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Benchmark risk analysis models

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Abstract

A so-called benchmark exercise was initiated in which the results of five sets of tools available in the Netherlands would be compared. In the benchmark exercise a quantified risk analysis was performed on a –hypothetical- non-existing hazardous establishment located on a randomly chosen location in the Netherlands. The plant was chosen to cover many of the scenario’s that will be part of a real analysis such as the release of flammable and toxic clouds; liquids, gases and liquefied gases; vessels and pipes etc. Using each participating method a complete risk analysis was performed. The participants were asked to perform a risk analysis according to the guidelines given in the coloured books. All participants however had deviations, sometimes due to the available software, sometimes due to arguments of practicality, sometimes due to matters of principle. It should be noted that in practice, these differences between consultants using different (software) tools will also occur, as the application of the methods as described in the coloured books is not prescribed by law. It is not to be expected that the competent authorities will be able to detect these deviations nor that they would consistently insist that the coloured books are followed religiously.

Not many differences were found in the consequences and frequencies used for those events that are listed in the coloured books. The less the methodology for the calculation of the effects of certain scenario’s is established the larger the differences that were found between the results of the participants as could be expected.

The results for all participants were found largely within one order of magnitude. Since the earlier benchmark exercises the situation with respect to the spread in the results has improved tremendously and more improvements are difficult if at all obtainable unless the application of the prescriptions of the coloured books is made a legal requirement.

Samenvatting

Het is welbekend dat de resultaten van risico-analyses aanzienlijk uiteen kunnen lopen, afhankelijk van de gebruikte methode en van de bij de analyse gehanteerde aannamen. Daarom heeft het bevoegd gezag een aantal rapporten laten maken met als doel de gebruikte methodologie tot op zekere hoogte te standaardiseren. Deze boeken, die de methoden beschrijven voor het berekenen van kansen (het Rode Boek), het berekenen van effecten (het Gele Boek) en het berekenen van schade (het Groene Boek) zijn al vele jaren beschikbaar.

Sinds kort zijn richtlijnen voor het uitvoeren van een risico-analyse (het Paarse Boek) beschikbaar. Hierin worden aanwijzingen gegeven voor het gebruik van de andere boeken, worden standaard scenario's gegeven en de daarbij te gebruiken frequenties.

Een zogenaamde benchmark studie is ondernomen, waarin de resultaten van vijf gereedschappen zijn vergeleken, die in Nederland verkrijgbaar zijn. Deze gereedschappen zijn combinaties van methoden en software. In deze benchmark studie is een risico-analyse uitgevoerd van een denkbeeldige inrichting met gevaarlijke stoffen die zich op een willekeurig gekozen plaats in Nederland bevindt. De inrichting was zo gekozen dat veel van de scenario's die in een werkelijke analyse zullen voorkomen aan bod komen, zoals het vrijkomen van brandbare en giftige stoffen; vloeistoffen, gassen en tot vloeistof verdichte gassen; vaten en leidingen etc. Met ieder gereedschap is een volledige risico-analyse uitgevoerd. De deelnemers werd gevraagd om deze analyse uit voeren overeenkomstig de richtlijnen uit de gekleurde boeken. Iedere deelnemer week echter op één of meer plaatsen van de voorschriften af. Soms omdat de beschikbare software dat nodig maakte, soms omdat men het voorschrift te moeilijk uitvoerbaar vond en soms omdat men principieel een andere methode voorstond. Opgemerkt wordt dat deze verschillen ook in de praktijk zullen voorkomen. Immers het toepassen van de gekleurde boeken is geen wettelijk voorschrift. Het kan niet worden verwacht dat het bevoegd gezag zulke afwijkingen zal ontdekken. Ook kan niet worden verwacht dat men consequent het toepassen van de gekleurde boeken zal verlangen.

Toch zijn er tussen de deelnemers geen grote verschillen gevonden in de effectberekeningen en de frequentietoewijzing, wanneer de scenario's in de gekleurde boeken zijn behandeld. Hoe slechter echter de toe te passen methode bekend is, of is beschreven, hoe groter de afwijkingen tussen de deelnemers, zoals kon worden verwacht.

De uitkomsten van de deelnemers lopen ongeveer één orde van grootte uiteen. Dit is in vergelijking met eerdere benchmark studies een aanzienlijke verbetering. Verdere verbeteringen zijn moeilijk te realiseren zonder de voorschriften in de gekleurde boeken tot wettelijk vereiste te maken.

Het is aanbevelenswaardig de methoden te inventariseren, die in Nederland in het kader van externe veiligheidsberekeningen worden aanvaard, maar die niet in de gekleurde boeken worden beschreven. Deze methoden geven aanzienlijk afwijkende uitkomsten. Het is ook aan te bevelen dat risico-analisten deze afwijkingen expliciet maken.

Tenslotte moet erop worden gewezen dat ook een globale risicoschatting zorgvuldig moet worden uitgevoerd.

Summary

It is well known that the results of risk analyses may vary considerably depending on the methodology used and the assumptions underlying the analysis. For this reason a number of reports have been commissioned on behalf of the authorities to standardise to a certain extent the analysis methodology. These books describing the methods to calculate probabilities (the Red Book), the methods to calculate consequences (the Yellow Book) and methods to calculate damage (the Green Book) have been available for many years.

Recently guidelines for performing a risk analysis (the Purple Book) giving among other guidance for the use of these books, standard scenario selection and frequency attribution has been issued.

A so-called benchmark exercise was initiated in which the results of five sets of tools available in the Netherlands would be compared. In the benchmark exercise a quantified risk analysis was performed on a –hypothetical- non-existing hazardous establishment located on a randomly chosen location in the Netherlands. The plant was chosen to cover many of the scenario's that will be part of a real analysis such as the release of flammable and toxic clouds; liquids, gases and liquefied gases; vessels and pipes etc. Using each participating method a complete risk analysis was performed. The participants were asked to perform a risk analysis according to the guidelines given in the coloured books. All participants however had deviations, sometimes due to the available software sometimes due to arguments of practicality, sometimes due to matters of principle. It should be noted that in practice, these differences between consultants using different (software) tools will also occur, as the application of the methods as described in the coloured books is not prescribed by law. It is not to be expected that the competent authorities will be able to detect these deviations nor that they would consistently insist that the coloured books are followed religiously.

Not many differences were found in the consequences and frequencies used for those events that are listed in the coloured books. The less the methodology for the calculation of the effects of certain scenario's is established the larger the differences that were found between the results of the participants as could be expected.

The results for all participants were found largely within one order of magnitude. Since the earlier benchmark exercises the situation with respect to the spread in the results has improved tremendously and that improvements are difficult if at all obtainable unless the application of the prescriptions of the coloured books is made a legal requirement.

It is advisable to take stock of those methodologies which are acceptable for use in the realm of external safety policy in the Netherlands, but which are not described in any of the coloured books. These deviating methodologies tend to give substantially different results.

It is also advisable to have consultants make all the deviations from the prescriptions in the coloured books explicit.

However, it should be borne in mind that even approximate risk analyses should be performed with care.

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1. Introduction

For some fifteen years now the external safety policy in the Netherlands has been based on quantified risk and quantified criteria. These criteria have been formulated in policy documents. It is the intention to increase the status of these criteria by making them into requirements of environmental quality under the Law on the Environment.

It is well known that the results of risk analyses may vary considerably depending on the methodology used and on the assumptions underlying the analysis. For this reason a number of reports have been commissioned on behalf of the authorities to standardise to a certain extent the analysis methodology.

Several methodologies are available to quantify the risks of chemical establishments. In the early 90ties a number of studies have been performed [1,2] to investigate the spread of results between the available methods. In these studies a very wide spread was found, up to four orders of magnitude in probabilities. With hindsight this was for a large part due to unclear understanding between the participants regarding a wide range of subjects such as the end point of the analysis, the interpretation of the description of the plant and many other aspects.

The desire to standardise the methodology of risk analyses performed under the legislative realm to a certain extent has existed from the late seventies. This desire led to the compilation of three so-called coloured books. These books describing the methods to calculate probabilities (the Red Book [3]), the methods to calculate consequences (the Yellow Book, CPR [4]) and methods to calculate damage (the Green Book [5]) have been available for many years.

Recently guidelines for performing a risk analysis (the Purple Book [6]) giving among other guidance for the use of these books, standard scenario selection and frequency attribution has been issued.

The question that arises subsequently is to what extent these guidelines lead to a reduction in the spread of the results of the sets of tools for performing risk analysis that are currently available in the market. To find an answer to this question a so-called benchmark exercise was initiated in which the results of four of the sets of tools most commonly used in the Netherlands would be compared. In the course of the investigation a fifth set of tools entered the market. It was decided to add this set of tools to the investigation.

In the benchmark exercise a quantified risk analysis was performed on a –hypothetical- non-existing hazardous establishment located on a randomly chosen location in the Netherlands. Using each participating method a list of scenario's was generated, the associated frequencies established and a complete risk analysis performed. The results of these analyses were compared.

The investigation into the underlying causes of resulting differences was not part of this study.

The separate reports of the five participants are assembled on the accompanying cd-rom.

2. Consistency, accuracy and uncertainty

The benchmark exercise described in this report compares the results of various calculation methods using computer programs under rules set by guidance documents. When the results of these calculations are close together, the methods are consistent under the rules.

It would not be a just conclusion that these results therefore also are accurate. It should be borne in mind that no comparison has been made in this study with real plant performance. So the results are accurate only to the extent that the rules, methods and guidance given in the coloured books are accurate. Similar considerations hold for models or methods used, that are not included in these books.

This is especially true for the estimates of the frequencies. As is described in the Purple Book there is serious suspicion that the numbers used to date in the Netherlands are low when compared with available statistical material.

Consistency between methods is no guarantee for certainty either. Whereas the use of different methods without guidance would have a higher probability of showing the uncertainty in scientific knowledge the use of guidance documents tends to cover up these uncertainties. This may well be justified in the light of the intended use of the results. It may indeed be difficult in a decision making process to handle visible signs of large uncertainty. This does however not take away the uncertainties. The current generally accepted range of uncertainty is estimated to be a factor of 10 in the frequency of probability of the final risk results. The comparison of different methods shows such an uncertainty when the area covered is not well described in the guidance documents and therefore the analysts have more freedom of interpretation.

In any case large differences between analysts can be expected without guidance as this reflects the current state of knowledge. Even although on a world wide scale accidents and incidents cannot be called rare events, the statistical basis for the data remains small.

As large scale experiments are also rare and increasingly difficult to organise both for financial reasons as for availability of test sites, the experimental basis for various models, such as the dispersion model, which is central to the calculations remains small also.

