are more probable than others.

The energy release can be enormous for the scenarios analyzed and in cases of fires in some of the storage tanks, extinguishing them will certainly be a challenge for CDFRS and demand much manpower, equipment, good knowledge and well organized plans, water availability and foam.

In case of fire in one of the two loading docks the main damage is to the fuel truck itself and the loading dock. It is not considered to affect nearby surroundings to a large degree, though the smoke might spread to nearby populated areas. Employees would be in greatest danger because of the fire radiation, but would probably be able to get to a safe distance from the fire soon after it starts.

In a situation where one or two storage tanks are burning it was calculated that they would probably not set other tanks on fire and thereby mostly causing damage to themselves. It is assumed that the cooling process has started before the fire has had the chance to warm up the surrounding tanks enough for ignition. Radiation caused by such a fire could threaten employees around the tanks if they could not get to a safe distance from the fire perimeter in time.

When the whole depot is on fire great energy will be released, probably in excess of 45 GW. The radiation from that kind of a fire is of concern for those working at the depot area and within 50-100 meters from the outer bounds of the depot, since people in the vicinity could suffer burn wounds or even die. It should though be mentioned that the whole depot will probably not be set all on fire at once which gives those individuals some time to get to a safe distance. Buildings further away could be set on fire because of the radiation. The nearby population 900 meters away will not suffer from the radiation because of the distance but would probably be affected by the smoke if the wind is blowing towards the city.

According to ODR, their trucks are only causing one accident per year or the probability of 2% per truck compared to 11% for other similar sized trucks in traffic. That number is based on observations over the last ten years at ODR. This year there have already been two severe accidents involving ODR trucks, which leads to the conclusion that this number of 2% can be questionable over a longer periods of time. Therefore is it estimated that the probability for an ODR truck to have an accident is somewhere between 2-11%, which is considered more realistic based on the known statistics.

Transportation of fuel by trucks is increasing every year because of increasing market demand. That increases the exposure of those trucks in traffic, and by that increasing the frequency of fuel transportation. When the frequency increases the risk becomes larger and people living or working on the transportation route are in more danger. The degree of tolerability for those individuals has not been accounted for in this report but it should be considered that those individuals are put in more danger than others by the transportation.

The most probable factor affecting the nearby surroundings is the concentration of smoke from the fire. The smoke can easily travel a long distance over the landmass but the concentration is diluted by the air as it travels further away from the source, making populated areas less vulnerable to smoke contamination because of depot fire. The compounds found in the smoke can cause health problems, especially when the exposure time is as long as the case would be if the whole depot is burning. Because of that it is very likely that the population of a large area would have to be evacuated from their facilities to some other place not affected by the toxic smoke. This number of people could go as high as 30.000 individuals.

The depot is not considered to be of any major threat for the nearby population. A major fire in one storage tank is estimated to occur every 220 years which might be considered a large interval, but it is estimated that the CDFRS can extinguish or control a fire of this. A large scale fire of that type when the whole depot is on fire is assumed to happen every 1100 years as can be seen in section 4.4. Even if that kind of fire occurs it must be considered that the nearby population is not in a major crisis since respond teams should be able to move the population away from the smoke before it would or could do any major harm. The smoke would on the other hand probably damage much of the housing stock etc. where the plume could level at ground after traveling in air for some time.

9.2 Conclusion

The work carried out here suggests that the depot itself is not a major threat to the people of Reykjavík. The radiation from a large fire in the depot is only causing injuries to the ones working within the depot area or in the immediate vicinity. It is however clear that a large fire would cause problems for the residents of Reykjavík due to smoke distribution over the city. By evacuating some houses, the risk that the smoke creates for lives would be eliminated or minimized. Property damage would probably result from the smoke.

During the progress of this work, it became apparent that it is necessary to lower the number of leakages from the tanks and overfilling of the transportation trucks. The probability of any fire breaking loose is too high because of those leakages and the risk for those individuals located at the area far too high compared to the given criteria both for the individual risk and the societal risk. It has been stated that if a fire occurs the nearby surroundings is not considered in real danger. That on the other hand, is an estimation. If a fire occurs the fire protection system is estimated to extinguish the fire in its early stages, before it can do any major harm to people and surroundings.

Moving the depot from its current location would be costly and probably not feasible if it would be based solely on the risk to the nearby population. The risk of fire is too high today and it should be reduced by lowering the frequency of leakages. There has never been a fire incident at the depot so far, but that does not mean that it is impossible. The frequency of a leakage at the loading rack in Örfirisey is 20 times more common than data from OK-Q8 indicates [16].

The risk caused by ODR trucks in traffic is not very alarming based on numbers from ODR. The frequency for an accident to occur was said to be one accident annually for their fifty trucks or 2% per truck, compared to 481 accidents for 4.533 other trucks above 5 tons, or about 11% per truck. These accidents have the return period of 12 years and 66 years respectively. The data from ODR is limited to ten years and merely ten observations. Two accidents this year, including one where several tons of gasoline were released, do change this statistic to some degree and should lead to the conclusion that the probability for an accident is somewhere between 2-11% per truck annually. Exposure of those trucks in traffic is increasing and thereby the frequency.

It is recommended that transportation of the fuel outside the capital area should not be through the city of Reykjavík. Transportation to nearby towns is responsible for much of the heavy vehicle traffic on Icelandic highways, and there the speed is usually higher than within the city perimeter. That and the fact that the number of transports are increasing each year, increases the probability of a traffic accident to take place. Those transportations could at least be reduced by 20% if the storing tanks in Helguvík (Reykjanesbær) would be used for storing the fuel for the international airport in Keflavík. Those tanks could also be used for the nearby population for storing fuel that is most commonly used. Fuel types that are not so widely used would probably be transported from the main depot because of high storing cost in Helguvík. Other depots for the western and southern parts of Iceland could also be taken into operation, reducing hazardous traffic through Reykjavík city center and sensitive areas such as the Hvalfjörður tunnel and water protection areas.

However, setting up other depots would probably reduce the transportation risks considerably, but could be a very costly operation. A thorough cost-benefit analysis as well as risk analysis, of such an action would need to be conducted before any clear statement of the benefits and drawbacks can be made.

10 References

1. Umhverfisráðuneytið (1998). "Reglugerð um hættumat í iðnaðarstarfsemi, 263/1998" (Directives regarding hazard analysis in industrial operation), Iceland.

2. Persson, H.; Lönnermark, A. (2004). "Tank fires – Review of fire incidents 1951-2003", SP Provnings Forskning, SP report 2004:14, Borås, Sweden.

3. Olíudreifing ehf. (2005). "Stefnumarkandi skjal fyrir olíubirgðastöðvar Olíudreifingar ehf." (Compulsory declaration for ODR oil depots), Reykjavík, Iceland.

4. Finnson, B. (2005-6). Asst. fire chief at CDFRS, e-mail 14.02.06 and interviews 2005.

5. Janek, P. (2005). "Explosion and fire at storage depot in Gdansk refinery", Slideshow received from the Icelandic Administration of Occupational Safety and Health in January 2006.

6. Olíudreifing ehf. (2005). "Handbók ökumanns." (Drivers manual for ODR drivers), Reykjavík, Iceland.

7. Guðjónsson G. (2005-6). Environmental engineer at ODR, e-mail and interview, Reykjavík, Iceland.

8. Sigurðsson, H. (2005). Organizer at the city of Reykjavík (Skipulags- og byggingarsvið), e-mail 30.11 2005, Reykjavík, Iceland.

9. International Electrotechnical Commission (1995). "International Standards, Dependability management – part 3: Application guide – Section 9: Risk analysis of technological systems", Genéve, Suisse.

10. American Institution of Chemical Engineers (1989). "CPQRA – Guidlines for Chemical Process Quantitative Risk Analysis", New York, USA.

11. Ingvarson, R.; Roos, A. (2003). "Metoder för risk-och sårbarhetsanalys", Report 5113, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

12. Vegagerðin (2000). "Snjóflóðahætta við munna jarðganga um Héðinsfjörð" (Danger caused by avalanches at tunnel openings at Héðinsfjörð – The Icelandic Road Administration), Reykjavík, Iceland.

13. Elvik. R., (1999). "Can injury prevention efforts go too far? Reflections on some possible implications of Vision Zero for road accident fatalities", Accident Analysis and Prevention 31, page 265-286.

14. Gudmundson A. (2004). “Lectures the fall 2004 and reading material related to the course in Människa, Teknik, Organisation och hantering av Risker (MTOR)”, Lund, Sweden.

15. Rúriksson H. (2006). Sergeant in the Reykjavík domestic airport flight tower, interview by phone in January 2006.

16. Bjerke, T.; Christiansson, J. (2001). “Riskanalys av oljedepån Lucerna I Västervik”, Report 5086, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

17. Karlsson, B.; Quintiere J. (2000). “Enclousure Fire Dynamics”, CRC Press LLC, New York.

18. NFPA (1991). “Fire Protection Handbook – Seventeenth edition”, Quincy, USA.

19. Ingason H. (1994). “Small scale test of a road tanker fire”, SP (Swedish National Testing and Research Institute – Fire Technology), Borås, Sweden.

20. Fire Protection Association (2006). “Fire Prevention, Fire Engineers Journal March 2006 – Blast resistance”, London, U.K.

21. Fischer, S.; Forsén, R.; Hertzberg, O.; Jakobsson, A.; Koch, B.; Runn, P.; Thaning, L.; Winter, S. (1997). “Vådautsläpp av brandfarliga och giftiga gaser och vätskor”, Försvarets Forskningsantalt (FOA), Stockholm, Sweden.

22. Auðunsson, T. (2005). “Skilgreining áhættumælikvarða (FAR) fyrir umferðaröryggi á Íslandi, Rannsóknarráð umferðaröryggismála” (Definition for risk measurement regarding traffic safety on Iceland), Reykjavík, Iceland.

23. Orion Ráðgjöf (2005). “Slysatíðni vöru- og hópbifreiða, Rannsóknarráð umferðaröryggismála” (Accident frequency for trucks and people transportation trucks), Reykjavík, Iceland.

24. Andersson, B.; Andersson, P. (1996). “Manual till datorprogrammet GASOL”, Report 3084, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

25. The Icelandic Administration of Occupational Safety and Health (1999). “Reglur um mengunarmörk og aðgerðir til að draga úr mengun á vinnustöðum”, stjtíð. B 19 nr.154/1999.

26. Jónasdóttir, E. (2005). Meteorologist at the Icelandic Meteoroligical Office, e-mail 07.18.05.

27. Clark, K. (2001). “Tolerability and Acceptable Risk Establishing Quantitative Targets for the Hydrocarbon/Petrochemical/Chemical (HPC) Industry”, Safety Users Group, U.S.A.

