



## **Assessment of uncertainties in risk analysis of chemical establishments. The ASSURANCE project. Final summary report**

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# **Assessment of Uncertainties in Risk Analysis of Chemical Establishments**

## **The ASSURANCE project**

### **Final summary report**

**Kurt Lauridsen, Igor Kozine, Frank Markert**

**Aniello Amendola, Michalis Christou, Monica Fiori**

# **Assessment of Uncertainties in Risk Analysis of Chemical Establishments**

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### **Final summary report**

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**May 2002**

**Abstract** This report summarises the results obtained in the ASSURANCE project (EU contract number ENV4-CT97-0627). Seven teams have performed risk analyses for the same chemical facility, an ammonia storage. The EC's Joint Research Centre at Ispra and Risø National Laboratory co-ordinated the exercise and led the comparison of results in order to reveal the causes for differences between the partners' results. The results of the project point to an increased awareness of the potential uncertainties in risk analyses and highlight a number of important sources of such uncertainties. In the hazard identification phase it was revealed that the ranking of hazardous scenarios by probabilistic and deterministic approaches could result in completely different conclusions. On the other hand, despite a large difference in frequency assessments of the same hazardous scenarios, there was good consensus on the ranking among the adherents of the probabilistic approach. Breaking down the modelling of both frequency and consequence assessments into suitably small elements and conducting case studies allowed identifying root causes of uncertainty in the final risk assessments. Large differences were found in both the frequency assessments and in the assessment of consequences. The report gives a qualitative assessment of the importance to the final calculated risk of uncertainties in assumptions made, in the data and the calculation methods used. This assessment can serve as a guide to areas where, in particular, caution must be taken when performing risk analyses.

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# 1 Introduction

This report is the publishable final report of the ASSURANCE project, which was running from May 1998 to April 2001. The central element in the project was a benchmark analysis where seven different teams performed a risk analysis of the same chemical facility, an ammonia storage.

The project was carried out by a consortium with the following members:

- Det Norske Veritas Limited, UK
- INERIS, Fr
- Health and Safety Executive, Major Hazards Assessment Unit, UK
- NCSR DEMOKRITOS Systems Safety and Risk Assessment, GR
- TNO, Dept. of Industrial Safety, NL
- Università di Bologna, DICMA, IT
- VTT Automation, FI
- The Joint Research Centre, Ispra
- Risø National Laboratory, DK

The JRC, Ispra, and Risø National Laboratory co-ordinated the project and drafted the concluding reports on the basis of the partners' analysis reports and discussions in the consortium at workshops.

The benchmark study had five phases: a documentation phase, three working phases, and an evaluation and dissemination phase. The working phases comprised a qualitative analysis phase, a quantitative analysis phase and a phase where detailed mechanisms were studied by means of case studies.

In addition to the present report the project has produced a number of other internal reports. The seven partners performing the risk analyses have produced comprehensive reports on their findings in the qualitative, quantitative and case study phases, and the co-ordinating partners have produced detailed reports about the comparisons of the risk analyses and case studies (cf. Chapter 9). These reports have not been made publicly available because they contained not consolidated discussion of the results or reference to partners confidential documents. The present report aims to contain sufficient details to diffuse the major lessons learnt to the wider risk assessment community.

## 2 General notes on uncertainty in risk analysis

Whereas Quantitative Risk Assessment (QRA) aims at the modelling of stochastic uncertainties associated with the occurrence and circumstances of a major accident, the process itself of carrying out a QRA is linked with several uncertainties. For the implementation of the risk assessment procedure a variety of techniques and models must be used, and uncertainties are introduced due to imperfect knowledge and expert judgement. As QRA is used as input in many decisions related to the control of major accident hazards and the need for accuracy in the results increases, the adequate management of these uncertainties gains increased importance.

An important source of differences in risk analysis is introduced by national philosophies underlying the analyst's effort. In addition, the application of different methods and methodologies will contribute to the total uncertainty/variability of the final outcome of a risk analysis. The complexity of establishing a model for the systems derives from the large number of different components, the control equipment used in modern processes and the interactions between all components and equipment, and the human operator. Further, uncertainty is introduced by the physical modelling tools, as they treat e.g. release and dispersion phenomena, according to the relevant meteorological and environmental conditions. Uncertainty is also connected to dose-consequences relationships. Finally, there is uncertainty resulting from the various judgements of the analysts during a risk analysis. This is an unavoidable part of the process, and depends very much on the background and the operational field of the experts. Other practical constraints (e.g. time and resources) may also result in different degrees of simplifications, which in turn add to the variability of the results.