Therefore the results of this exercise, how favourable it may be, should not blind the users of the results for the uncertainties and inaccuracies inherent in the methodology.

3. The process

The benchmark exercise is nothing less and nothing more than a comparison of the results of a quantified risk analysis performed by five different participants each using its own tools.

The common ground for the analysis was a hypothetical plant located at some spot in the Netherlands as to provide realistic data for population, weather and wind.

The plant was chosen to cover many of the scenario's that will be part of a real analysis such as the release of flammable and toxic clouds; liquids, gases and liquefied gases; vessels and pipes etc. A real plant has many details in its design and operation that influence the risk results. Most of these details have been left out. They do not contribute to the purpose of the exercise, which is comparing results of risk calculations, and make detection of the causes of differences unnecessarily difficult.

After it was established that all participants understood the description of the plant in the same way, each participant developed an event list, which was discussed between the participants. In cases were differences could be attributed to misinterpretation of the coloured books, badly defined features of the model plant or just plain mistakes, these were repaired.

Subsequently the analyses were carried out to the end. Each participant calculated the individual risk contours and the societal risk curves (FN curves) for each section of the plant and for the total.

These results were compared again. Again some differences could be attributed to different interpretations of the initial plant data and were repaired leading to the final results.

The methodologies used by the five participants were taken as they are. No attempt was made to change or adapt models or force participants to adhere to the methods of the coloured books if they thought they had good reason to deviate. The Purple Book allows such deviations when sufficiently argued and differences due to such deviating methods therefore can be encountered in practice.

In these results the differences are due to differences in interpretation and methods within the boundaries given by the coloured books and therefore are differences that could be expected to occur in practice.

4. The participants

Five consultants took part in the exercise. Each of them made a full report. The reports are assembled on the accompanying cd-rom. A short description of each of them and the tools that they are using is given in this chapter.

Except for Shell Global Solutions all companies state that their methods and software is fully compliant with the coloured books. Shell Global Solutions states explicitly that their methods for calculating the effects from unconfined vapour cloud explosions and of BLEVES are based on research and full scale experiments performed by laboratories of the SHELL group. Their methods differ from the methods in the coloured books.

4.1 AVIV

AVIV is a consultancy bureau located in Enschede. It has some 15 years of experience in the field of risk analysis. It developed its own software, RISKCALC. AVIV uses this software and sells it. RISKCALC is a semi-automated system. The user has to define his own scenario's and attribute frequencies. Some manual operations are necessary to transfer data of the consequence analysis part to the risk calculation part.

4.2 DNV

The risk analysis consultants of DNV form an international subgroup of the larger DNV organisation. The participants in this exercise are located in Rotterdam. DNV has some 25 years of experience in this field. DNV developed several risk analysis packages. The predominant are PHAST and SAFETI. The latter product was used in the analysis. Although automated generation of failure cases is possible, in practice this is often done by hand by the analyst. After the definition of these cases the process is fully automated. PHAST and SAFETI are commercially available.

4.3 SAVE

SAVE is a consultancy bureau located in Apeldoorn. The bureau has some 20 years of experience. It developed its own software under the name of SAVEII. The software consists of separate consequence and damage modules that have to be run separately after the initial events have been generated by hand. SAVEII is commercially available.

4.4 SHELL

Shell Global Solutions is a network of technology companies of the Royal Dutch / Shell Group, providing an integrated portfolio of services to companies inside and outside the group. With over 50 years of experience, the HSE Consultancy team covers the full spectrum of technical services within health, safety and the environment (HSE).

In recent years specialist software tools for hazard consequence modelling (FRED) and quantitative risk assessment (Shell Shepherd Desktop) were developed, based on in-house R&D and supported by full-scale experiments. These tools, previously only available within Shell, are now being made available to all companies.

4.5 TNO

TNO/MEP is a group in the large TNO organisation. It has some 25 years of experience in quantified risk analysis. Of the four coloured books it produced two (the Yellow and the Green Book). TNO uses two software products EFFECTS, which is the software implementation of the Yellow Book and RISKCURVES, which uses the results of EFFECTS to generate risk numbers. EFFECTS is commercially available.

5. The establishment

The hypothetical establishment chosen for the analysis is located somewhere in the centre of the Netherlands, such that realistic data on weather, wind, and population could be made available. The reference co-ordinates of the plant are (133800,456000) on the Dutch National Grid. This locates this hypothetical plant along the Amsterdam Rijn Kanaal.

The plant consists of units to provide a gamut of scenario’s that covers most of the situations commonly present at real plants, such as gases, liquids, and compressed gases; vessels and pipes, storage and processing; stationary and moving equipment and loading and unloading. The units are:
1 Acryl-nitril storage
2 Chlorine tank
3 Propane tank
4 Butane tank
5 Sulphur Dioxide tank
6 H_2S line
7 Loading facility
8 Marshalling yard
These units are described in more detail below.

It should be borne in mind that these units are schematic. Many features that could be present in a real plant are not included. Such items could be gas detection systems, deluge systems, spray curtains and many other features that in practice could reduce the risks of these sorts of equipment. However the only purpose of the “plant” was to provide a model for analysis.
The results of the analyses should not be taken as being typical for the risks of real plants having these storages or types of processes. A map of the plant is given in Appendix 2.

5.1 Acrylonitril storage tank

The relative co-ordinates of this unit with respect to the plant co-ordinates are (302,225). The tank is a vertical cylindrical tank with a diameter of 18 m and a height of 16 m. The normal inventory is 3700 m^3. It is located in the centre of square bund, 40 m long. The height of the bund wall is such that the bund can take all contents. There is a high level alarm to the control room.

Acryl-nitril (ACN) is stored under atmospheric conditions. On top of the tank is a bleeder valve. The maximum allowable over pressure in the tank is 120 mm H_2O, The maximum allowable under-pressure is 50 mm H_2O. The feeder line to the tank is 10" in diameter; the pump rate is 150 m^3/hr from a jetty located elsewhere on the site.

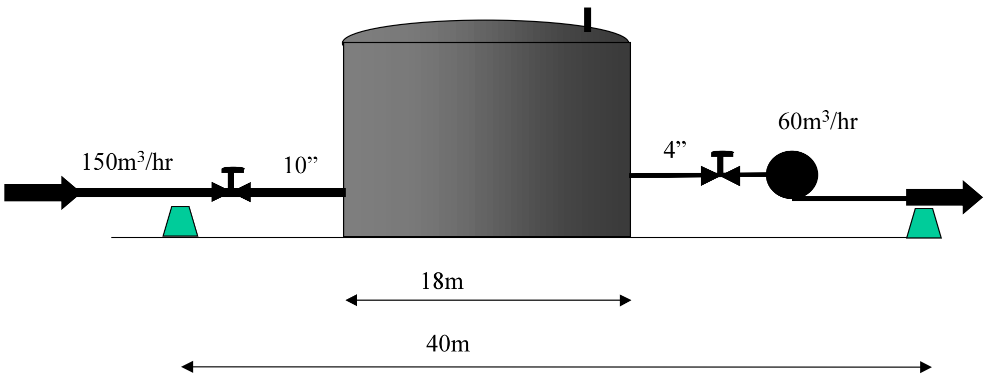

Figure 1 Acrylonitril storage tank

The feeder pump is located at the jetty. It is controlled from the control room. An emergency stop is located at the jetty.

The discharge line has a diameter of 4". It discharges by ways of a pump with a rate of 60 m^3/hr to the railcar loading facility. The valves are remotely controlled from the control room and are located in the bund. The discharge pump is located in the bund. It is controlled from the control room. An emergency stop is located at the loading facility. The railcars are loaded using a hose of 4" diameter. The railcars are 50 m^3 each. They are operated under atmospheric conditions. The lines to the railway-car loading dock are kept full.

The tank is filled from a ship at the jetty. A loading arm is located at tip of jetty (430,400). The line on the jetty is cleared after loading by purging with nitrogen.

The ship is not part of the system to be analysed. For reasons of modelling the ship is considered as an unlimited supply of ACN. No collision risk or other risks associated with the ship are considered.

The tank is topped up every 19th day with pumps at the rate as stated above. The pattern of unloading is determined by the railcar traffic pattern.

5.2 Chlorine tank

Chlorine is stored under pressure in a spherical tank with 120 m^3 capacity operated at 3 bar. The design pressure of the tank is 9 bar. The unit is located at plant co-ordinates (410,388). The pressure is maintained by a cooling system. For the sake of the analysis it can be assumed that this system does not fail.

Loading and unloading of the tank takes place through a dip-pipe of 2" diameter using railcars. The pump-rate is 20 m^3/hr. The pump is located at the storage. The loading arm used at the railcar-facility is stainless steel.

A pressure relief valve is fitted wit a set pressure of 6 bar. The valve is diameter 2". The valve reliefs to a scrubber. For the sake of the analysis the scrubber can be assumed to be effective when caustic supply is maintained. Maintaining caustic is part of the standard operating procedure under control of operator.

The railcars with a volume of 50 m^3 are standard European railroad cars. The loading and unloading lines are kept full.

Unloading is continuous at a rate of 2 railcars per week. When the tank is almost empty the

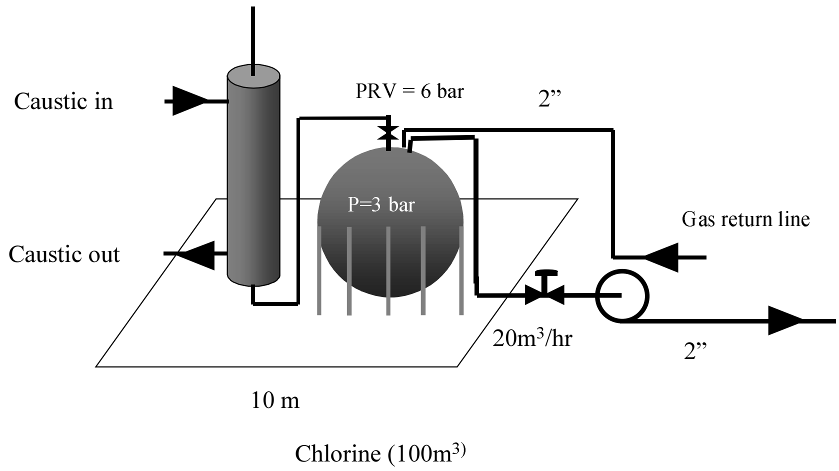

Figure 2 Chlorine storage

tank is filled. For the sake of the analysis this filling is not part of the system so as far as the analysts are concerned the tank fills it self (by magic).

5.3 Pressurised flammables

Two storages of pressurised flammables are kept on the premises: one with propane and one with butane.

The co-ordinates of the propane tank are (425,230). It is a 3000 m^3 sphere. The maximum fill level is 90% full. Propane is stored at ambient temperature. The pressure relief valve has a diameter of 2" set at 20 bar.