28. Rosberg, J.; Thorsteinsson, D. (2002). “Environmental and health risk management for road transportation of hazardous material”, Report 5114, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden

29. Guðjónsson, G. (2000). “Mengunarhætta af umferð um Reykjanesbraut og Grindavíkurveg (Pollution risk from traffic on Reykjanesbraut and Grindavíkurveg)”, Olíudreifing, Iceland.

30. Pálsson, G. (2004). “Risk Management in Hvalfjörður Tunnel”, Report 5136, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

31. Briggs, A.H. (2001). “A bayesian approach to stochastic cost-evvectiveness analysis”, International of Journal of Technology Assessment in Healt Care 17:1, 69-82, Cambridge University Press.

32. Drysdale, D. (2002). “An Introduction to Fire Dynamics, second edition”, John Wiley & sons, Chicester, England.

33. Gojkovic D. (2004). “Formelsamling för värmetransportdelen i kursen Brandkemi, VBR 022”, Brandteknik, Lund, Sweden.

34. Gojkovic, D. (2004). “Tabellsamling – Brandkemi (VBR022)”, Brandteknik, Lund, Sweden.

35. Jones, L.; Atkins, P. (1999). “Chemistry – Molecules, Matter, and Change, fourth edition”, W.H.Freeman and Company, New York, USA.

36. Brandteknik (2002). “Brandskyddshandboken, En handbok för projektering av brandskydd i byggnader”, Brandskyddslaget och Brandteknik vid LTH, Lund, Sweden.

Web pages:

a. http://www.raddningsverket.se/templates/SRV_SearchPage____16027.aspx?quicksearchquery=skum

b. http://www.engr.mun.ca/~fkhan/EN-6601/risk%20calc.doc

c. http://www.planecrashinfo.com/cause.htm

d. http://www.shellchemicals.com/msds/1,1098,1136,00.html

e. http://www.mfb.is/byggidn/Januar2003/greinar_2003_5.html

f. http://www.hanford.gov/fire/safety/hm_firefacts.htm

g. http://en.wikipedia.org/wiki/Acetic_acid

h. http://en.wikipedia.org/wiki/Acrolein

i. http://en.wikipedia.org/wiki/Carbon_dioxide

j. http://en.wikipedia.org/wiki/Carbon_monoxide

k. http://en.wikipedia.org/wiki/Nitrogen_oxides

l. http://www.hcdoes.org/airquality/monitoring/so2.htm

m. http://en.wikipedia.org/wiki/Volatile_organic_compounds

n. http://en.wikipedia.org/wiki/Particulates

o. http://www.cdc.gov/niosh/idlh/idlhintr.html#CNU

p. http://fire.nist.gov/aloft/

q. http://www.hse.gov.uk/comah/assessexplosives/step5.htm

r. http://www.almannavarnir.is/

s. www.mats.is (Photo © Mats)

t. http://www.dot.ca.gov/hq/tpp/offices/ote/Benefit_Cost/index.html

Appendix A : Details on the fuel tanks on the island

The tables here below show the fuel type in each tank in the island, its volume, diameter and area. That information is important when it comes to the heat release calculation later on.

ODR tanks

Petroleum	Tank no.	Volume (m^3)	Tank diameter (m)	Area (m^2)
Fuel oil	1	3.875	18,3	262,9
Waste oil	2	2.860	18,3	262,9
Diesel oil	3	7.010	24,38	466,6
Diesel oil	4	6.970	24,36	465,8
Diesel oil	5	8.176	25,43	507,6
Diesel oil	7	3.990	19	283,4
Fuel oil	8	1.100	9,56	71,7
Waste oil	9	70	5,57	24,4
Waste oil	10	80	5,78	26,2
Waste oil	10A	180	5,78	26,2
Gasoline	11	8.220	25,43	507,6
Gasoline	12	2.400	15,88	198,0
Gasoline	13	1.600	13,72	147,8
Gasoline	14	4.015	17,81	249,0
Gasoline	15	9.216	28,6	642,1
Diesel oil	16	5.945	25	490,6
Diesel oil	17	5.934	25	490,6

Table 11. Tanks owned by ODR in Örfirisey.

Shell tanks

Petroleum	Tank no.	Volume (m^3)	Tank diameter (m)	Area (m^2)
Diesel oil	1	7.700	24,35	465,4
Diesel oil	2	7.700	24,35	465,4
Jet A1	3	7.900	24,8	482,8
Diesel oil	4	3.200	17,46	239,3
Diesel oil	5	270	7,63	45,7
JET A-1	6	7.900	24,8	482,8
Fuel oil	7	7.900	24,8	482,8
Diesel oil	8	7.900	24,8	482,8
AVGAS 100 LL	9	1.900	14,22	158,7
Gasoline	10	3.500	17,83	249,6
White spirit	11	1.300	12,01	113,2
Gasoline	12	8.200	25,46	508,8
Waste oil	13	210	6,68	35,0
Waste oil	14	280	6,68	35,0
Jet A1	15	5.200	20,37	325,7

Table 12. Tanks owned by Skeljungur in Örfirisey.

Appendix B : Fuel compartments at the depot

Five different compartments are found in the peninsula which is meant to prevent a leakage at one boundary from flowing to the next one. Bundles of tanks are within each boundary and they are accounted for here below.

Gasoline boundary	Volume (m^3)	Tank diameter (m)	Area (m^2)
Shell 8	7.900	24,8	483,1
Shell 9	1.900	14,22	158,8
Shell 10	3.500	17,83	249,7
Shell 11	1.300	12,01	113,3
Shell 12	8.200	25,46	509,1
ODR 11	8.220	25,43	507,9
ODR 12	2.400	15,88	198,1
ODR 13	1.600	13,72	147,8
ODR 14	4.015	17,81	249,1
ODR 15	9.216	28,6	642,4
Total	48.251	195,8	3.259,3

Table 13. Tanks within gasoline boundary.

West boundary	Volume (m^3)	Tank diameter (m)	Area (m^2)
Shell 15	5.200	20,37	325,9
ODR 16	5.945	25	490,9
ODR 17	5.934	25	490,9
Total	17.079	70,4	1.307,6

Table 14. Tanks within west boundary.

East boundary	Volume (m^3)	Tank diameter (m)	Area (m^2)
ODR 5	8.176	25,43	507,9
Total	8.176	25,43	507,9

Table 15. Tank at east boundary.

Shell diesel boundary	Volume (m^3)	Tank diameter (m)	Area (m^2)
Shell 1	7.700	24,35	465,7
Shell 2	7.700	24,35	465,7
Shell 3	7.900	24,8	483,1
Shell 4	3.200	17,46	239,4
Shell 5	270	7,63	45,7
Shell 6	7.900	24,8	483,1
Shell 7	7.900	24,8	483,1
Total	42.570	148,2	2.665,7

Table 16. Tanks within diesel boundary.

ODR/Shell diesel boundary	Volume (m^3)	Tank diameter (m)	Area (m^2)
ODR 1	3.875	18,3	263,0
ODR 2	2.860	18,3	263,0
ODR 3	7.010	24,38	466,8
ODR 4	6.970	24,36	466,1
ODR 7	3.990	19	283,5
ODR 8	1.100	9,56	71,8
ODR 9	70	5,57	24,4
ODR 10	80	5,78	26,2
ODR 10a	180	5,78	26,2
Shell 13	210	6,68	35,0
Shell 14	280	6,68	35,0
Total	26.625	144	1.961

Table 17. Tanks within ODR/Shell diesel boundary.

Boundary	Volume (m^3)	Tank area (m^2)	Boundary area (m^2)	Total area (m^2)
Gasoline boundary	48.251	3.259	8.348	11.607
West boundary	17.079	1.308	4.650	5.958
East boundary	8.176	508	1.672	2.180
Shell diesel boundary	42.570	2.666	2.041	4.707
ODR/Shell diesel boundary	26.625	1.961	5.416	7.377

Table 18. Total amount of fuel, tank area, boundary area and total area at each boundary.

Appendix C : Fire at the loading rack

C.1 Energy release at the loading rack

The energy available from a pool fire is calculated according to the equation [17]:

$$\dot{Q} = A_f \, \dot{m}'' \chi \Delta H_c \qquad \text{[Eq.C-1]}$$

Where

A = Area of the pool fire (77,26 m^2 is the area needed for HRR=130MW, which is the most probable HRR for this fire according to @RISK)

$\dot{m}''$ = Mass burn rate per area (0,055 kg/m^2s)

χ = Combustion efficiency (0,7 will be used for gasoline)

ΔH_c = Heat of combustion (43,7 MJ/kg for gasoline)

The heat release rate for this scenario is then:

$$\dot{Q} = 77{,}26 m^2 \cdot 0{,}055 kg / m^2 s \cdot 0{,}7 \cdot 43{,}7 MJ / kg = 130 MW$$

The energy from pool fires can vary depending on the size of the pool. The effects of larger pool can be seen in Table 19.

Area of pool (m^2)	Diameter of pool (m)	Burning rate (kg/s)	Heat release rate (MW)
50,0	8,0	2,8	84,1
60,0	8,7	3,3	100,9
70,0	9,4	3,9	117,8
80,0	10,1	4,4	134,6
90,0	10,7	5,0	151,4
100,0	11,3	5,5	168,2
150,0	13,8	8,3	252,4

Table 19. Relation between the area and the heat release rate.

C.2 Heating of the gasoline tanker

It is of interest to know if the energy release rate described above is enough to cause ignition of the gasoline tank on the truck. For that to happen the temperature within the tank needs to reach the auto ignition temperature of 420°C, which is the minimum temperature which the vapor/air mixture over a liquid spontaneously catches fire. The vapor/air mixture must also be of right proportion since the flammability limits of gasoline are from 1,3 – 7,9 % [32].

The fact that aluminum has a melting point of 640°C is something worth taking into those considerations. When the temperature reaches this degree the tank begins to melt on its outer boundaries, by that weakening its strength to some degree. Eventually the tank will burst if the heat is enough and the fuel found inside the tank feeds the fire further.

The gasoline tank is never exactly full and therefore there is always some space with vapor/gas mixture found at the top of the tank. Therefore the gasoline fumes can warm up to this temperature, increasing the possibility of ignition or a possible explosion of the tank because of the increased pressure.