However, despite the fact that the approach and definitions for risk analysis vary in the risk assessment community; in general, it is considered that uncertainty is of two types:

- Aleatory, also known as stochastic uncertainty or due to randomness. This can be called irreducible. Even if a certain narrowing of the range in which the risk figures are defined can be achieved through a better knowledge of their distributions, quantities such as failure rates, and meteorological conditions at the time of a release, size of a breakage etc. can only be defined through probability distributions. Aleatory uncertainties can be treated by well-established methods, e.g. propagated through the analysis by Monte Carlo simulation.
- Epistemic (also called reducible uncertainty) is related to incomplete knowledge about phenomena of concern and inadequate matching of available databases to the case under assessment, etc.

A great challenge is to treat epistemic uncertainties that come from incomplete (or lack of) knowledge about fundamental phenomena. In fact, any benchmark exercise is directed toward the analysis of uncertainty due to lack of knowledge. As far as physical modelling is concerned, this is made generally by benchmarking different models with respects to experimental reference data sets.

However this way of considering uncertainties does not cover what can be defined "operational" uncertainty, as discussed in the following. Indeed even in comparing physical models, many times experience has shown the importance of the "human factor", i.e. the use of the same computer code by different analysts resulting in a significant differences.

The variability in the assessments of commonly defined representative risk figures and completeness of hazardous and basic/intermediate events identified by different expert teams reflect both the degree of epistemic uncertainty, and the "operational" variability. Furthermore, when the risk figures are defined as "point values", the variability is also due to "aleatority": different point values assumed for basic events or parameters may have been selected by the same distribution. However an early exercise on systems reliability has shown that the error ranges assessed by the single teams are significantly narrower than the ranges of point values assumed by the involved teams.<sup>1</sup>

Furthermore, and differently, the uncertainty has been categorised into three types: parameter uncertainty, modelling uncertainty, and completeness uncertainty. Parameter uncertainty results from the variability in numerical input data for the same events and characteristics. Modelling uncertainty can be thought of as addressing the uncertainty in the appropriateness of the structure or mathematical form of the model. And completeness uncertainty is a special category of model uncertainty that is associated with the degree to which the model addresses all the phenomena associated with the system being modelled. This classification seems to fit better the nature of the spread found by benchmarking different assessments of

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<sup>1</sup> A. Amendola: Uncertainties in Systems Reliability Modelling: Insight gained through European Benchmark Exercises. Nucl. Eng. Des. 93 (1986) 215-225



a common case. But we prefer to maintain the term "operational" which includes a number of different issues linked with the choices performed by an analyst (or a team of analysts):

- the implicit or explicit assumptions about the "nature" of probability, and choices among databases, and within a same data base
- the choice of the modelling for hazards identification, for structuring the quantification of the event frequencies, (in theory a different system decomposition for the modelling should result in similar frequencies if data are adapted consistently, but in the practice the choice might bias in some way the results)
- the choice and the use of the physical models (which only in part derive from epistemic uncertainty)
- the bias introduced by the context (e.g. in a regulatory environment which in some way prescribes certain parameters, models)
- the completeness of the analysis, which can derive from practical constraints but also choices in the boundaries
- the basic experience of the analysts and his operational background etc.

By introducing this definition, one can differentiate the case in which the knowledge does not exist (what really collectively is not well known and therefore there is an epistemic uncertainty) from the real operational aspects of the analysis, which is made of judgement and constraints.

## 3 The documentation phase

The first phase of the ASSURANCE project was a documentation and plant familiarisation phase where documentation from the plant was collected and distributed to the partners. During the documentation phase a visit to the site was arranged, so that all partners had the opportunity to get familiar – to a certain extent – with the reference plant and pose questions to the staff. Further questions were asked and answered as the documentation was provided. Practical and economical reasons limited the number of site visits to only one, whereas the gap of limited access to information was bridged with an extensive “questions-and-answers” session, the adoption of common assumptions and the use of common fictitious data. Because a detailed analysis of human and managerial factors was outside the scope of the project, this procedure should not have introduced a significant bias in the analysis of the uncertainties. The plant documentation was compiled in [1] together with common assumptions and the above mentioned questions and answer. As it was a prerequisite from the plant owners that the identity of the plant should not be revealed, changes were made in the descriptions of surroundings and weather conditions. Furthermore, a more dense population than near the real plant was assumed in order to avoid that low risk values and therefore low doses involved could increase significantly the spread of the results, since the uncertainties both on concentrations and on probit values are quite larger at large distance from the plant.