Loading/unloading of the tank takes place, using railcars fitted with a vapour return line 2". The loading/unloading lines are 4" in diameter. The railcars are loaded using a loading arm. The pump rate is 60 m^3/hr.

The railcars used are 50 m^3 standard VTG. The unloading pattern is determined by the tank car traffic. The tank is unloaded at a rate of 3 railcars per day, 7 days a week. Also this tank, when empty, fills itself by miracle.

The butane tank is located at (465,230). It is similar to the propane tank, but has a volume of 1000 m^3. There are lines to a filling station for 50 liter gas tanks. In the storage 200 of these tanks are kept. For the sake of the analysis it is assumed that the tank is filled from rail cars 3 cars a day, 7 days a week. It is assumed that butane leaves the tank at the same rate.

Propane and butane tank are kept in a bund of 30*70 m. The bund is designed to take the contents of the propane tank.

A fire detection system and deluge system is available. The operator has to activate the system after the alarm is raised in control room.

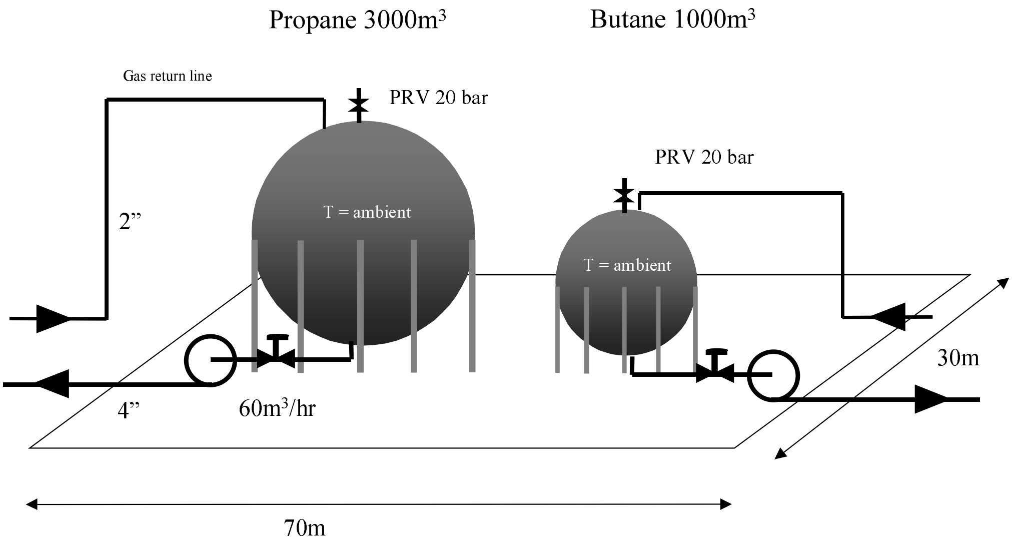

Figure 3 Propane and butane storage facility

5.4 Ethylene oxide tank

Ethylene oxide is kept in a 50 m^3 bullet tank of 2 m diameter at ambient temperature. The co-ordinates of the tank are (300,190). All connected pipe work has a diameter of 2". The tank is emptied by applying 3 bar N_2. The railcars used for this chemical are smaller: 10 m^3. They are filled to 90% of their capacity. The tank is run down to 10% of its nominal volume by filling rail cars. Tank is topped up every 4th day. Loading and unloading of the railcars is done through a loading arm.

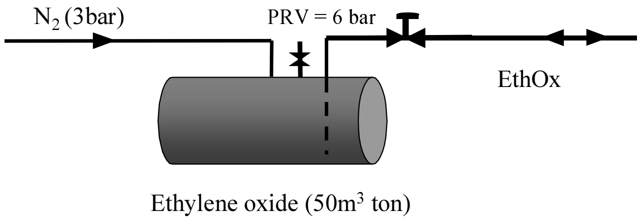

Figure 4 Ethylene storage

5.5 Sulphur Dioxide tank

Sulphur dioxide is stored at co-ordinates (300,173). The construction of the tank is the same as the ethylene oxide tank except that emptying takes place by a suction pump. Also for this chemical railcars are 10 m^3. The tank is topped up every 4th day.

The Ethylene oxide and SO_2 tanks are kept on a concrete plate.

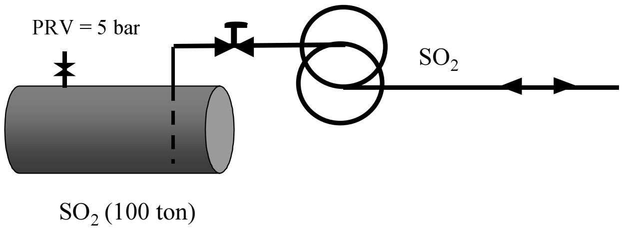

Figure 5 Sulphur dioxide tank

5.6 Pesticide storage

There is a building size 20*40*10 m^3; co-ordinates (430,140). In this building pesticides are stored of which the composition is $C_{3.6}H_{5.3}O_{0.4}N_{0.9}S_{1.3}Cl_{0.8}$.

A sprinkler system is provided.

5.7 Hydrogen Sulphide (H_2S) line

An H_2S-line runs under the site. The co-ordinates are (x, 145).

The diameter of the line is 100 mm; the pressure is 12 bar; the depth is 1.25 m. The line has block valves every 15 km. The closing time of these valves after the control room becomes aware of a leak is 15 minutes. The line is of infinite length. H_2S is to be taken as toxic only. No flammable effects of this line are considered. No special protection measures have been taken.

5.8 Lines

All loading and unloading lines run over pipe racks as indicated on drawing. It is assumed that the lines run over the centre co-ordinates as indicated. The loading station of jetty is at the end.
The co-ordinates of the lines are as follows:

- Acrylonitryl loading from ship: (430,400); (375,340); (375,242); (328,242); (328,225); (302,225)
- Acrylonitryl unloading to railcar: (302,225); (328,225); 328,242); (375,242); 375,070); (310,005)
- Chlorine: (410,338); (402,190); (375,190); (375,070); (310,005)
- Propane: (425,230); (425,242); (375,242); (375,070); (310,005)
- Butane: (465,230); (465,242); (375,242); (375,070); (310,005)
- Ethylene oxide: (300,190); (328,190); (328,242); (375,242); (375,070); (310,005)
- SO_2: (300,173); 328,173); (328,242); (375,242); (375,070); (310,005)

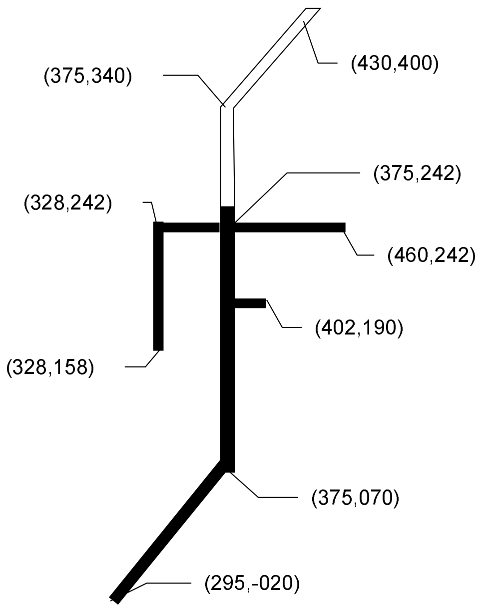

Figure 6 Pipework

5.9 Marshalling yard

The Marshalling yard is used for loading and unloading rail cars and for assembling/disassembling trains. Trains go mixed cargo except Chlorine. The car pattern is as follows. ACN: 4 cars/day; Chlorine 2 cars/week; Propane 5 cars/day; Butane 3 cars/day; Ethox two 10 m^3 cars/day; SO_2 1 car/day.

Trains are collected twice per day: one at 3 AM, 1 at noon. Chlorine trains leave every Wednesday at 00:20. Full Chlorine cars are parked at end of the marshalling yard.

The main line carries 4 trains per hour in each direction. (I.e. 4 trains south on western track, 4 trains north on eastern track). Traction is electric except on sidings where it is diesel. The data on train traffic are given for ignition probabilities if needed. No collision risk is taken into account in this study.

All loading/unloading takes place on tracks (x,20) and (x,5) except Chlorine, which is at (x,-5). Tracks (x,20) and (x,5) have 3 loading stations each. All chemicals can be handled at each station. The loading stations are under the pipe rack.

Track (x,-19) is electrified.

The marshalling yard is part of establishment. No interference of the main track with the marshalling yard has to be considered, nor collisions of trains leaving/entering the yard.

5.10 Additional data

For railcars standard provisions against overfilling can be assumed.
Except for ACN, no special description is given, where the material with which the various tanks are filled originates.

Contents pattern of all tanks: 1/4 of the time 90% of volume filled, 1/2 of the time 1/2 filled, 1/4 time 10% filled. After period of 10% filling tanks are topped up in one go as indicated under the specific tanks.

Filled railcars all are parked at (200,5) and (200,20). Chlorine cars wait at (450,-5)

6. Risk analysis

The participants were asked to perform a risk analysis according to the guidelines given in the coloured books. Shell Global Solutions were asked to do the same even though they entered the project in a later stage. All participants however had deviations, sometimes due to the available software sometimes due to arguments of practicality sometimes due to matters of principle.

These deviations could not be taken away without extensively changing the operations of the participants, which was felt to be outside the scope of the exercise. It should be noted that in practice, these differences between consultants using different (software) tools will also occur, as the application of the methods as described in the coloured books is not prescribed by law. It is not to be expected that the competent authorities will be able to detect these deviations nor that they would consistently insist that the coloured books are followed religiously.

6.1 Events

From the event lists given in the five reports on the cd-rom several observations can be drawn.

All participants have the same loss of containment events (LOC) for the vessels. Differences occur with the LOC's for pumps, loading arms and similar equipment. Some participants attribute events associated with this equipment to the pipe work in general. Some of them make these explicit. Of the participants the event lists by DNV and TNO are the most detailed. The event list by Shell Global Solutions is the least detailed (partly due to the late entry into the benchmark study). The frequencies attributed to the events are all within the prescriptions given by the Purple Book.

It should be noted however that considerable discussion was needed on each of the event lists. Considerable care has to be taken in this stage to select the proper numbers even from the Purple Book. As in most (external) safety reports, the details of the analysis are not given and thus cannot be checked by the authorities, a special responsibility lies with the contractor and the owner of the establishment.

6.2 Frequencies

Not many differences were found in the frequencies used for those events that are listed in the Purple Book. Some participants indicate in their separate report that they would have used different numbers if the use of the Purple Book would not have been prescribed. Numbers vary considerably when the Purple Book does not give any guidance, such as for the failure frequency of valves.