To calculate the time it takes for the temperature to reach 420°C the method of lumped heat capacity [33] will be used. It is assumed that the total mass of the gasoline tank consist only of aluminum and not considering the time it takes for the mass of the gasoline to warm up to this temperature.

$$\frac{\left(T - T_g\right)}{\left(T_0 - T_g\right)} = e^{\frac{-t}{t_c}} \qquad \text{[Eq. C-2]}$$

Where

T = Temperature at certain distance within the object (420 °C)

T_0 = Surrounding temperature (7 °C)

T_g = Flame temperature (800°C)

t = Time (s)

t_c which is the time constant for the system (s), is calculated according to the equation:

$$t_c = \frac{c \cdot \rho \cdot d}{h} \qquad \text{[Eq. C-3]}$$

Where the values for aluminum are

c = Specific heat capacity ($0{,}896 \cdot 10^3$ J/kgK)

ρ = Density (2.707 kg/m^3)

d = Thickness of the tank (0,005 m)

h = Heat transfer coefficient (100 W/m^2K)

k = Thermal conductivity (249 W/mK)

This method is only valid if Bi is equal to or less than 0,1

$$Bi = \frac{hd}{k} \leq \frac{100W/m^2K \cdot 0{,}005m}{249W/mK} = 0{,}02 \leq 0{,}1 \qquad \text{[Eq. C-4]}$$

The method is valid according to this.

C.2.1 Scenario calculation

Calculations according to the previously described method can now be done.

$$t_c = \frac{c \cdot \rho \cdot d}{h} = \frac{\left(0{,}896 \cdot 10^3 J/kgK\right) \cdot 2707kg/m^3 \cdot 0{,}005m}{100W/m^2K} = 121{,}3s$$

This will be put in eq. C-2 to estimate the time it takes for the aluminum to be heated to 420 °C. The Celsius scale (°C) will be used instead of the Kelvin scale (K) in the following calculations.

$$\frac{(420°C - 800°C)}{(7°C - 800°C)} = e^{\frac{-t}{121{,}3}} \Rightarrow t = 89{,}2s$$

Duration of this pool fire needs to be known to see if it exceeds this time. It is assumed that 400 l of gasoline are spilled at the loading place. The density of the gasoline is 745 kg/m^3 and therefore the total mass of the fuel is 298 kg. Total mass rate is dependent on the pool area and therefore is it:

0,055 kg/m^{2}s * 77,26 m^2 = 4,25 kg/s

The duration of the fire is therefore 70,1 seconds which is not enough to warm up the tank for ignition.

The time it would take for the aluminum to reach 640°C is 194,2 s according to eq. C-2. The leakage volume is certainly not enough to withstand the fire for this period of time and therefore not of further interest.

This method does not take under consideration that inside the tank is a mass of fuel that slows down the heating process of the aluminum it self by cooling down that side of the tank. The critical temperature needed to equal the fire duration time is about 900°C. This means that the temperature has to be at least 900°C to be able to cause any problem and by that ignoring few other factors that also affects cooling of the tank.

Table 20 demonstrates the relation between the time to ignition and the flame temperature outside the gasoline tank.

Temperatur T_g (°C)	1000	900	800	750	700	650	600	500
Time to ignition (s)	65,2	75,3	89,2	98,4	109,9	124,7	144,6	220,6

Table 20. Different values for ignition time depending on the flame temperature.

Those other cooling factors mentioned above are above all the wind. If the maximum theoretical temperature of this fire is 800°C then it is unlikely to be the real value also. Average wind speed in Reykjavík for the year 2005 was 4,1 m/s according to the Icelandic meteorological office, which should affect the temperature to some degree.

C.3 Radiation

Radiation must be considered to see its effect on the surroundings and to see if this kind of fire is able to set the nearby tanks on fire. The flame heights need to be accounted for to be able to calculate the view factor for the radiation.

But first the diameter of the pool is calculated.

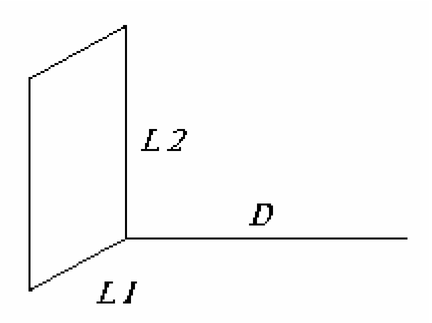
$$d = \sqrt{\frac{4 \cdot A}{\pi}} = 9{,}92\,m \qquad \text{[Eq. C-5]}$$

Where A is the area of the pool.

The flame height is calculated using the equation below [17].

$$L = 0.235\dot{Q}^{2/5} - 1.02D = 0{,}235 \cdot 130.000kW^{2/5} - 1{,}02 \cdot 9{,}92\,m = 15{,}98m \qquad \text{[Eq. C-6]}$$

By dividing this flame which is 15,98m * 9,92m into four equal rectangles the view factor can be found from various tables [34].



$$S = \frac{L_1}{L_2} = \frac{4{,}96}{7{,}99} = 0{,}621 \qquad \text{[Eq. C-7]}$$

$$\alpha = \frac{(L_1 \cdot L_2)}{D^2} = 0{,}0236 \qquad \text{[Eq. C-8]}$$

D in this equation is the distance to the nearest tank or Shell 15 which is about 41 m and its volume is 5200m^3, filled with Jet A1 airplane fuel, see Figure 25.

The partial view factor ϕ for this scenario is 0,007 and the total view factor is then 0,028.

Figure 29. Location of the gasoline loading rack in Örfirisey.

The heat flux can now be calculated.

$$\dot{q}'' = \phi \cdot \varepsilon \cdot \sigma \cdot T^4 \qquad \text{[Eq. C-9]}$$

Where

q" = Rate of heat transfer per unit area (kW/m^2)

ϕ = Total view factor

ε = Emissivity (value for steel 0,8 [32])

σ = Stefan Boltsman constant (5,67 * 10^{-8} W/m^{2}K^4)

T = Temperature in Kelvin (assumed to be 1073 K)

The flux on storage tank Shell 15 is:

$$\dot{q}'' = 0{,}028 \cdot 0{,}8 \cdot 5{,}67 \cdot 10^{-8} W/m^2K^4 \cdot 1073K^4 = 1684 W/m^2$$

This rate is only 1,68 kW/m^2 if the average flame temperature of 800°C is used, which is not considered very high. The temperature that this radiation creates on the outside of the tank can be calculated using equation C-10 [21]. Steady state is assumed in this relation.

$$\dot{q}'' = \sigma \cdot T^4 \qquad \text{[Eq. C-10]}$$

Equation C-10 gives us the temperature of 415 K or 142°C. This temperature is not able to warm up the nearby tank enough to set it on fire. If 900°C would have been used instead for the fire in the gasoline truck the temperature at the storage tank would only increase to 181°C, which does not either produce any real danger for the tank.

Table 21 shows how larger fire increases the temperature on the storage tank Shell 15. The fire is as before estimated to be at 800°C and is calculated up to about 250 MW.

Diameter of pool (m)	Flame height m)	Φ	q'' (W/m^2)	T_{tank} (°C)	Heat release rate (MW)
8,0	13,79	0,024	1.443	126	84,1
8,7	14,67	0,024	1.443	126	100,9
9,4	15,46	0,028	1.684	142	117,8
10,1	16,17	0,032	1.924	156	134,6
10,7	16,82	0,036	2.165	169	151,4
11,3	17,42	0,040	2.405	181	168,2
13,8	19,93	0,054	3.247	216	252,4

Table 21. Different temperature on Shell 15 in relation to different heat release rate.

Appendix D : Fire at the gasoline boundary

D.1 Energy release rate

The energy available from a pool fire is calculated according to the equation:

$$\dot{Q} = A_f \, \dot{m}'' \chi \Delta H_c \qquad \text{[Eq. C-1]}$$

Where

A = Area of the pool on fire (1000 m^2)

$\dot{m}''$ = Mass burn rate per area (0,055 kg/m^2s)

χ = Combustion efficiency (0,7 will be used for gasoline)

ΔH_c = Heat of combustion (43,7 MJ/kg for gasoline)

The heat release rate for this scenario is then:

$$\dot{Q} = 1000 m^2 \cdot 0{,}055 kg/m^2 s \cdot 0{,}7 \cdot 43{,}7 MJ/kg = 1{,}68 GW$$

As before the energy from the pool depends on the size of the pool. Values for larger pool and the heat release can be seen in Table 22.

Area of pool (m^2)	Diameter of pool (m)	Burning rate (kg/s)	Heat release rate (GW)
500	25,24	27,5	0,84
1.000	35,69	55	1,68
1.500	43,71	82,5	2,52
2.000	50,48	110	3,36
8.348	103,12	459,1	14,05
11.607	121,60	638,4	19,53

Table 22. Relation between the area and the heat release rate.

The two last values used for the area, is the boundary area and the boundary area with the total tank area for the gasoline boundary. This gives an idea of the total energy release if the whole area is on fire.

D.2 Heating of nearby tanks

In cases where the pool is as large as this one, other tanks are inevitable in danger. If this is a pool fire because of a leakage beside the tank, the pool obviously spreads over a large area making the fire more than possible to reach other nearby tank since the distance to the next tanks is from 14-20 meters.

The diameter of the pool has been estimated over 35 meters and by that saying that nearby tanks is in direct reach of the flames. It will be assumed here that tank ODR 12 is surrounded by flames since its diameter is little under 16 meters and the distance to it about 14 meters.

Again the temperature of 420°C is the critical one, meaning that if the gasoline reaches that degree an auto ignition occurs. The energy needed to warm up the gasoline in this particular tank to this critical temperature will be calculated to estimate the time it will take for a certain given energy release to do so [35].

$$q = m \cdot C_s \cdot \Delta T \qquad \text{[Eq. D-1]}$$

Where

q = Heat (kJ)

m = Mass of gasoline (kg)

C_s = Specific heat capacity (2,0 kJ/kg°C for gasoline)

ΔT = Change in temperature (°C)

The heat needed to warm the gasoline from 10°C which it is kept at, to 420°C is:

$$q = 1.788.000 kg \cdot 2{,}0 kJ/kg°C \cdot 410°C = 1{,}466 \cdot 10^9\ kJ$$

The heat release rate was earlier calculated 1,68 GW or $1{,}68 \cdot 10^6$ kJ/s. That gives us an estimation of 14,55 minutes to the point where gasoline in ODR 12 reaches the critical temperature of 420°C. Tank ODR 12 is the smallest one of those who is located next to the leaking tank Shell 12. The other ones who are larger need more time to reach that temperature since they are containing more volume.

Tank	Mass (kg)	Heat (kJ)	Time to ignition (min)
ODR 11	6.123.900	5.021.598.000	49,82
ODR 12	1.788.000	1.466.160.000	14,55
Shell 8	5.885.500	4.826.110.000	47,88
Shell 10	2.607.500	2.138.150.000	21,21

Table 23. Time to auto ignition for tanks near the fire.