### 3.1 Description of the reference plant

The reference plant is an ammonia storage plant with the relevant loading/unloading facilities. The plant is part of a large industrial complex and it serves in feeding a fertiliser plant with ammonia. For reasons of simplicity and due to the limited scope of the study, only the sections related to ammonia storage and loading/unloading are considered.

Both refrigerated storage and storage under pressure takes place in the plant. Ammonia is imported by ship, by truck tankers or from an ammonia feed pipeline, which transfers it from a production site located

away from the industrial complex where the reference plant belongs. From the storage area ammonia is sent to the fertilisers plant according to the demand. The functioning of the whole system is schematically presented in Figure 1.

The ammonia storage plant is therefore divided into the following sections:

- (i) Cryogenic ammonia storage
- (ii) Ammonia unloading/loading ship terminal
- (iii) Ammonia feed pipeline and terminal
- (iv) Storage of ammonia under pressure
- (v) Loading/unloading station from truck tankers

An outline of the most important components is given in Figure 2.

Refrigerated (cryogenic) ammonia storage takes place in a cylindrical stainless steel tank with a capacity of 15000 te of liquefied ammonia at -33°C temperature and atmospheric pressure (operating pressure 150 – 350 mmH<sub>2</sub>O). The tank is surrounded by a concrete wall, which also acts as a containment basin. The space at the top of the tank and the concrete wall is sealed and nitrogen under slight overpressure is maintained in the space between steel and concrete walls. The roof and the basement of the tank are insulated, too. A refrigeration system consisting of 3 compressors and 2 condensers keeps the temperature low. The tank is loaded by ships arriving at a nearby terminal and sometimes by a small amount of ammonia from the Ammonia Feed Pipeline (from the ammonia production site). Liquid ammonia is pumped to the fertilisers plant (USERS) and/or the pressurised storage tanks after having heated up to about 15-20°C at a pressure of 24.5 bars.

The ammonia unloading/loading ship terminal, is located on the river (see Figure 2) and handles cryogenic ammonia at -33°C. The ships, each of capacity of about 8 000 – 10 000 te, arrive from the sea and along the river at the terminal and unload ammonia to the cryogenic tank at a rate of about 700 m<sup>3</sup>/h. The unloading procedure is supervised by the staff of the cryogenic storage.

The ammonia feed pipeline connects the storage under study with the ammonia production plant. Its diameter is 8” and it runs mostly underground. Thirteen Motor Operated Valves placed along the pipeline divide it into sections. The analysis of the pipeline is limited to its final section, i.e. after valve N° 12 (which is located within the borders of the establishment). Liquid ammonia at 10-25°C temperature and 24.5 bar pressure is transported from the ammonia production plant to the cryogenic storage tank (only a small amount of about 5 te/hr), to the pressurised storage area and to the fertiliser plant. The maximum annual import of the ammonia feed pipeline is 300 000 te/yr.

The ammonia storage under pressure consists of 10 horizontal cylindrical tanks of 200 m<sup>3</sup> each, that is a maximum capacity of 100 te each (1000 te total) of ammonia at ambient temperature and a maximum pressure of 17 bar. The pressurised tanks are mainly loaded from truck tankers, but they can receive ammonia either from the pipeline or from the cryogenic tank (heated up to 15-20°C and 24.5 bar). The pressurised tanks can feed the fertilisers plant with ammonia.

The truck loading/unloading facility, operated by the pressurised storage staff, is located at 200m distance from the pressurised storage area. Trucks with a capacity of 24 te of ammonia arrive at the loading/unloading station, where unloading takes place due to pressure difference (ammonia flows from the truck to the tank, where the pressure is lower).

All of the above mentioned components are equipped with adequate safety and control systems and instruments. In the case of an emergency at any part of the storage (cryogenic or pressurised), gaseous ammonia can be diverted to a flare located near the cryogenic tank.

The surroundings of the plant include a densely populated urban area, a small village, an industrial and commercial area (occupied mainly during the day), a stadium (occupied only a few hours per week) and a tourist resort, very crowded during the summer.