6.3 Consequences

Although the conditions of the exercise specified the use of Yellow Book models several participants deviated from this condition. Shell Global Solutions specified explicitly that they use their own BLEVE models for pressurised flammable gases. SAVE uses correction factors on calculations performed with older models. The differences in the calculated effect distances are reflected in the final FN curves by differences in the frequencies of the larger events. These are, as will be seen later in this report, very limited. The spread in calculated effect distances is larger when the consequences are smaller (which may partly be explained by differences in discretisation of the model calculations).

6.4 Risk

In the Dutch environmental policy two quantities have been defined, that are used to measure risk:

- *Individual risk* is defined as the probability that a person staying at a fixed location permanently is killed as a result of an accident in the hazard source. It is expressed in units per year.
- *Societal risk* is defined as the probability that in a single accident in the hazard source a certain number of victims is exceeded. It is expressed as the relationship between the number of people killed and the probability per year that that number is exceeded. When this relationship is represented in a graph in which the logarithm of the number (N) is plotted against the probability or frequency of exceeding this number (F) it is referred to as the FN curve.

These quantities form the end point of the calculations.
The consequences calculated earlier are combined with the frequencies and with data on population and weather to get the risk results. Apart from occasional confusion over the direction of North, the most notable point of attention is the grid resolution used to generate the risk contours and the FN curve. With the smaller events that have an effect range of only a few hundred meters too large a grid size may lead to very deviating risk results.
TNO, SAVE and Shell Global Solutions use two weather classes (with the latter allowing 3 wind speeds per weather category). DNV and AVIV use six classes. The Purple Book specifies that at least six weather classes should be used to cover the range of possibilities in a sufficiently detailed manner. The results, as described below, show that the differences between the modelling results are generally very limited.

7. Results

In Appendix 1 a summary of the results is given. Some aspects of these results are discussed below.

7.1 Individual risk

The first section gives the distances to a certain risk level. Also given are the 95% confidence intervals for the distances.

As can be seen the estimates of the individual risk at a certain distance usually are within one order of magnitude, which, given the remaining non uniformity in the methodologies, is remarkably close.

A notable exception is ACN for which especially DNV has much larger risk results than the other participants. The deviating results of Shell Global Solutions in the cases of butane and propane can be expected as they use a different model approach. As Shell Global Solutions has done extensive research in this area it seems advisable to reconsider the modelling in the coloured books in view of these results.

As far as the pesticide storage is concerned there is room for further investigation as to the causes of the relative large discrepancies between the results produced by the various participants. It should be noted however that the coloured books do not give any more guidance for such a storage than referral to the Dutch national dispersion model and that specific models only became available at the end of the study period. Therefore these models could not be incorporated.

7.2 Societal risk

The societal risks are generally found within one order of magnitude. In comparison to the results of previous benchmark exercises this result is extremely good. It should be noted however that the overall results are dominated by chlorine, for which the agreement between the participants happens to be the best. In case of another composition of the risk, larger differences can be expected, although they would not be more then two orders of magnitude apart. This supports the usefulness of guidelines in which the end points of the calculations, scenario definitions and frequency numbers are harmonised wherever possible and reasonable within the general uncertainty of the art.

Some notable exceptions are the results for the ACN storage and the pesticide storage. The precise reasons warrant further investigation.

8. Discussion and conclusion

The less the methodology for the calculation of the effects of certain scenario's is established the larger the differences that were found between the results of the participants. When methods are used that differ from those described in the coloured books, differing results are found, as could be expected.

This benchmark study shows that a certain level of harmonisation improves the coherence of the results. However, it also shows that there is a remaining uncertainty of about one order of magnitude. Part of this spread is certainly attributable to the fact that, despite the project specification that all methodologies that were applied should conform to the coloured books, all participants deviated from these specifications. It proved to be impossible to have all participants apply all coloured books specifications, as that would have implied major changes in their operating procedures or in their software. It is not known what part of the spread in the results is due to this factor. However, it should be borne in mind, that only if the application of the methods of the coloured books is required by law these differences will largely disappear. It should be noted again that this does not reduce the inherent uncertainty in the results.

Of the other part of the spread in the results only in part is this due to the fact that it is neither possible nor desirable to specify every detail of every applicable method. To a larger extent the remaining spread of results is due to area's in the analysis where methods are in development or even absent. Special attention should be given to risk analyses where the distances to the relevant individual risk contours is small. These tend to be influenced by technicalities in the numerical process and therefore warrant precise application of the methodology, even if the methodology leads to results with a large margin of uncertainty.

Although traditionally spray-release and evaporation modelling are suspected of giving rise to considerable differences in results, the homogeneity of the results for chlorine suggests that the causes for differences have to be found somewhere else. It would be advisable to study the causes of the differences in more detail as to establish which part of the modelling gives the larger contribution to these differences. This among other will require detailed intermediate results, which in the present study were not available.

In conclusion it should be said that since the earlier benchmark exercises [7,8] the situation with respect to the spread in the results has improved tremendously and that more improvements are difficult if at all obtainable unless the application of the prescriptions of the coloured books is made a legal requirement.

It is advisable to take stock of those methodologies which are acceptable for use in the realm of external safety policy in the Netherlands but which are not described in any of the coloured books. These deviating methodologies tend to give substantially different results.

It is also advisable to have consultants make all the deviations from the prescriptions in the coloured books explicit.

There is not an easy answer to the question whether it would be advisable to make application of the coloured book methods a legal obligation. A legal obligation would make it necessary for the authorities to make computer programs available, possibly at low cost. It is worthwhile in this respect to mention that some computer programs available in the public domain, such as that for the heavy gas dispersion model SLAB, cannot be used in the commercial domain. Other problems associated with a strictly binding prescription of methods are the potential negative effect that that might have on further development of methods and the hindering of the commercial market. This is a problem that lends itself for long debate and it remains doubtful, whether the final situation would be better than the present one, in which the margins between the various outcomes is known; authorities could be aware of problems resulting from deviations from the coloured books and from areas in analyses, where methods are lacking or ill described.

In summary the differences in results between the various consultants is within what could be expected given the state of the art. The differences are much smaller than they were a decade ago. Potential problem areas in the analyses are well known and the results seem adequate for the decisions at hand. However it should be borne in mind that even approximate risk analyses should be performed with care, as intercomparison of the results of intermediate steps of the analysis of the various participants revealed considerable differences due to errors.

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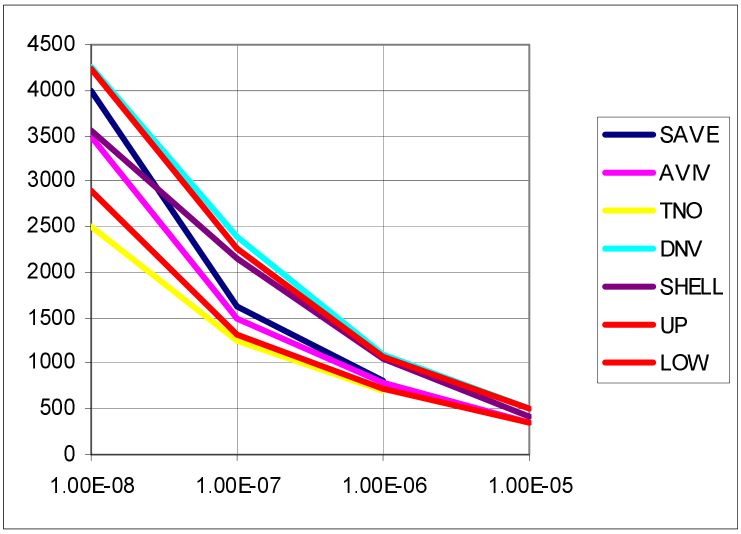
Appendix 1 Summary of the results

Distances (in meters) to a certain individual risk level

In this section of Appendix 1 the results of the participants to the BRAM study for individual risk is given. The limits of the upper and lower 95% confidence interval assuming normally distributed results have been given in the tables as well as in the figures.

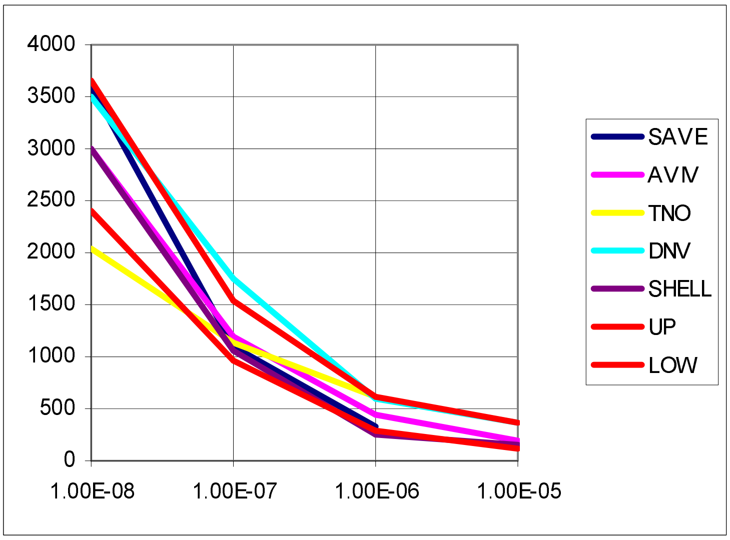
The whole site

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05		350		500	414	497	346	1.4
1.00E-06	810	800	710	1100	1053	1066	723	1.5
1.00E-07	1625	1500	1250	2400	2146	2259	1309	1.7
1.00E-08	4000	3500	2510	4250	3559	4230	2898	1.5



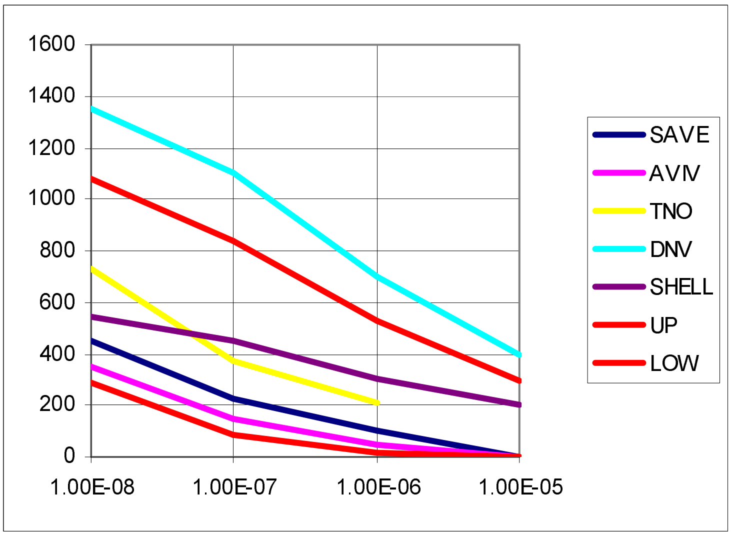
Marshalling yard

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05		200		375	150	360	124	3
1.00E-06	320	450	610	600	250	608	284	2
1.00E-07	1100	1200	1130	1750	1064	1533	964	2
1.00E-08	3600	3000	2030	3500	3003	3649	2405	2