In those calculations it is assumed that all the energy from the fire is being used to warm up the gasoline in the tank. That is of course not the case in real scenarios but is never the less used in the calculations. It must also be stated that the gasoline in the tank is not being mixed while this heating happens, which should slow the process down for some time. Other factors like cooling from surroundings are not either accounted for. What has been done here is an estimation of the minimum time to ignition or worst case scenario.

By using the lumped heat capacity method here would have given a solution with some degree of error. The fact that the flames have reached the nearby tanks does demand other methods like the one done here above. It is certain that the steel in the tanks will warm up and therefore was it more interesting to see how the fuel its self would respond to the calculated heat release or rather how much time we have before the next tank starts burning.

D.3 Radiation

Radiation from a fire like that can affect its surroundings. The radiation can possibly warm up other tanks further away to eventually set them on fire. The radiation has to be accounted for and as in Appendix C the flame heights has to be calculated in an attempt to find the view factor.

The diameter of the pool is calculated with equation C-4.

$$d = \sqrt{\frac{4 \cdot A}{\pi}} = 35{,}69\,m$$

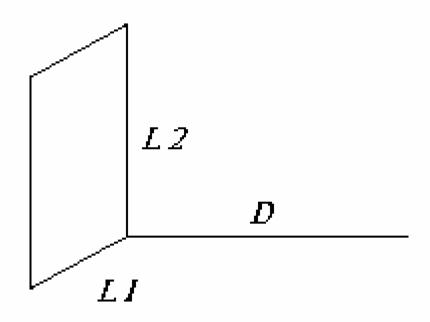
Where A is the area of the pool.

The flame height is calculated with the equation below.

$$L = 0.235\dot{Q}^{2/5} - 1.02D = 0{,}235 \cdot 1.680.000kW^{2/5} - 1{,}02 \cdot 35{,}69\,m = 36{,}24\,m \qquad \text{[Eq. C-6]}$$

According to the Brandskyddshandboken [36] the flame height for very large fires does probably not over rise 10-20 meters. That height is probably the correct one but the calculated flame height of 36,24 meters will be used to see the worst case scenario. If the fire would reach so far to the sky the radiation would be stronger than for a fire with lower flames.

The area of the flame which is 35,69 m * 36,24 m is divided into four equal rectangles to estimate the view factor.



$$S = \frac{L_1}{L_2} = \frac{17{,}85}{18{,}12} = 0{,}985$$

$$\alpha = \frac{(L_1 \cdot L_2)}{D^2} = 0{,}808$$

D in this equation is 20 m since that is the distance to Shell 10, ODR 13 and 14 from the fire, which had already reached ODR 12. It is of interest to see how those tanks respond to the radiation because of their proximity. Those three tanks contain gasoline with the volume of 3500 m^3, 1600 m^3 and 4015 m^3 respectively.

The partial view factor ϕ for this scenario is about 0,125 and the total view factor is then 0,5.

The heat flux can now be calculated.

$$\dot{q}'' = \phi \cdot \varepsilon \cdot \sigma \cdot T^4 \qquad \text{[Eq. C-8]}$$

Where

q" = Rate of heat transfer per unit area (kW/m^2)

ϕ = Total view factor

ε = Emissivity (value for steel 0,8)

σ = Stefan Boltsman constant ($5{,}67 * 10^{-8}\ W/m^2K^4$)

T = Temperature in Kelvin (1073 K)

The flux on storage tanks Shell 10, ODR 13 and ODR 14 is:

$$\dot{q}'' = 0{,}5 \cdot 0{,}8 \cdot 5{,}67 \cdot 10^{-8} W/m^2K^4 \cdot 1073K^4 = 30{,}1 kW/m^2$$

It is of interests to find out the temperature that this flux creates on the outside of the two tanks to see if ignition is possible. For that to happen the temperature must at least reach the critical temperature of 420°C.

$$\dot{q}'' = \sigma \cdot T^4 \qquad \text{[Eq. C-10]}$$

Equation C-10 gives us the temperature of 853 K or 580°C. This temperature is well above the critical temperature and therefore has the possibility of ignition in nearby tanks increased substantially.

Table 24 shows the relation between larger pool and increased heat flux on the storage tanks because of increased flame height. The temperature was 800°C.

Area of pool (m^2)	Diameter of pool (m)	Flame height m)	Φ	q" (kW/m^2)	T_{tank} (°C)	Heat release rate (GW)
200	16,0	21,90	0,22	13,5	425	0,34
350	21,1	26,22	0,30	18,0	478	0,59
500	25,2	29,34	0,36	21,6	513	0,84
1.000	35,7	36,28	0,50	30,1	580	1,68
1.500	43,7	40,90		34,6	611	2,52

Table 24. Relation between larger pool area and heat flux.

The value for 1.500 m^2 is not valid since the pool has reached the target tanks and view factors not appropriate anymore. To estimate the minimum time to ignition of the fuel, the lumped heat capacity method will be used.

$$\frac{(T - T_g)}{(T_0 - T_g)} = e^{\frac{-t}{t_c}} \qquad \text{[Eq. C-2]}$$

Where

T = Temperature at certain distance within the object (420 °C)

T_0 = Surrounding temperature (7 °C)

T_g = Flame temperature (580°C)

t = Time (s)

t_c which is the time constant for the system (s), is calculated according to the equation:

$$t_c = \frac{c \cdot \rho \cdot d}{h} \qquad \text{[Eq. C-3]}$$

Where the values for steel are

c = Specific heat capacity (460 J/kgK)

ρ = Density (7.800 kg/m^3)

d = Thickness of the tank (0,010 m)

h = Heat transfer coefficient (100 W/m^2K)

k = Thermal conductivity (45 W/mK)

This method is only valid if Bi is equal to or less than 0,1

$$Bi = \frac{hd}{k} \leq \frac{100W/m^2K \cdot 0{,}01m}{45W/mK} = 0{,}022 \leq 0{,}1 \qquad \text{[Eq. C-4]}$$

The method is valid according to this.

$$t_c = \frac{c \cdot \rho \cdot d}{h} = \frac{(460\,J/kgK) \cdot 7800kg/m^3 \cdot 0{,}01m}{100W/m^2K} = 359s \qquad \text{[Eq. C-3]}$$

$$\frac{(420°C - 580°C)}{(7°C - 580°C)} = e^{\frac{-t}{359}} \Rightarrow t = 458\ s \qquad \text{[Eq. C-2]}$$

That is the critical time we don’t want to exceed. After this time the steel in the storage tanks is estimated to be warm enough to conduct the heat through it and the fuel might reach its auto-ignition stage of 420°C, after certain period of time. This method would add 264 seconds to the time ODR12 would start burning if the flame temperature would be 800°C, see table 23.

Appendix E : Fire at the whole depot

E.1 Energy release rate

To estimate the energy release when the whole depot is on fire the equation for pool fire will be used again:

$$\dot{Q} = A_f \, \dot{m}'' \chi \Delta H_c \qquad \text{[Eq. C-1]}$$

Where

A = Area of the pool on fire (m^2)

$\dot{m}''$ = Mass burn rate per area (kg/m^2s)

χ = Combustion efficiency (0,7 will be used for all fuel types)

ΔH_c = Heat of combustion (MJ/kg)

Some properties for the petroleum products can be found in Table 25.

Petroleum	Density at 15°C (kg/m3)	Mass burning rate (kg/m^2s)	Heat of combustion (MJ/kg)
Gasoline	720-770	0,055	43,7
Diesel oil	800-880	0,044	44,4
Fuel oil	960-980	0,035	39,7
JET A-1	775-840	0,039	43,2
AVGAS 100 LL	700-720	0,055	43,7
White spirit	780	0,055	43,7
Waste oil	900	0,044	44,4

Table 25. Some properties for the petroleum products involved in the fire.

As the table demonstrates the values are close to each other for the different kinds of petroleum products, only minor deviation. Values for density in this thesis are the median of those numbers given in the table.

The heat release rate found in Table 26 is calculated for each and every boundary. Large majority of petroleum products in the boundaries are gasoline and diesel oil. The values for HRR are calculated from the properties of those two products for the whole area, even if the fuel was JET A-1 or some other product. It shouldn’t give large degree of error since the values for the petroleum properties are very similar as has been stated and also is the bulk majority of the petroleum in the island is either gasoline or diesel oil or 71,4% of the total amount.

Boundary	Volume (m^3)	Total area (m^2)	Mass burning rate (kg/m^2s)	Heat of combustion (MJ/kg))	Heat Release Rate (GW)
Gasoline boundary	48.251	11.607	0,055	43,7	19,32
West boundary	17.079	5.958	0,044	44,4	8,15
East boundary	8.176	2.180	0,044	44,4	2,98
Shell diesel boundary	42.570	4.707	0,044	44,4	6,44
ODR/Shell diesel boundary	26.625	7.377	0,044	44,4	10,09
Total	142.701	31.829			47,18

Table 26. Heat Release Rate for the different boundaries.

An estimation of the heat release rate is 47 GW according to this hand calculation. This is solely based on the fuel found in the island and therefore has nothing else been accounted for like burning houses etc.

E.2 Duration of the fire

To estimate the duration of the fire, the burning rate was calculated based on multiplication of the total area and the mass burning rate. The outcome gives an idea of the burning rate of fuel each second (kg/s) as can be seen in Table 27.

Boundary	Total area (m^2)	Mass burning rate (kg/m^2s)	Burning Rate (kg/s)	Heat Release Rate (GW)
Gasoline boundary	11.607	0,055	638,4	19,32
West boundary	5.958	0,044	262,2	8,15
East boundary	2.180	0,044	95,9	2,98
Shell diesel boundary	4.707	0,044	207,1	6,44
ODR/Shell diesel boundary	7.377	0,044	324,6	10,09
Total	31.829		1.528	47,18

Table 27. Burning rate of fuel in the boundaries.

The total or maximum amount of fuel found in the island each time is 117.300 tons. By dividing the total amount into the burning rate the fire is estimated to last for at least 76.766 seconds or 21,32 hours.

E.3 Radiation

Radiation must be accounted for to see its affect on the surroundings. In this case the surrounding is not other tanks but rather the operation around the depot. The depot is all on fire and nothing more there can burn.

The diameter of the pool is calculated with equation C-4.

$$d = \sqrt{\frac{4 \cdot A}{\pi}} = 201{,}3\,m$$

Where A is the area of the pool or total area of 31.829 m^2.

Flame height correlations according to equation C-6 will not be done here, since that formula is estimated to give to high value (85m). According to Brandskyddhandboken [36] the flame height for very large fires or fires with the diameter of about 100 meters, the flame height should be about 10-20 m for such fires. That is a very open assumption in the book, but on the other hand it does give certain clue of the height. The flames in Buncefield oil depot fire where estimated to be leaping 200 feet into the air [20]. That is of course the leaping height and the actual flame height is estimated to be around 30% lower.