Indicative distances between main components and pipeline lengths:

Ship loading/unloading arm – Cryogenic tank: 900 m

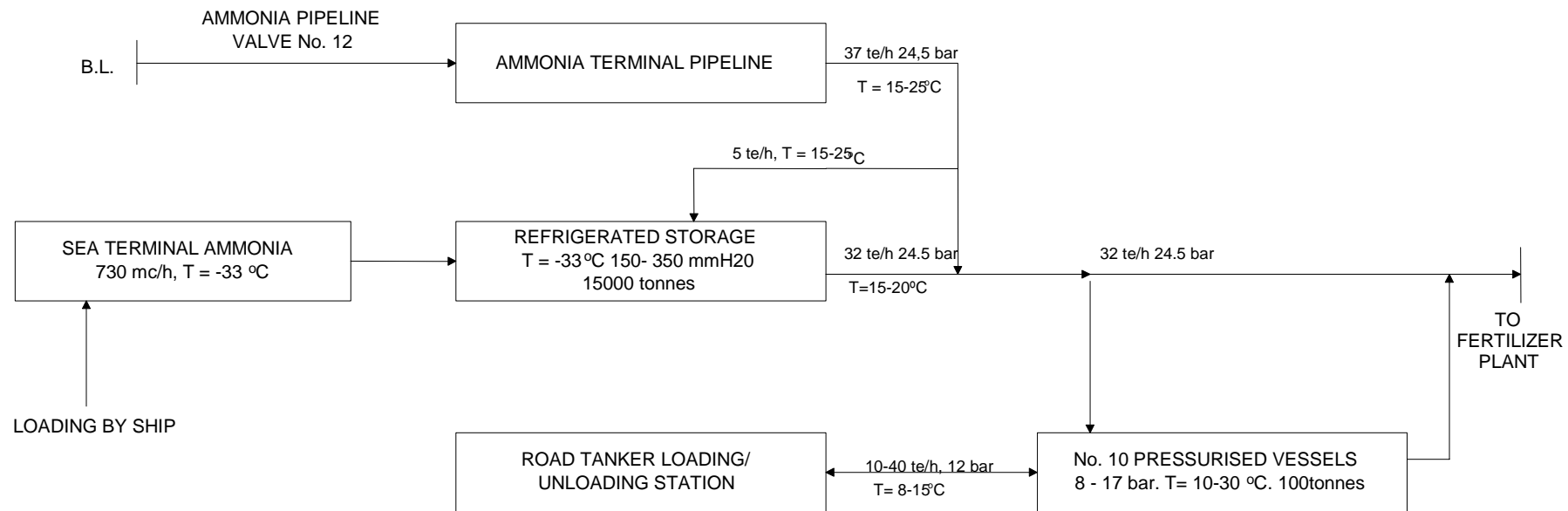
Cryogenic tank – Pipeline terminal: 50 m

Pipeline Valve 12 – Pipeline terminal: 966 m

Cryogenic tank – Pressurised storage area: distance=1200m, pipework=1500m

Cryogenic tank – Flare: 20m (flare at a height of 45m)

Pressurised storage area – Trucks loading/unloading facility: 200 m.