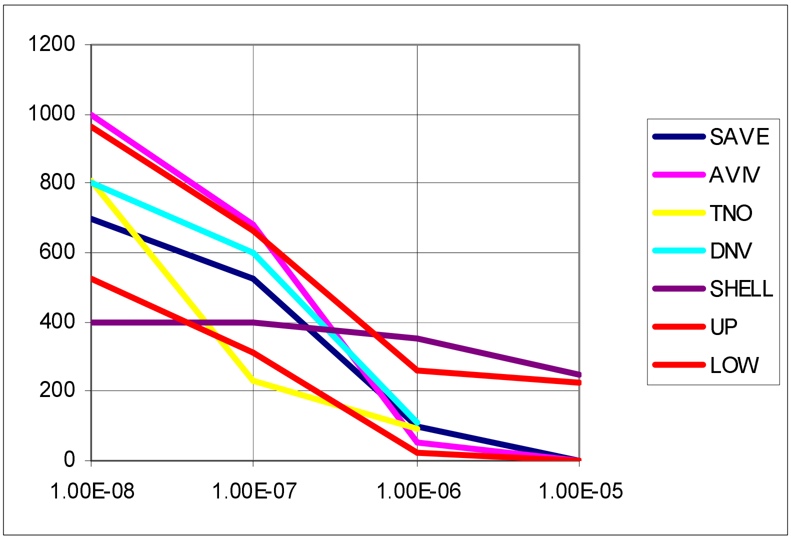
ACN

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0		400	200	299	0	
1.00E-06	100	50	210	700	300	530	14	38
1.00E-07	225	150	370	1100	450	836	82	10
1.00E-08	450	350	730	1350	546	1082	288	4



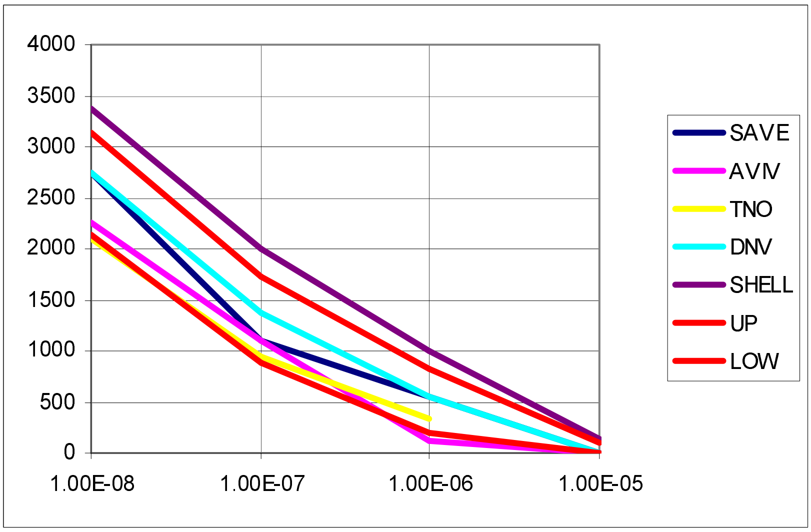
Butane

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0			250	228	0	
1.00E-06	100	50	90	110	350	260	20	13
1.00E-07	525	680	230	600	400	664	310	2
1.00E-08	700	1000	810	800	400	962	522	2



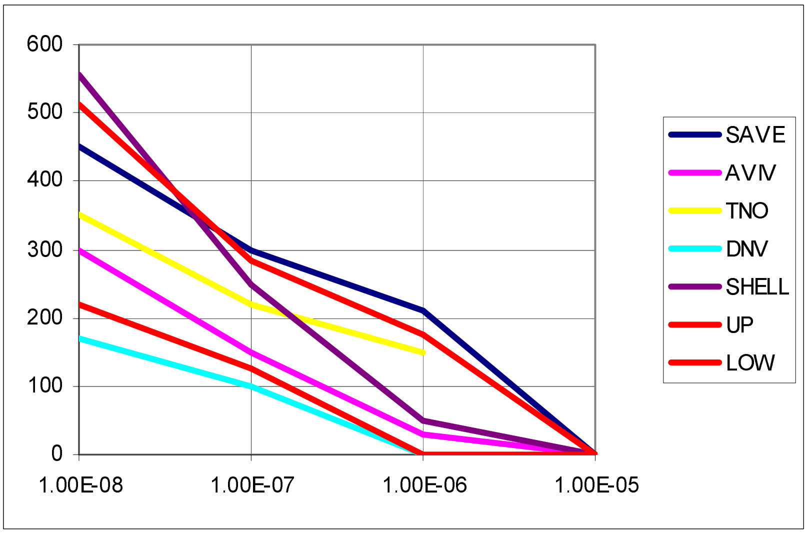
Chlorine

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0		0	130	98	0	
1.00E-06	550	125	340	550	991	832	190	4
1.00E-07	1100	1100	950	1375	1996	1720	888	2
1.00E-08	2750	2250	2090	2750	3364	3142	2140	1



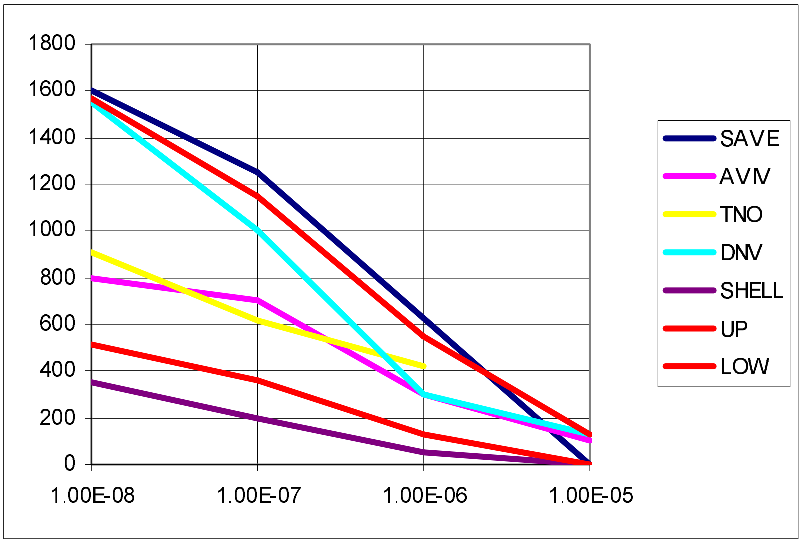
Ethox

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0			0	0	0	
1.00E-06	210	30	150	0	50	176	0	
1.00E-07	300	150	220	100	250	284	124	2
1.00E-08	450	300	350	170	557	513	218	2



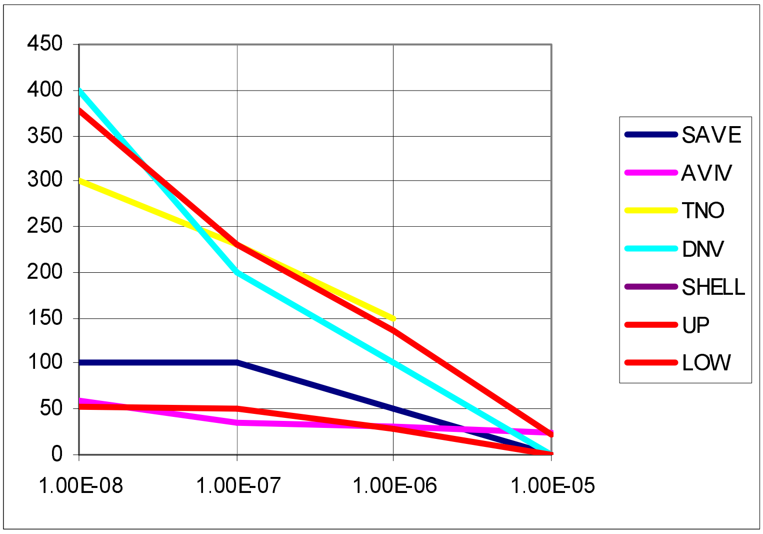
H_2S

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	100		130	0	125	0	
1.00E-06	625	300	420	300	50	548	130	4
1.00E-07	1250	700	620	1000	200	1152	356	3
1.00E-08	1600	800	910	1550	350	1572	512	3



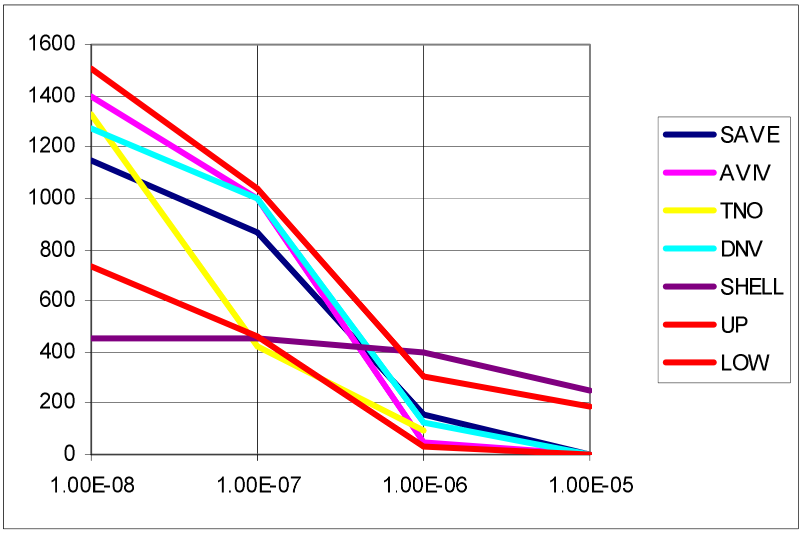
Pesticide storage

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	25		0		23	0	
1.00E-06	50	30	150	100		136	29	5
1.00E-07	100	35	230	200		231	51	5
1.00E-08	100	60	300	400		377	53	7