Because of this the flame height used if everything is burning in the depot, is estimated not to be higher than 37 m (App.D, Table 25). It will be assumed that the flames doesn't go any higher than that since the mass burning rate in the middle of the fire decreases because of insufficient access to oxygen and also because of what has been said here before.

The view factor is found by using equation E-1 [21]:

$$F_{\max} = \sqrt{F_h^2 + F_v^2} = 0{,}1056 \qquad \text{[Eq. E-1]}$$

Where F_h is the horizontal radiation plan and F_v the vertical radiation plan. F_{max} is the maximum angle coefficient for the radiation. The fire is considered as a big cylinder.

Equation E-1 is could also been used for the scenarios found in Appendix C and D, and it does give similar values as are used there. On the other hand this equation has more possibilities especially if the diameter of the fire is large compared to its flame height, as is it is in this case.

D in this equation is 200 meters, but other values will also be considered in Table 28.

The heat flux can now be calculated.

$$\dot{q}'' = \phi \cdot \varepsilon \cdot \sigma \cdot T^4 \qquad \text{[Eq. C-8]}$$

Where

q" = Rate of heat transfer per unit area (kW/m^2)

ϕ = Total view factor

ε = Emissivity (value for steel 0,8)

σ = Stefan Boltsman constant (5,67 * 10^{-8} W/m^{2}K^4)

T = Temperature in Kelvin (1073 K)

The flux on steel cladding on building or something other in that distance from the fire is:

$$\dot{q}'' = 0{,}1056 \cdot 0{,}8 \cdot 5{,}67 \cdot 10^{-8} W / m^2 K^4 \cdot 1073 K^4 = 6{,}35 kW / m^2$$

The temperature created at that place is around 305°C according to equation C-10.

Distance to object (m)	Φ	q'' (kW/m^2)	T_{tank} (°C)
150	0,2342	14,08	433
200	0,1057	6,35	305
250	0,0599	3,60	229
500	0,0121	0,73	64
700	0,0058	0,35	7
1000	0,0028	0,17	-
1500	0,0012	0,07	-

Table 28. Different values for the flux depending on the distance.

Table 28 shows that the heat flux is not of any concern if the distance is greater than 500 meters from the outer perimeter of the fire.

E.4 Injuries to people

The distance from the fire is crucial when it comes to burn injuries because of radiation from the fire. The farther away from it the better it is. The radiation a person can withstand for a long period of time without getting burned is 1 kW/m^2. Radiation of 2 kW/m^2 can be withstood for up to one minute and 20 kW/m^2 for less than two seconds [21].

Distance to object (m)	Φ	q'' (kW/m^2)	T_{tank} (°C)	t*q''$^{4/3}$ (*10^6)	Percentage of 2nd degree burn
1	0,6241	37,53	629	18,846	100
5	0,5945	35,74	618	17,662	97,5
10	0,5430	32,65	598	15,654	94
15	0,4881	29,35	575	13,578	85
20	0,4365	26,25	552	11,701	80
30	0,3492	21,00	507	8,690	58
40	0,2822	16,97	197	6,539	25
50	0,2313	13,91	431	5,016	7
100	0,1048	6,30	304	1,745	-
150	0,0595	3,58	228	0,820	-
200	0,0383	2,31	176	0,457	-
250	0,0268	1,61	137	0,283	-
300	0,0198	1,19	107	0,189	-
400	0,0121	0,72	63	0,098	-
500	0,0081	0,49	32	0,058	-
800	0,0044	0,26	-	0,025	-

Table 29. Burn injuries on people caused by the radiation.

To calculate the number dead because of the radiation the total number of those who got 2nd degree burn must be accounted for. It is estimated that 15% of those individuals will die because of their injuries.

Appendix F : Transportation of the fuel

F.1 Vehicles on Iceland

Total number of vehicle on Iceland the year 2004 was 200.224. This number contains all passenger vehicles, trucks, transportation vehicles, busses and motorcycles. All trucks are only about 4,3% of the total number and ODR trucks are much smaller fraction or about 0,025%.

Location	All vehicles	All transportation trucks	Total driven km for all trucks	Ratio all trucks/all vehicles	Ratio ODR trucks/all vehicles
Capital area	126.951	4.352	163.134.720	0,0343	0,000394
Suðurnes	10.069	460	17.243.100	0,0457	0,004966
Vesturland	9.744	638	23.915.430	0,0655	0,005131
Vestfirðir	4.742	307	11.507.895	0,0647	0,010544
Suðurland	14.656	924	34.636.140	0,0630	0,003412
Norðurland west	6.648	437	16.380.945	0,0657	0,007521
Norðurland east	16.176	666	24.965.010	0,0412	0,003091
Austurland	8.407	632	23.690.520	0,0752	0,005947
Unknown address	2.831	180	6.747.300	0,0636	0,017662
Total	200.224	8.596	322.221.060	0,0429	0,000250

Table 30. Ratio of all trucks to vehicles on Iceland.

Transportation trucks on Iceland are estimated to be driven 37.485 km [22]. That will also be used for ODR trucks in this project. Transportation trucks here are trucks less than 5 tons, equal or over 5 tons and those above 12 tons.

F.2 Loadings over the year

The total volume of fuel that goes through the island over the year is about 430.000 m^3. That has to be divided by the capacity of the petroleum trucks to find out the total loadings over the year.

Petroleum	Volume (m^3)	24 m^3	30 m^3	35 m^3	40 m^3
Gasoline	111.453	4.644	3.715	3.184	2.786
Diesel oil	194.385	8.099	6.480	5.554	4.860
Fuel oil	38.625	1.609	1.288	1.104	966
JET A-1	63.000	2.625	2.100	1.800	1.575
AVGAS 100 LL	5.700	238	190	163	143
White spirit	3.900	163	130	111	98
Waste oil	11.040	460	368	315	276
Total	428.103	17.838	14.270	12.232	10.703

Table 31. Number of loadings for the trucks depending on tank sizes.

As can be seen from the table, the petroleum trucks are loaded between 10.700 and 17.800 times over the year, depending on their tank capacity. The average value of 32 m^3 will be used for calculation in this relation.

F.3 Frequency of accidents

When the frequency of accidents in Iceland is considered, numbers where gathered for the years 2001 to 2004. Those numbers show all accidents over the period independent of their severity. Those who are classified as major ones are the ones where people are killed and/or seriously injured. Minor accidents are where people get away with minor injuries. The third category is the one where no one is hurt and only property damage is involved. The accidents in Table 32 are distributed over the whole week and occur at all times over the day. The percentage ratio in the table will be used for ODR accidents in later on calculations.

Traffic accidents	2004	2003	2002	2001	Average	Ratio (%)
Major accidents	117	140	152	147	139	1,7%
Minor accidents	693	667	855	716	733	9,1%
Only property damages	7848	7145	6825	6976	7199	89,2%
Total	8658	7952	7832	7839	8070	100,0%

Table 32. Total number of traffic accidents on Iceland 2001-2004.

Thorough analysis of where each accident happened has not be done, nor at what time of the day. It must be noted that the ODR trucks are probably not much in use during nighttime and over weekends, but it is hard to say if all the other heavy trucks are too. It is customary to express the number of accidents as a part of million vehicle kilometers and that will be the case in this report. The units used are called FAR (Fatal Accident Rate) and NFAR (None Fatal Accident Rate).

This method is considered one of the best when analysis of the traffic is done. That is because the method does not consider the user to know how the individual died or got injured, only the number of injured individual and the total driven kilometers that particular year. In this case we are looking at the total number of accidents by that using both FAR and NFAR numbers in the calculation.

If all vehicles are about 200.224 and we have an average of 8.070 accidents every year, then it can be stated that the probability for a vehicle to have some kind of accident is 4,03% over the year.

It is known for trucks above 5 tons that they where involved in almost 6% of all accidents over the period of 2001 to 2004 [23], or a total of 483 accidents. Because of that knowledge the information found in Table 32 regarding the accidents ratio, has been updated to get a clearer view of actual accidents caused by those trucks. The updated numbers where used for calculation of traffic accidents per million vehicle kilometers in Table 33.

The method used for calculating the accidents per million kilometers was as follows:

$$Accidents\ per\ million\ km = \frac{Known\ \ traffic\ \ accidents}{Driven\ million\ km\,(vehicle\ km)} \cdot 10^{6}$$

Vehicles	All vehicles	Trucks >5 t	ODR trucks
Number of vehicles	200.224	4.533	50
Total driven km	2.008.839.455	169.919.505	1.874.250
Major accidents per million km	0,0651	0,0489	0,0092
Minor accidents per million km	0,3430	0,2577	0,0484
Only property damages per million km	3,3692	2,5321	0,4759
Total	3,7773	2,8387	0,5335

Table 33. Traffic accidents per million vehicle km.

The frequency for ODR fuel trucks is only one accident over the year according to Guðjónsson at ODR. That is the statistic that will be used for the fuel trucks from ODR in this thesis. As can be seen in Table 33 the total number of accidents per million vehicle km are about five times less for ODR trucks compared to other similar trucks.