**Figure 1 Schematic presentation of the functioning of the reference plant**

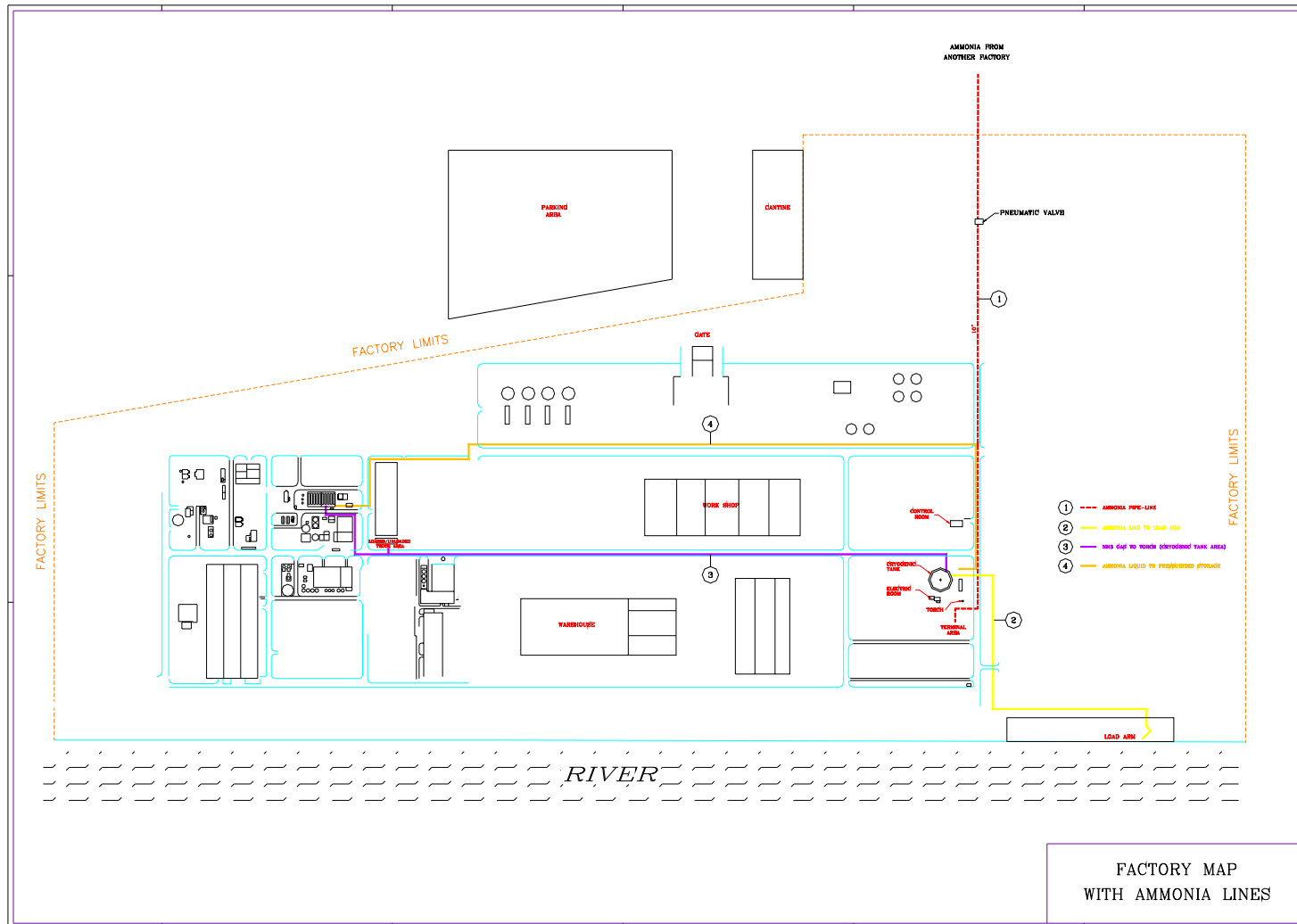


Figure 2 Outline of the reference plant

## 4 The qualitative analysis phase

The second phase of the project was a qualitative analysis phase (including hazard identification and qualitative risk ranking). Seven partners carried out hazard identification and screening on the facility. Two partners, the JRC, Ispra, and Risø National Laboratory drafted the comparison report on the basis of the partners' reports. The whole consortium discussed the findings at a workshop before the report on Qualitative Analysis was finalised.

After the documentation phase, still unresolved questions were discussed by email, ensuring that the same information became available to all the partners. Out of several reasons also common assumptions and reporting formats were agreed on during the workshop.

The qualitative analysis by the participants resulted in a starting point for the quantification (identification of hazards to be quantified in a later stage) and a ranking of the accidents likely to cause damage beyond the boundaries of the plant site. The main items emerging from the more extensive analysis described in the comparison report can be summarised as follows:

- Many different approaches for hazard identification were used
- Hazard identification was done using a combination of complementary approaches
- Three groups of approaches could be distinguished:
  - Methods based on a *top-down analysis*, mainly represented by the Master Logic Diagram, having a form similar to fault trees, starting from a top event and going down to combinations of basic events, capable to provoke accident;
  - Methods based on a *bottom-up analysis*, like HAZOP, SWIFT, HAZSCAN and HCA, which investigate whether deviations of the process variables and failures of individual devices can provoke a major accident; and
  - Methods based on the systematic identification of possible release events, mostly supported by the use of *checklists* or based on *national standards*, after division of the plant into areas.
- For several partners the definition and risk labelling of the categories used in the screening and ranking of identified hazards vary from project to project. No predefined categories are used.
- The understanding of what e.g. "catastrophic event" or "likely event" means differs from partner to partner. Therefore, great care has to be taken not to introduce misunderstandings using labels in discussions among experts or in risk communication to the public.
- The strategies to define consequence categories are rather different ranging from the application of release times, release rates, total releases and consequence lengths. Comparing these strategies, a very good correlation for the categories was found. Nevertheless, using only release rates to categorise may lead to larger differences in the screenings.
- The severity of the scenarios is assessed using an evaluation matrix defined by the categories for the frequencies and the consequences. In order to select the most important scenarios relevant for quantification the risk matrix is reduced. This is in most cases done by cutting off the scenarios in the lowest consequence category regardless the value of the frequency. In the second step, the next lowest consequence category combined with the lowest frequency category is also reduced.
- The scenarios with very low probability are preserved in the highest consequence categories. Some partners, furthermore, emphasise the importance of the consequences using marking.
- The scenarios selected by the partners differ substantially in detail, but the most important hazardous events were identified by all participants.