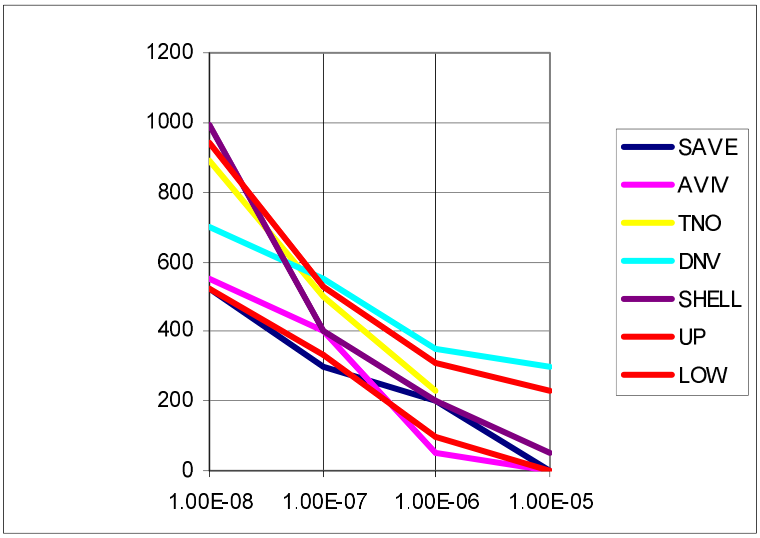
Propane

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0		0	250	188	0	
1.00E-06	160	50	90	125	400	303	27	11
1.00E-07	870	1000	420	1000	450	1039	457	2
1.00E-08	1150	1400	1330	1275	450	1507	735	2



SO_2

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	UP/LOW
1.00E-05	0	0		300	50	231	0	
1.00E-06	200	50	230	350	200	313	99	3
1.00E-07	300	400	500	550	400	527	333	2
1.00E-08	525	550	890	700	996	939	525	2

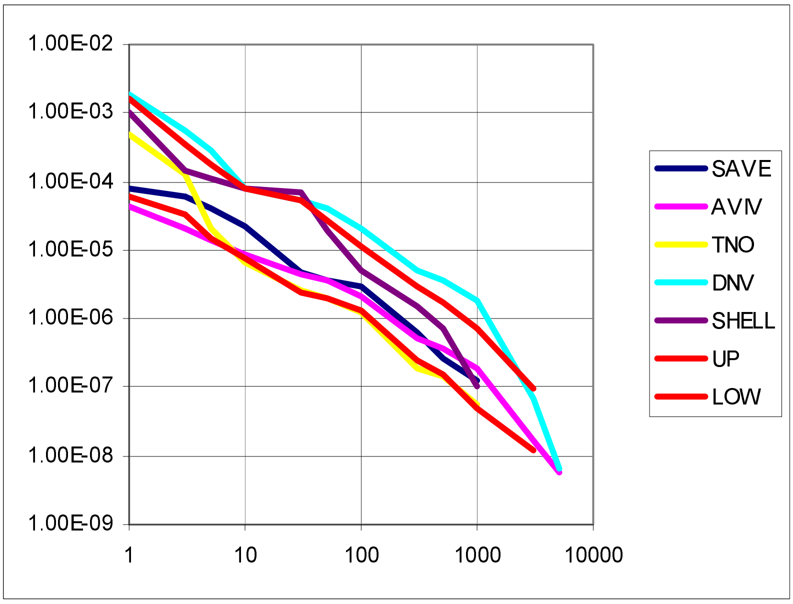


Societal Risk

In this section of the appendix the results for societal risk are given. The societal risk is defined as the probability that in a single accident in the hazard source a certain number of victims is exceeded. It is expressed as the relationship between the number of people killed (given in the first column) and the probability per year that that number is exceeded. The upper and lower 95% confidence interval is calculated on the assumption that the frequencies calculated by the various participants have a log normal distribution.

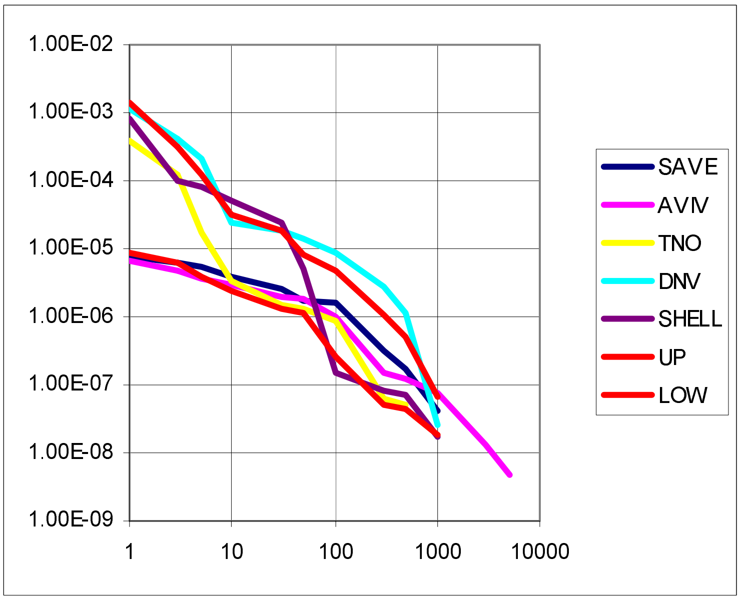
The whole establishment

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	7.70E-05	4.31E-05	5.00E-04	1.90E-03	1.00E-03	1.62E-03	6.15E-05	26
3	6.20E-05	2.13E-05	1.28E-04	5.39E-04	1.50E-04	3.50E-04	3.24E-05	11
5	4.00E-05	1.36E-05	2.06E-05	2.85E-04	1.10E-04	1.77E-04	1.48E-05	12
10	2.20E-05	8.57E-06	6.66E-06	7.90E-05	8.00E-05	7.81E-05	7.36E-06	11
30	4.80E-06	4.34E-06	2.52E-06	5.33E-05	7.00E-05	5.40E-05	2.42E-06	22
50	3.50E-06	3.66E-06	1.93E-06	4.11E-05	2.00E-05	2.68E-05	1.98E-06	14
100	3.00E-06	2.07E-06	1.26E-06	2.05E-05	5.00E-06	1.11E-05	1.31E-06	8
300	6.30E-07	5.18E-07	1.87E-07	5.08E-06	1.50E-06	2.96E-06	2.48E-07	12
500	2.70E-07	3.60E-07	1.43E-07	3.55E-06	7.00E-07	1.74E-06	1.50E-07	12
1000	1.30E-07	1.88E-07	5.78E-08	1.87E-06	1.00E-07	7.36E-07	5.03E-08	15
3000		1.65E-08		6.92E-08		9.31E-08	1.23E-08	8
5000		5.90E-09		6.67E-09				
10000								



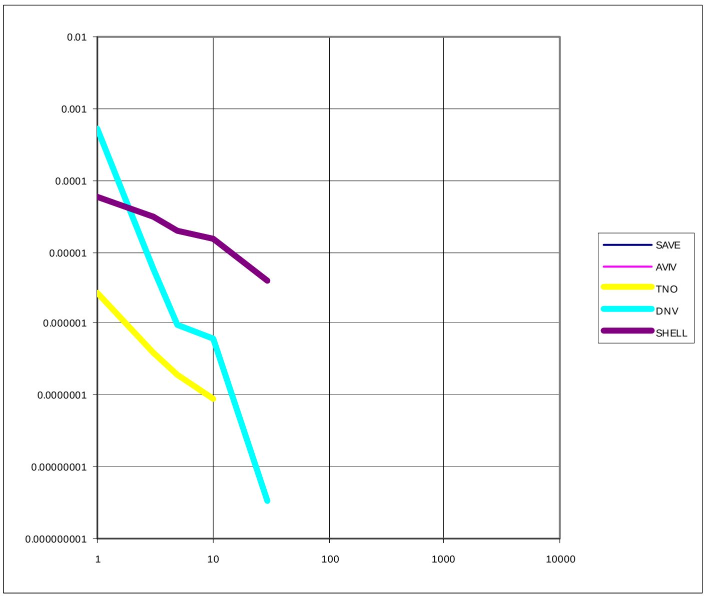
marshalling yard

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	7.50E-06	6.70E-06	0.000387	1.16E-03	8.00E-04	1.45E-03	8.74E-06	166
3	6.40E-06	4.70E-06	0.00012	4.27E-04	1.00E-04	3.12E-04	6.04E-06	52
5	5.30E-06	3.70E-06	1.67E-05	2.05E-04	8.00E-05	1.25E-04	3.95E-06	32
10	4.00E-06	2.90E-06	3.41E-06	2.48E-05	5.00E-05	3.21E-05	2.34E-06	14
30	2.50E-06	2.00E-06	1.49E-06	1.80E-05	2.40E-05	1.87E-05	1.35E-06	14
50	1.70E-06	1.80E-06	1.29E-06	1.44E-05	5.00E-06	8.44E-06	1.14E-06	7
100	1.60E-06	9.70E-07	8.81E-07	8.88E-06	1.50E-07	4.86E-06	2.62E-07	19
300	3.20E-07	1.50E-07	6.42E-08	2.82E-06	8.00E-08	1.08E-06	5.08E-08	21
500	1.70E-07	1.20E-07	5.11E-08	1.12E-06	7.00E-08	5.09E-07	4.55E-08	11
1000	4.10E-08	7.70E-08		2.62E-08	1.70E-08	6.57E-08	1.80E-08	4
3000		1.30E-08						
5000		4.70E-09						
10000								



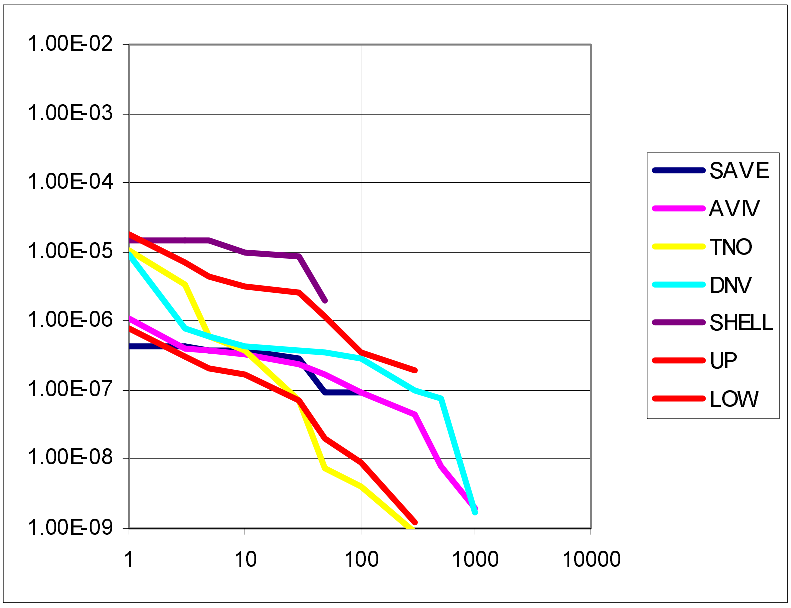
ACN

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1			2.61E-06	0.000513	6.00E-05	6.15E-04	3.03E-06	203
3			4.00E-07	5.96E-06	3.00E-05	3.68E-05	4.69E-07	78
5			1.98E-07	9.70E-07	2.00E-05	1.63E-05	1.50E-07	109
10			9.00E-08	6.31E-07	1.50E-05	1.25E-05	7.17E-08	175
30				3.45E-09	4.00E-06	1.72E-05	7.99E-10	21579
50								
100								
300								
500								
1000								
3000								
5000								
10000								