F.4 BLEVE calculations

To estimate the size of the fire ball, the following equation was used:

$$D_{Max} = 6,46 * m^{0,325}$$

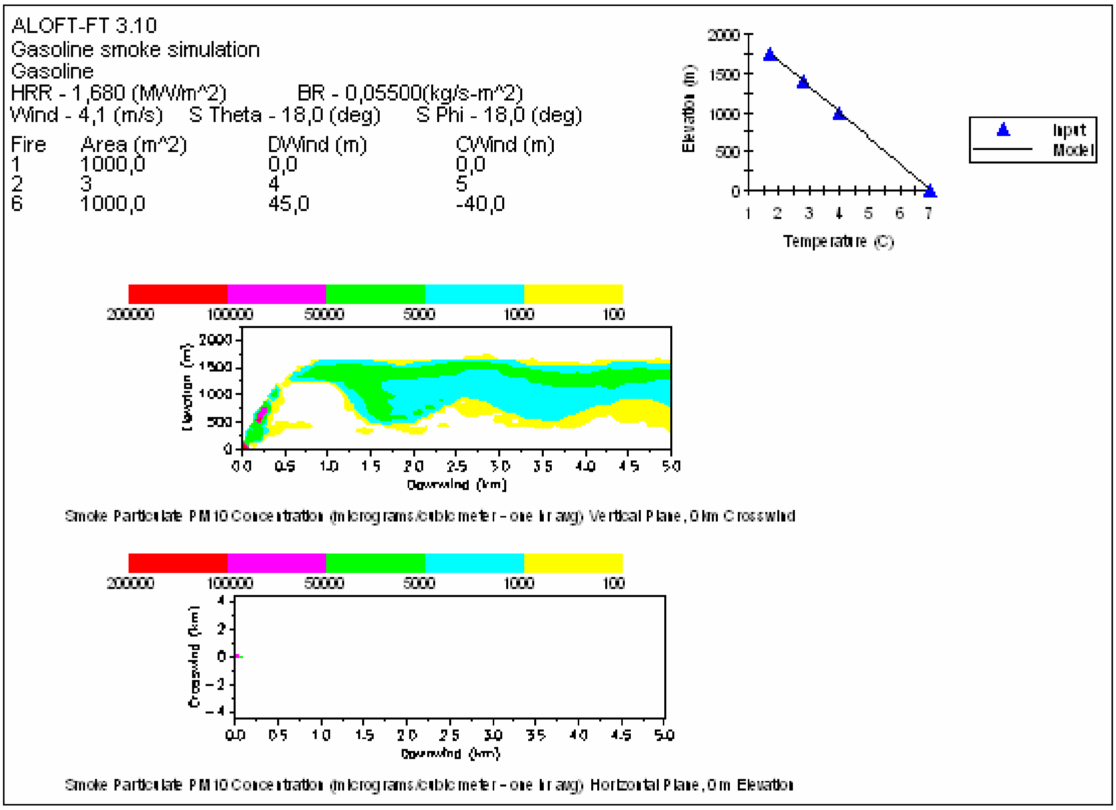
Where

D = Maximum diameter (m) of the fire ball

m = Mass of fuel (kg)

Appendix G : ALOFT results

The results from ALOFT can be found in this appendix. The concentration differs depending on the substance involved. The colors in the figures demonstrate different strength of concentration of the chemicals involved.



ALOFT-FT 3.10
Gasoline smoke simulation
Gasoline
HRR - 1,680 (MW/m^2)   BR - 0,05500(kg/s-m^2)
Wind - 4,1 (m/s)   S Theta - 18,0 (deg)   S Phi - 18,0 (deg)

Fire	Area (m^2)	DWind (m)	CWind (m)
1	1000,0	0,0	0,0
2	3	4	5
6	1000,0	45,0	-40,0

Figure 30. ALOFT summary.

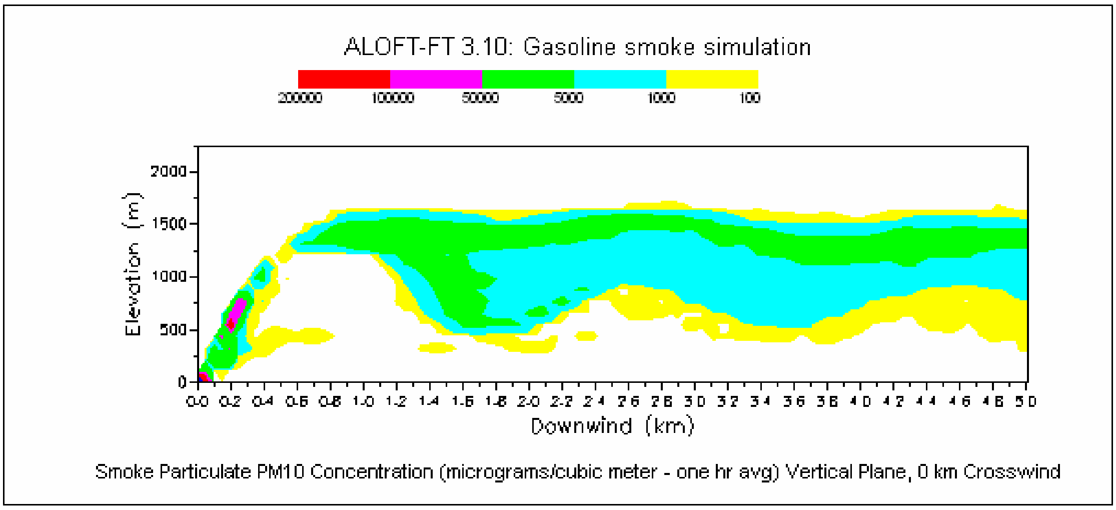


Figure 31. Vertical profile of PM10 concentration.

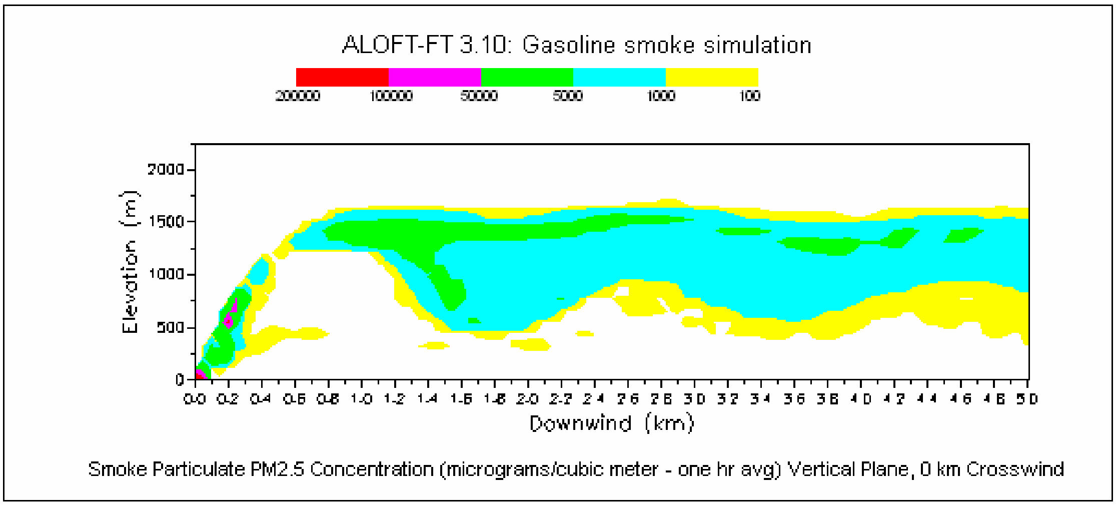


Figure 32. Vertical profile of PM2,5 concentration.

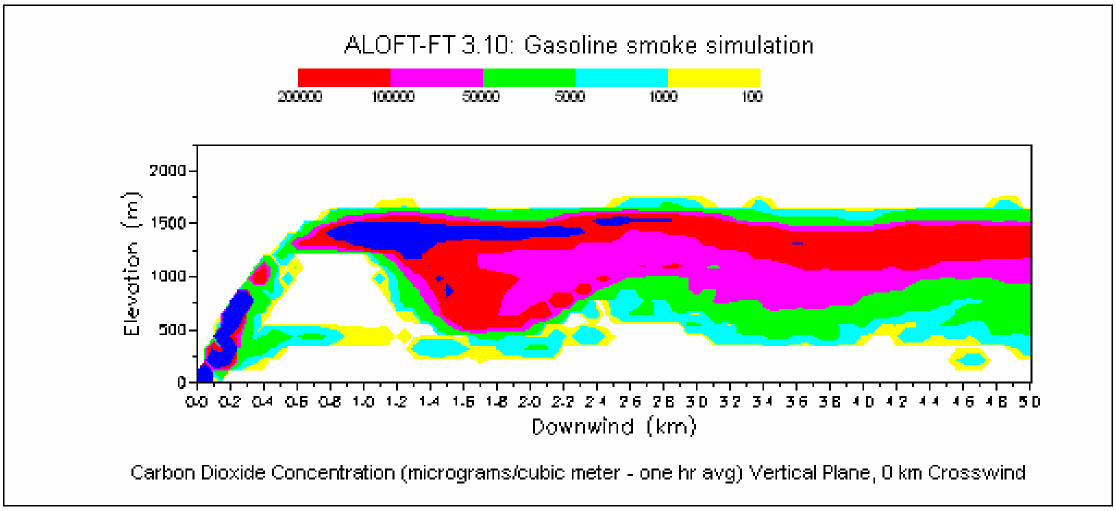


Figure 33. Vertical profile of Carbon dioxide concentration.

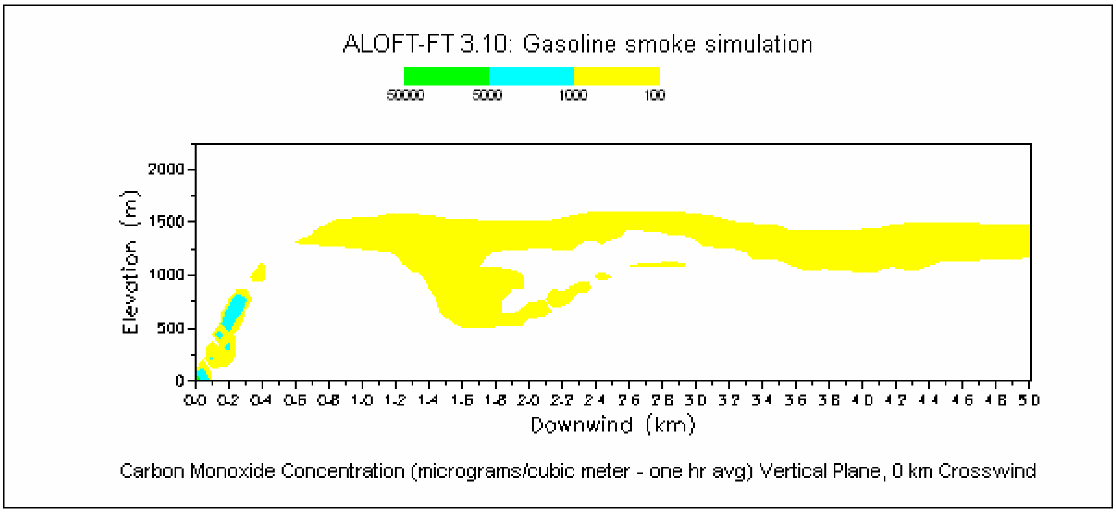


Figure 34. Vertical profile of Carbon Monoxide concentration.