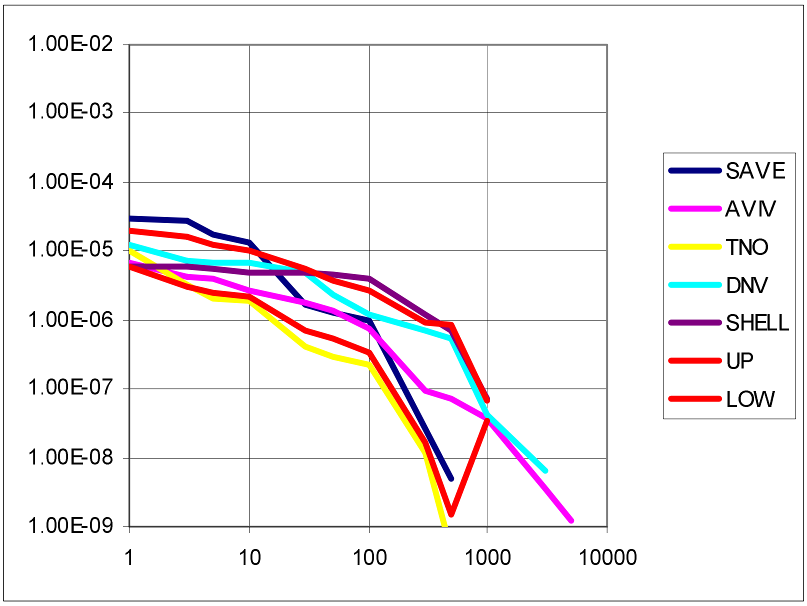
Butane

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	4.30E-07	1.10E-06	1.08E-05	9.44E-06	1.50E-05	1.83E-05	7.62E-07	24
3	4.20E-07	4.00E-07	3.35E-06	7.92E-07	1.50E-05	6.95E-06	3.08E-07	23
5	3.80E-07	3.80E-07	6.03E-07	6.03E-07	1.50E-05	4.53E-06	2.01E-07	23
10	3.80E-07	3.30E-07	3.76E-07	4.37E-07	1.00E-05	3.16E-06	1.68E-07	19
30	2.80E-07	2.30E-07	6.98E-08	3.76E-07	8.50E-06	2.56E-06	7.15E-08	36
50	9.40E-08	1.70E-07	7.54E-09	3.45E-07	2.00E-06	1.17E-06	1.99E-08	59
100	9.00E-08	9.40E-08	3.96E-09	2.88E-07		3.52E-07	8.82E-09	40
300		4.50E-08	8.82E-10	9.70E-08		1.95E-07	1.26E-09	155
500		8.00E-09		7.82E-08				
1000		2.00E-09		1.73E-09				
3000								
5000								
10000								



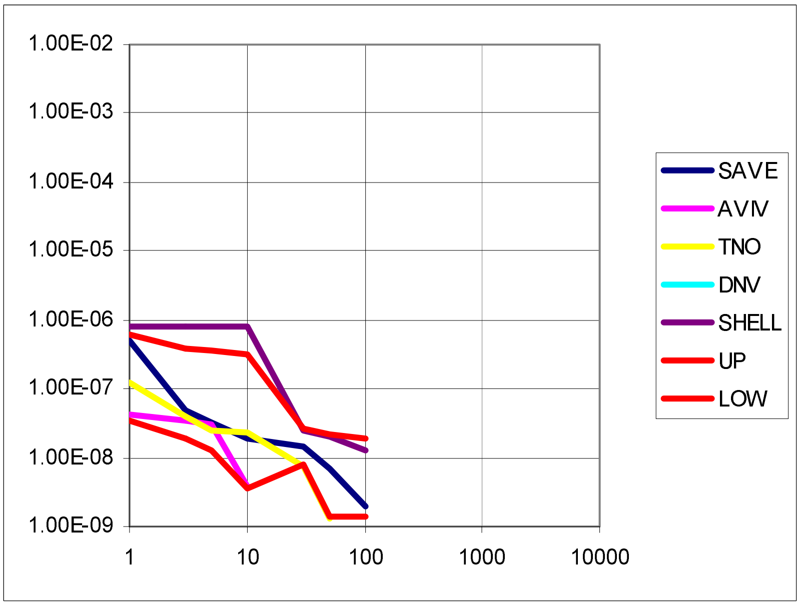
Chlorine

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	2.90E-05	6.60E-06	1.05E-05	1.25E-05	6.00E-06	2.04E-05	5.78E-06	4
3	2.70E-05	4.40E-06	3.22E-06	7.50E-06	6.00E-06	1.59E-05	3.11E-06	5
5	1.70E-05	4.00E-06	2.07E-06	7.03E-06	5.50E-06	1.21E-05	2.58E-06	5
10	1.30E-05	2.70E-06	1.87E-06	6.68E-06	5.00E-06	9.97E-06	2.18E-06	5
30	1.70E-06	1.80E-06	4.04E-07	5.05E-06	5.00E-06	5.61E-06	7.06E-07	8
50	1.30E-06	1.40E-06	2.99E-07	2.31E-06	4.50E-06	3.85E-06	5.20E-07	7
100	1.00E-06	7.40E-07	2.27E-07	1.16E-06	4.00E-06	2.66E-06	3.41E-07	8
300	2.70E-08	9.30E-08	1.18E-08	6.95E-07	1.20E-06	8.89E-07	1.62E-08	55
500	5.00E-09	7.20E-08	4.43E-10	5.26E-07	7.00E-07	8.36E-07	1.53E-09	546
1000		3.70E-08		4.26E-08	7.00E-08	6.70E-08	3.43E-08	2
3000		3.50E-09		6.67E-09				
5000		1.20E-09						
10000								



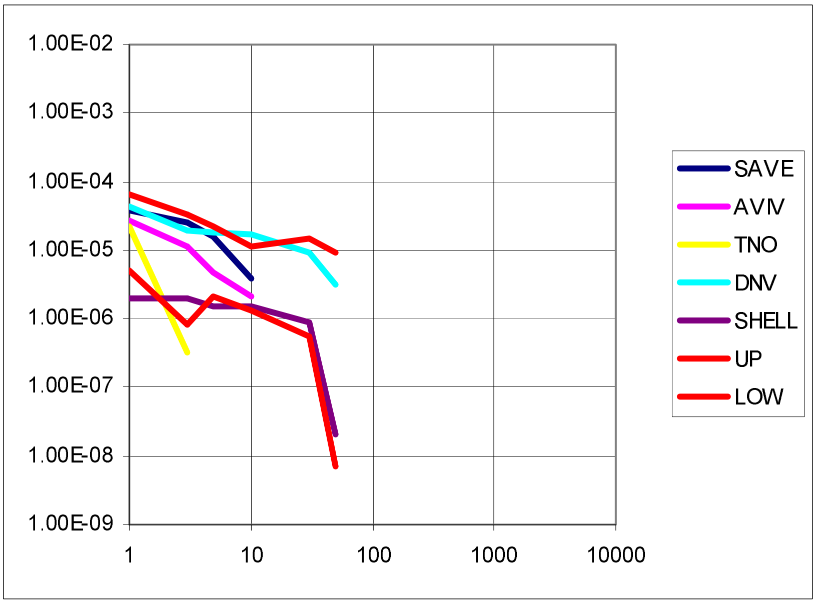
Ethox

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	5.00E-07	4.20E-08	1.27E-07	3.13451E-08	8.00E-07	6.20E-07	3.45E-08	18
3	4.70E-08	3.50E-08	4.04E-08		8.00E-07	3.81E-07	1.91E-08	20
5	3.30E-08	3.10E-08	2.40E-08		8.00E-07	3.51E-07	1.26E-08	28
10	1.90E-08	3.90E-09	2.27E-08		8.00E-07	3.23E-07	3.60E-09	90
30	1.50E-08		7.49E-09		2.50E-08	2.58E-08	7.70E-09	3
50	6.80E-09		1.29E-09		2.00E-08	2.23E-08	1.41E-09	16
100	2.00E-09				1.30E-08	1.92E-08	1.36E-09	14
300					0.00E+00			
500					0.00E+00			
1000					0.00E+00			
3000								
5000								
10000								



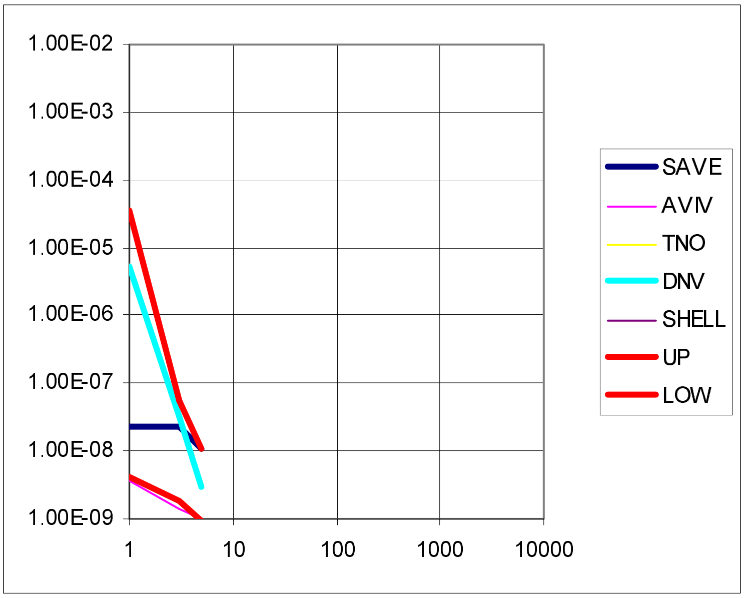
H_2S

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	3.80E-05	2.70E-05	2.29E-05	4.42782E-05	2.00E-06	6.51E-05	5.17E-06	13
3	2.60E-05	1.10E-05	3.22E-07	1.93E-05	2.00E-06	3.22E-05	8.16E-07	40
5	1.60E-05	4.80E-06		1.87E-05	1.50E-06	2.21E-05	2.10E-06	11
10	4.00E-06	2.10E-06		1.72E-05	1.50E-06	1.13E-05	1.30E-06	9
30				9.11E-06	9.00E-07	1.47E-05	5.57E-07	26
50				3.22E-06	2.00E-08	9.21E-06	6.98E-09	1318
100								
300								
500								
1000								
3000								
5000								
10000								