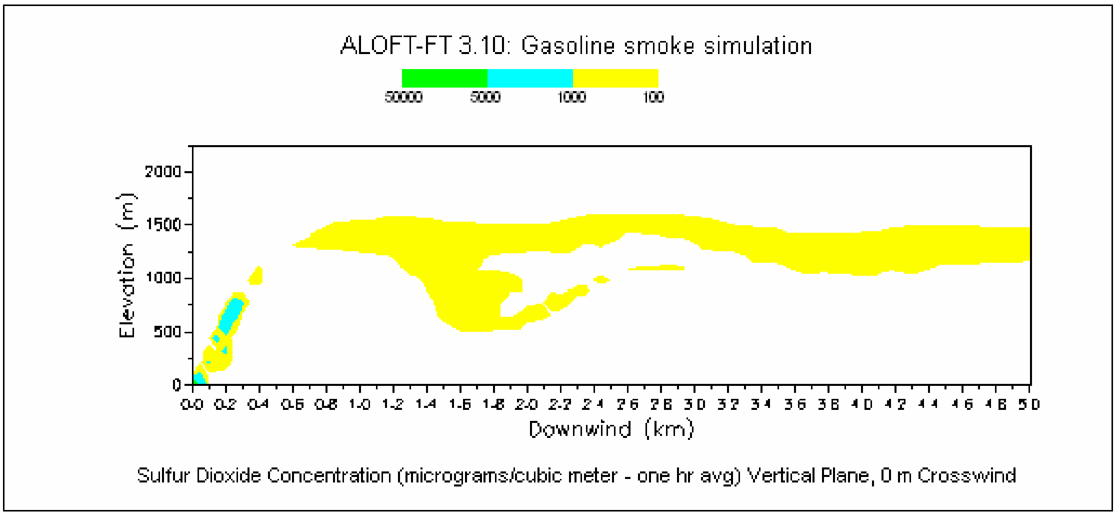


Figure 35. Vertical profile of Sulfur Dioxide concentration.

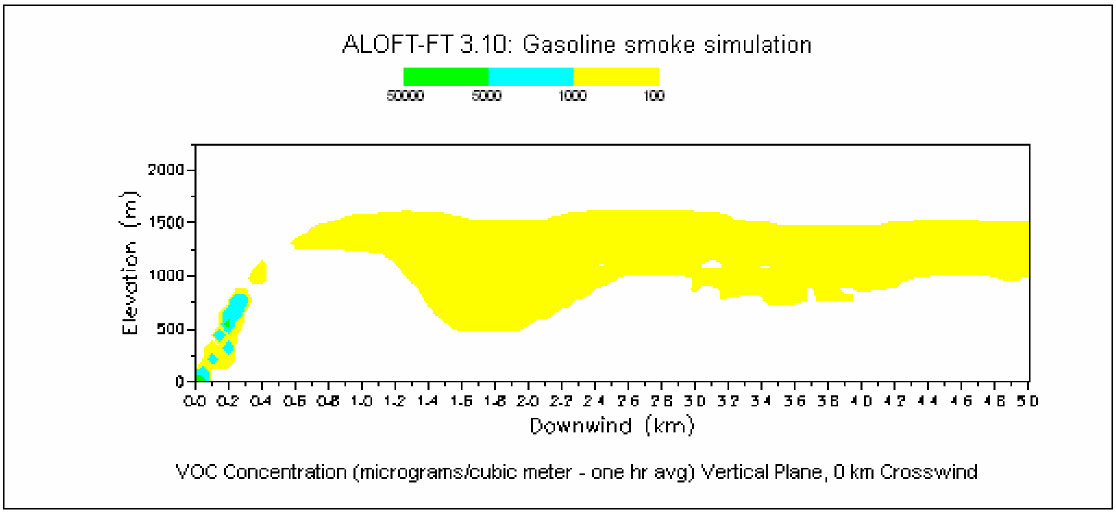


Figure 36. Vertical profile of VOC concentration.

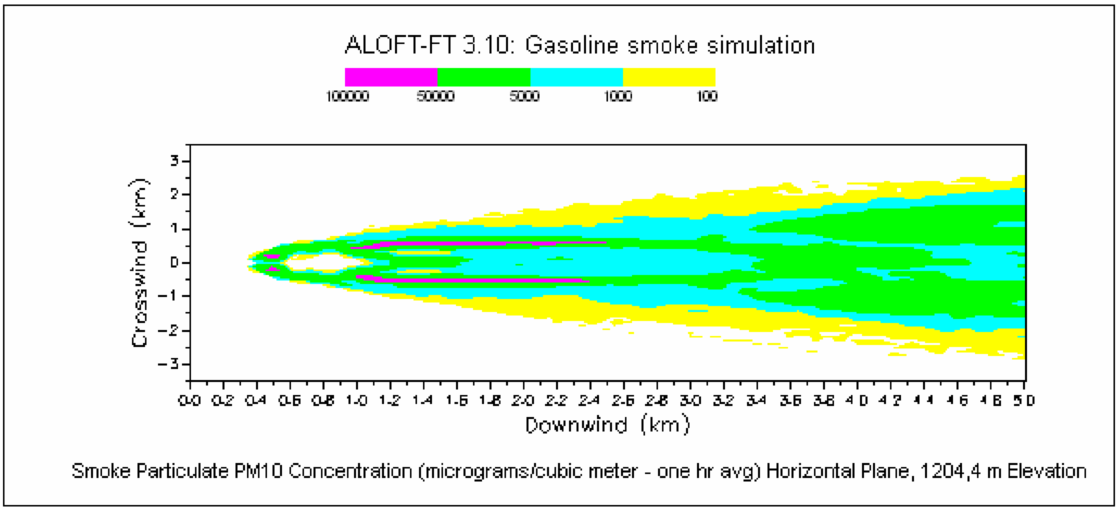


Figure 37. Horizontal profile of PM10 concentration at 1204 m elevation, 5 km downwind.

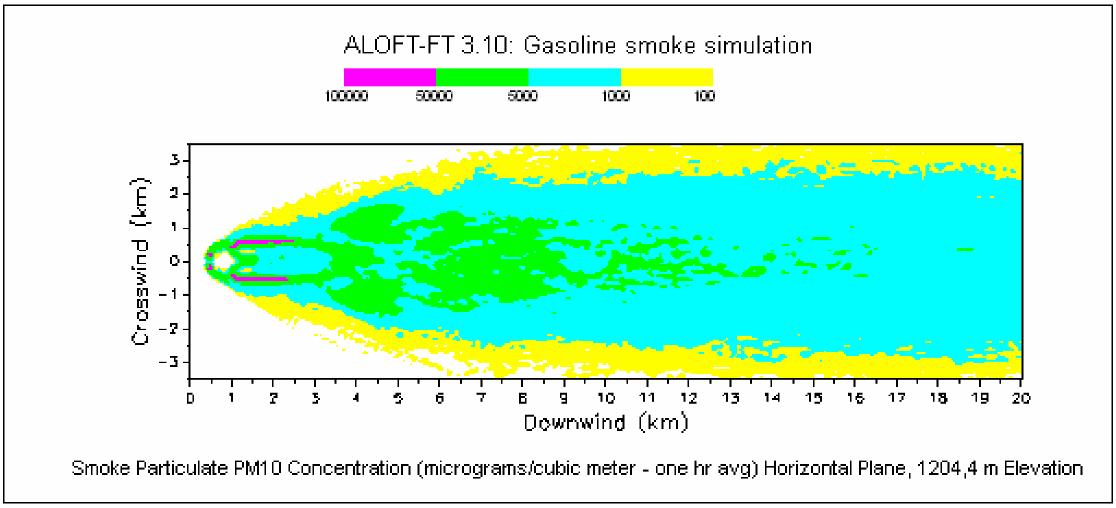


Figure 38. Horizontal profile of PM10 concentration at 1204 m elevation, 20 km downwind.

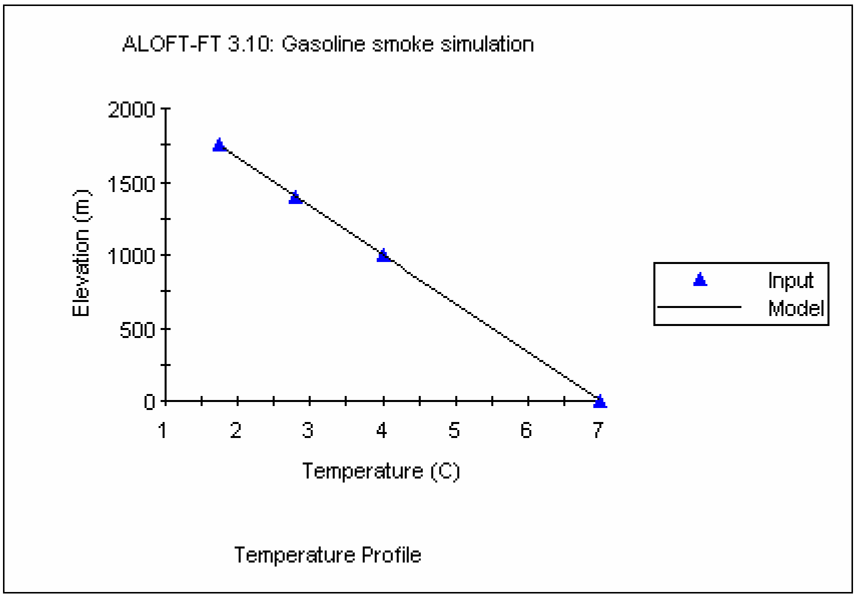


Figure 39. Temperature profile of the gasoline smoke simulation.

Figure 40. Overview of the city of Gdansk and the smoke plume in distance.

Figure 41. Concentrated smoke from the depot fire.

Appendix H : Risk evaluation

H.1 Radiation on people

To estimate who will survive and who will die in situations like considered here, the percentage of those who will encounter a second degree burn where calculated. It is estimated that 15% of those who suffer a 2nd degree burn do not survive and will die.

To calculate how many will suffer from this kind of burning the following formula was used [21]:

$$t \cdot q''^{4/3} \qquad \text{[Eq. H-1]}$$

Where:

t = Time of radiation (assumed 15 seconds in this case)

q" = Rate of heat transfer per unit area caused by the radiation (kW/m^2)

The time of 15 seconds is estimated to be the worst case scenario for an individual to be in contact with the radiation. It is assumed that as soon as an individual feels the heat caused by the radiation he will start running from the heat source. If the individual is capable of moving he will most likely not be in contact with the severe heat longer than 15 seconds.

Values from equation H-1 are then put in diagram [21] and the percentage of 2nd degree burn can be seen in Tables 34-36.

Scenario 1

Distance to object (m)	Φ	q'' (kW/m^2)	T_{tank} (°C)	$t*q''^{4/3}$ (*10^6)	Percentage of 2nd degree burn
1	0,535703044	32,21	595	15,373	94
5	0,352891879	21,22	509	8,811	58
10	0,233344743	14,03	432	5,076	7
15	0,16233728	9,76	371	3,129	1
20	0,117412228	7,06	321	2,031	-
30	0,067680229	4,07	246	0,975	-
40	0,043193111	2,60	190	0,535	-
50	0,029701324	1,79	148	0,325	-
100	0,008441866	0,51	34	0,061	-
150	0,003892093	0,23	-	0,022	-
200	0,00222677	0,13	-	0,010	-
250	0,001439051	0,09	-	0,006	-
300	0,001005638	0,06	-	0,004	-
400	0,000570001	0,03	-	0,002	-
500	0,000366428	0,02	-	0,001	-
800	0,00014407	0,01	-	0,000	-

Table 34. Effects of heat flux on persons within certain distance from the fire in scenario 1.

Scenario 2

Distance to object (m)	Φ	q'' (kW/m^2)	T_{tank} (°C)	$t*q''^{4/3}$ ($*10^6$)	Percentage of 2nd degree burn
1	0,5852	35,19	614	17,295	97,5
5	0,4780	28,74	571	13,204	85
10	0,3870	23,27	527	9,963	70
15	0,3175	19,09	489	7,654	40
20	0,2626	15,79	453	5,943	16
30	0,1876	11,28	395	3,796	1
40	0,1334	8,02	340	2,408	-
50	0,0999	6,01	297	1,638	-
100	0,0340	2,04	162	0,389	-
150	0,0166	1,00	91	0,150	-
200	0,0098	0,59	46	0,074	-
250	0,0064	0,39	14	0,042	-
300	0,0045	0,27	-	0,026	-
400	0,0026	0,16	-	0,013	-
500	0,0017	0,10	-	0,007	-
800	0,0007	0,04	-	0,002	-

Table 35. Effects of heat flux on persons within certain distance from the fire in scenario 2.

Scenario 3

Distance to object (m)	Φ	q'' (kW/m^2)	T_{tank} (°C)	$t*q''^{4/3}$ ($*10^6$)	Percentage of 2nd degree burn
1	0,6241	37,53	629	18,846	100
5	0,5945	35,74	618	17,662	97,5
10	0,5430	32,65	598	15,654	94
15	0,4881	29,35	575	13,578	85
20	0,4365	26,25	552	11,701	80
30	0,3492	21,00	507	8,690	58
40	0,2822	16,97	466	6,539	25
50	0,2313	13,91	431	5,016	7
100	0,1048	6,30	304	1,745	-
150	0,0595	3,58	228	0,820	-
200	0,0383	2,31	176	0,457	-
250	0,0268	1,61	137	0,283	-
300	0,0198	1,19	107	0,189	-
400	0,0121	0,72	63	0,098	-
500	0,0081	0,49	32	0,058	-
800	0,0044	0,26	-	0,025	-

Table 36. Effects of heat flux on persons within certain distance from the fire in scenario 3.

More details about previously done calculations in Tables 34-36 can be seen in Appendices C, D and E.

H.2 Individual risk calculations

To estimate the individual risk for the different scenarios, the tables in section H.1 where used. The distance from the fire that was considered to cause 2nd degree burn on human because of radiation was used as a benchmark. Actual risk contours where hard to draw since the distance from the fire, which was considered critical, was only about 50 meters. This on the other hand gives the reader idea of how much the distance from a fire is crucial regarding own safety.

To calculate the individual risk the following equation was used [10]:

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \qquad \text{[Eq. H-2]}$$

Where

$IR_{x,y}$ = the total individual risk of fatality at geographical location x,y (chances of fatality per year).

$IR_{x,y,i}$ = the individual risk of fatality at geographical location x,y from incident outcome case i (chances of fatality per year).

n = the total number of incident outcome cases considered in the analysis.

The inputs to previous equation H-2 are obtained from:

$$IR_{x,y,i} = f_i p_{f,i} \qquad \text{[Eq. H-3]}$$

Where

f_i = frequency of scenario outcome for each and every scenario.

$p_{f,i}$ = probability that a fire will result in fatality at certain location (percentage of burn/100)*0,15

	Scenario 1		**Scenario 2**		**Scenario 3**	
Distance to object (m)	**Percentage of 2nd degree burn**	**IR/year**	**Percentage of 2nd degree burn**	**IR/year**	**Percentage of 2nd degree burn**	**IR/year**
1	94	1,96E-03	97,5	6,63E-04	100	1,36E-04
5	58	1,21E-03	85	5,78E-04	97,5	1,33E-04
10	7	1,46E-04	70	4,76E-04	94	1,28E-04
15	1	2,09E-05	40	2,72E-04	85	1,16E-04
20	-	0,00E+00	16	1,09E-04	80	1,09E-04
30	-	0,00E+00	1	6,80E-06	58	7,89E-05
40	-	0,00E+00	-	0,00E+00	25	3,40E-05
50	-	0,00E+00	-	0,00E+00	7	9,53E-06
100	-	0,00E+00	-	0,00E+00	-	0,00E+00

Table 37. IR for the three scenarios.

H.3 Societal risk calculations

Calculations for societal risk where committed for all three scenarios at once. It was estimated that if the whole depot is on fire the consequences of the smaller scale fires would accumulate with the large scale fire as well. Therefore is it estimated that those who might die in the smaller scale fires will also die in the large one.

Again the distance calculated earlier for a person to get a 2nd degree burn was used as a meter for those who will die and who won't. That information is then expressed in the so called FN curve, which shows the relationship between cumulative frequency (F) and number (N) of fatalities.

To calculate the societal risk the following equation was used [10]:

$$N_i = \sum_{x,y} P_{x,y} p_{f,i} \qquad \text{[Eq. H-4]}$$

Where

N_i = The number of fatalities resulting from incident outcome case i.

$P_{x,y}$ = The number of people at location x,y, in this case the number of employees of twenty individuals who are working in the depot.

$p_{f,i}$ = probability that a fire will result in fatality at certain location (percentage of burn/100)*0,15.

To estimate the frequency in this relation the following equation was used [10]:

$$F_N = \sum_{i} F_i \quad \text{for all incident outcome case I for which } N_i \geq N \qquad \text{[Eq. H-5]}$$

Where

F_N = The frequency of all incident outcome cases affecting N or more people.

F_i = the frequency of incident outcome case i, and N_i is the number of people affected by incident outcome case i.

F_i for the case here above is the calculated frequency for each and every scenario multiplied by the percentage burned and divided by 100.

All the scenarios where then added to each other and the frequency given in Table 38 is the sum of the three scenarios. Then this frequency was accumulated to plot the FN curve in relation to number of deaths. That has also been done for the number of people fatalities. That number was also rounded to the nearest whole number since it is not estimated that a half a person can die.

Number of people dead	Frequency of each incident	Cumulative frequency
5	1,84E-02	1,84E-02
5	1,28E-02	3,12E-02
4	5,00E-03	3,62E-02
3	2,72E-03	3,89E-02
3	1,45E-03	4,04E-02
2	5,72E-04	4,09E-02
1	2,27E-04	4,12E-02
0	6,35E-05	4,12E-02
0	0,00E+00	4,12E-02

Table 38. Indata for societal risk in the oil depot.

Appendix I : Overview of the oil depot in Örfirisey

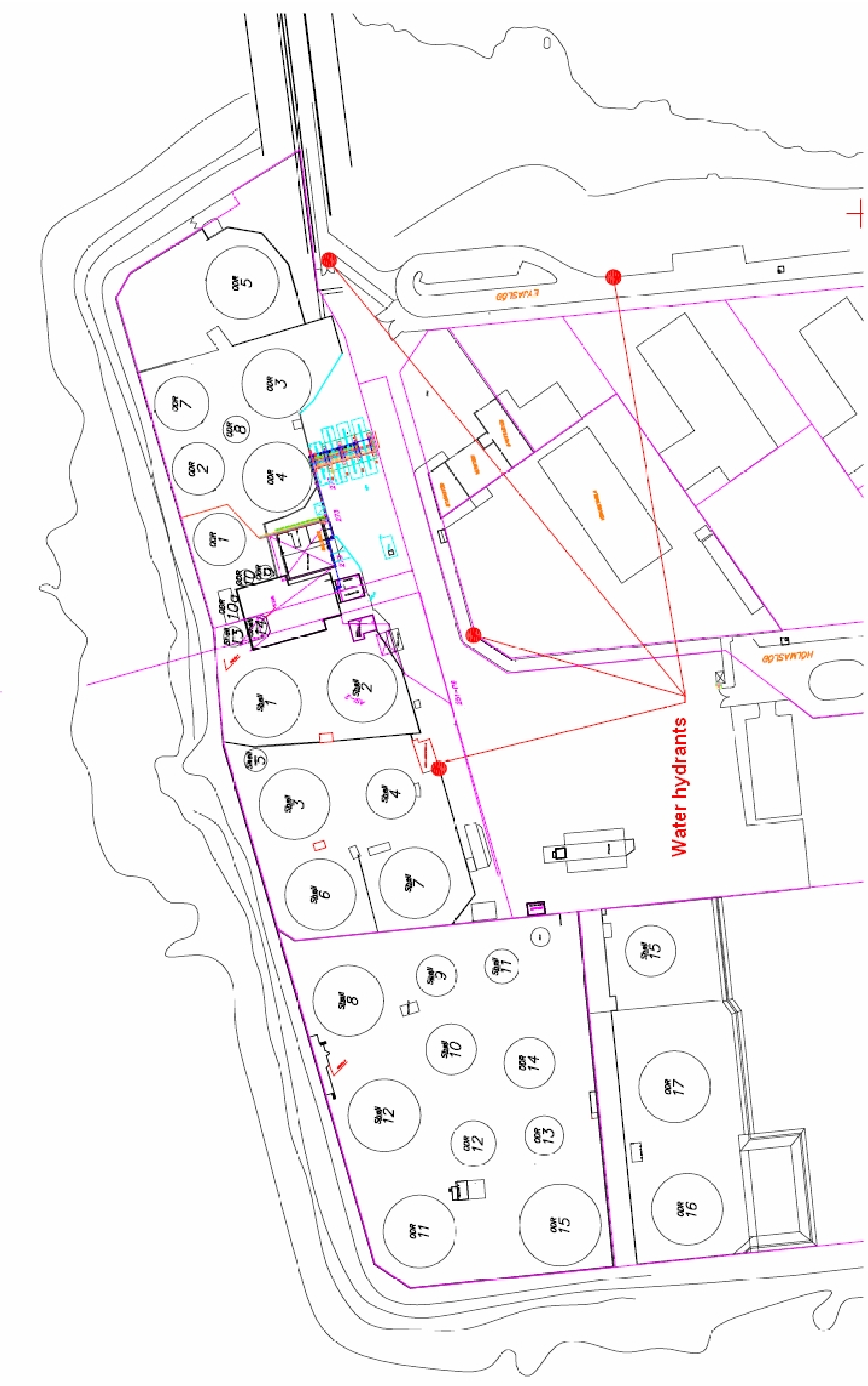


Figure 42. Overview of the oil depot in Örfirisey.