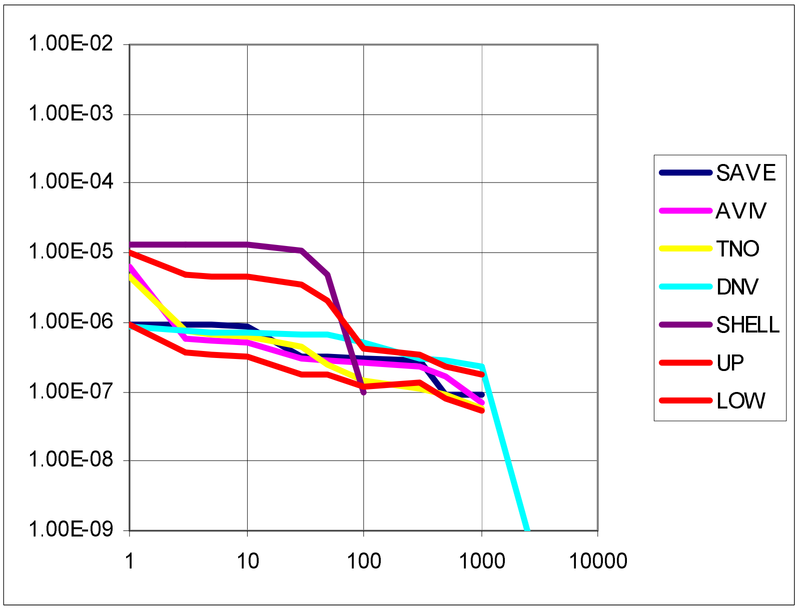
Pesticide storage

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	2.30E-08	3.60E-09	5.36E-05	5.25E-06		3.55E-05	4.31E-09	8232
3	2.30E-08	1.40E-09		3.13E-08		5.55E-08	1.81E-09	31
5	1.10E-08	1.00E-09		2.96E-09		1.06E-08	9.61E-10	11



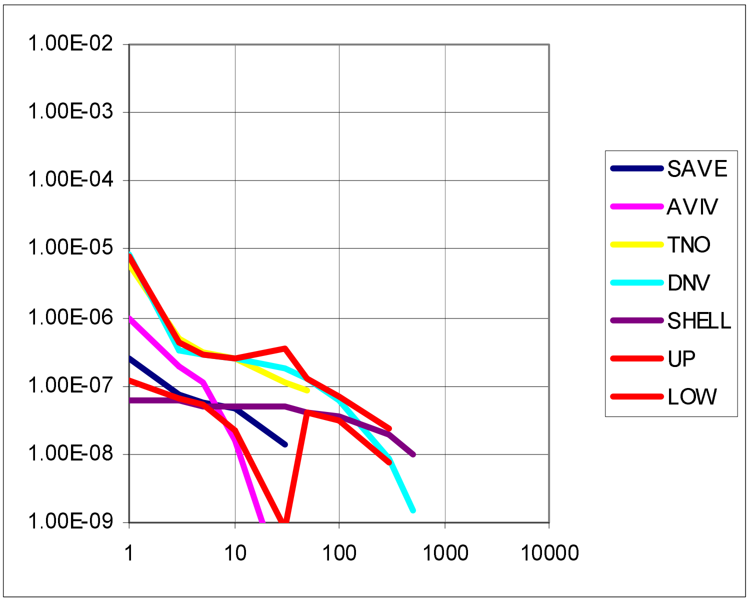
Propane

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	9.40E-07	6.30E-06	4.58E-06	8.61E-07	1.30E-05	1.04E-05	9.43E-07	11
3	9.40E-07	5.80E-07	7.50E-07	7.35E-07	1.30E-05	4.78E-06	3.60E-07	13
5	9.30E-07	5.60E-07	6.56E-07	7.19E-07	1.30E-05	4.71E-06	3.38E-07	14
10	8.60E-07	5.20E-07	6.35E-07	7.15E-07	1.30E-05	4.63E-06	3.19E-07	15
30	3.30E-07	3.10E-07	4.33E-07	6.73E-07	1.10E-05	3.57E-06	1.79E-07	20
50	3.30E-07	2.90E-07	2.46E-07	6.63E-07	5.00E-06	2.08E-06	1.73E-07	12
100	3.00E-07	2.70E-07	1.44E-07	5.10E-07	1.00E-07	4.30E-07	1.19E-07	4
300	2.80E-07	2.30E-07	1.10E-07	3.05E-07	0.00E+00	3.43E-07	1.36E-07	3
500	9.30E-08	1.60E-07	9.09E-08	2.74E-07	0.00E+00	2.34E-07	8.22E-08	3
1000	8.80E-08	7.20E-08	5.78E-08	2.27E-07	0.00E+00	1.74E-07	5.23E-08	3
3000				3.61E-10				
5000								
10000								

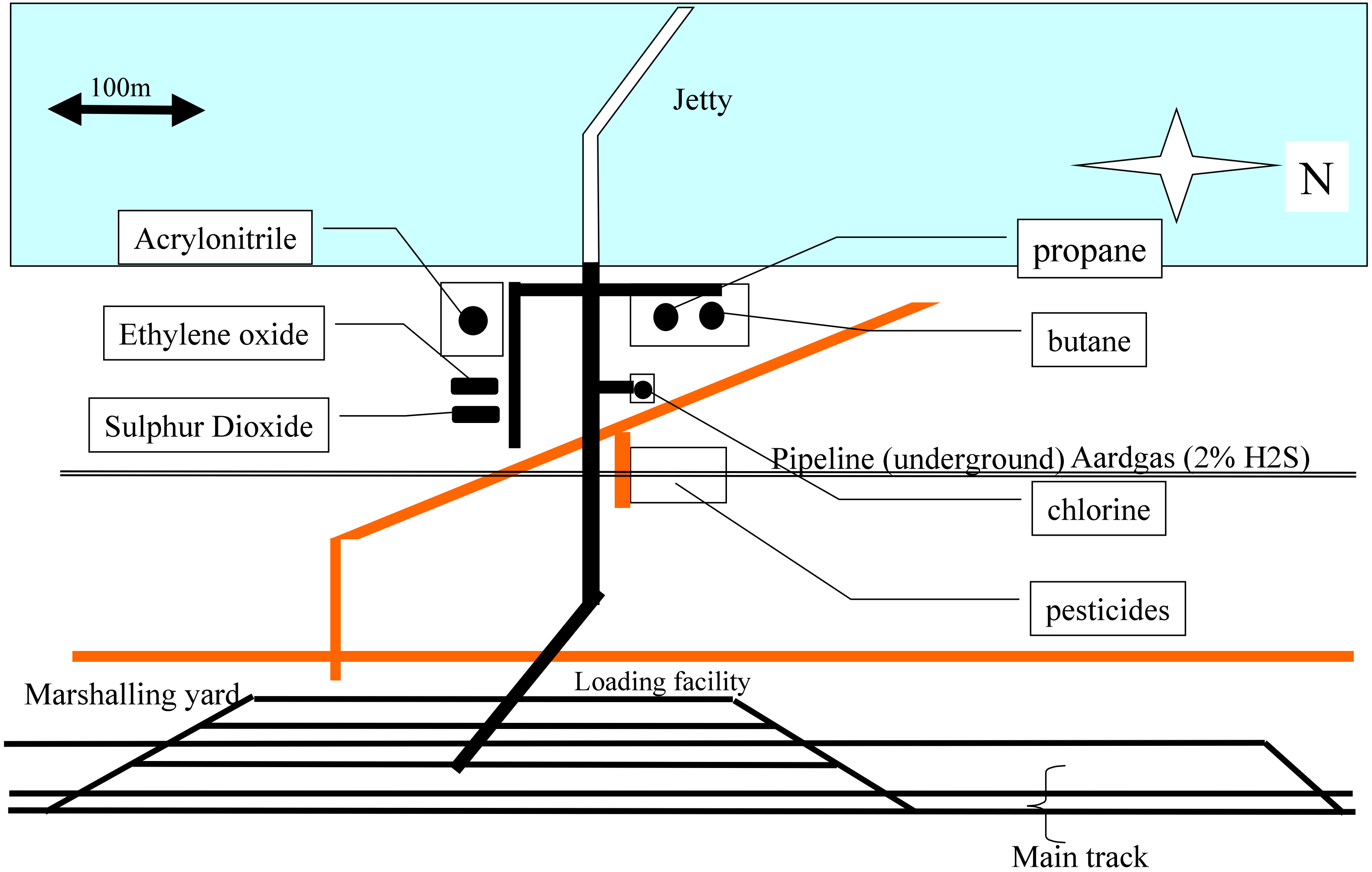


SO_2

	SAVE	AVIV	TNO	DNV	SHELL	UP	LOW	ÚP/LOW
1	2.50E-07	1.00E-06	6.05E-06	8.45E-06	6.00E-08	7.73E-06	1.16E-07	67
3	7.30E-08	1.90E-07	5.08E-07	3.23E-07	6.00E-08	4.25E-07	6.69E-08	6
5	5.90E-08	1.10E-07	3.10E-07	2.95E-07	5.00E-08	2.95E-07	5.24E-08	6
10	4.60E-08	1.60E-08	2.58E-07	2.58E-07	5.00E-08	2.53E-07	2.25E-08	11
30	1.40E-08	1.00E-10	1.16E-07	1.84E-07	5.00E-08	3.59E-07	8.22E-10	436
50			8.30E-08	1.25E-07	4.00E-08	1.33E-07	4.19E-08	3
100				6.17E-08	3.50E-08	6.94E-08	3.11E-08	2
300				8.75E-09	2.00E-08	2.37E-08	7.37E-09	3
500				1.48E-09	1.00E-08			
1000								
3000								
5000								
10000								



Appendix 2 The plant



Appendix 3 Mailing list

1 - 15	Directoraat-Generaal Milieubeheer, directie Lokale Milieukwaliteit en Verkeer
16	plv. Directeur-Generaal Milieubeheer
17	Depot Nederlandse Publikaties en Nederlandse Bibliografie
18	Directie RIVM
19	Directeur Sector Risico's, Milieu en Gezondheid
20	Hoofd van het Laboratorium voor Stralingsonderzoek
21 – 26	Auteurs
27	SBD/Voorlichting & Publications
28	Bureau Rapportenregistratie
29	Bibliotheek RIVM
30	Bibliotheek LSO
31– 41	Bureau Rapportenbeheer
42– 46	Reserve-exemplaren LSO