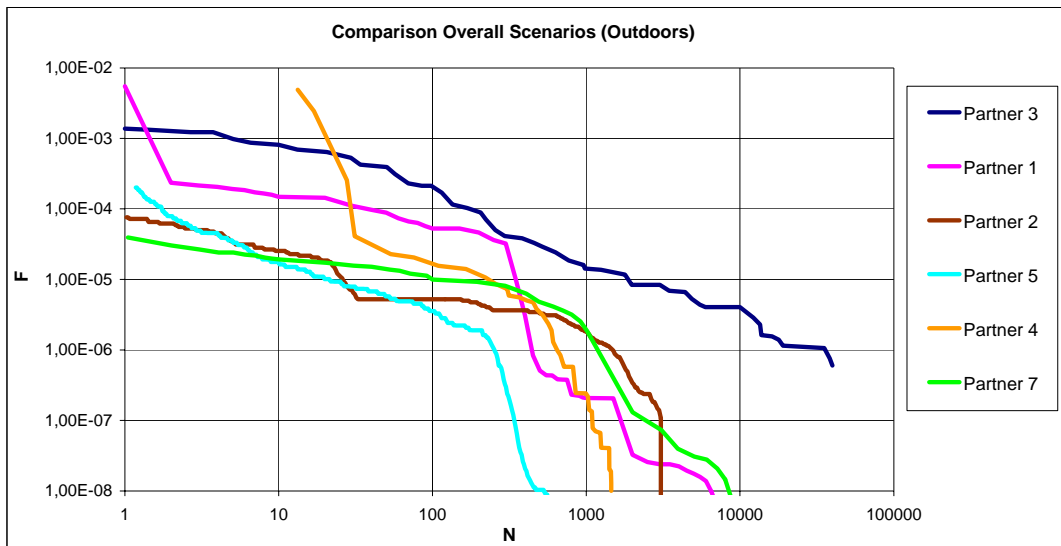
## 5 The quantitative analysis phase

In the third phase the seven teams performed a Quantitative Risk Analysis (QRA), according to their own experience, methodology and tools. Each team analysed the accident scenarios identified by the team itself during the qualitative phase, as well as the common reference scenarios (listed in ANNEX I). The results of the third phase were compared and discussed during a second workshop. At that workshop the details of special case studies to be evaluated in the fourth phase were agreed. The reference scenarios established in the first workshop constituted the basis of these case studies. Moreover, as far as possible, engineering assumptions were made on a common basis in order to eliminate their influence on the final results.

The first set of results concerned the assessment of individual risk – defined as the probability of fatality for a person living 24 hours a day at a specific position in the neighbourhood of the plant due to an accident at the plant – and the assessment of societal risk, expressing the frequency with which a certain number of fatalities or more may occur. The comparison of the results revealed significant variations. This outcome was not surprising, and it directed the project towards a careful examination of the causes of these discrepancies. Figure 3 and Figure 4 give examples of these discrepancies for individual risk and societal risk, respectively.



**Figure 3 Discrepancy in the results of individual risk calculations: Maximum and minimum distances for the isorisk curve  $10^{-5}$  yr<sup>-1</sup>**



**Figure 4 Discrepancy in societal risk calculations (based on fictitious population data)**

The differences depicted in Figure 3 and Figure 4 do not represent the most significant results from the project. Instead, they should be considered a starting point for the analysis of the results. In order to understand how individual effects contribute to the overall uncertainty, a number of scenarios, case studies and detailed analyses were performed. Available literature on uncertainty in risk assessment (see as an example<sup>2</sup>) discusses a number of theoretical and relevant issues, but is lacking empirical investigations of uncertainty and variability as they appear from in-field studies. Therefore it was necessary to investigate in depth a number of scenarios and case studies, as follows.

The investigations to find the causes for uncertainties in the quantitative results were logically divided in studies of factors related to the assessment of frequencies and factors related to the assessment of consequences.

## 5.1 Uncertainties related to the assessment of frequencies

### 5.1.1 Introductory notes

The assessment of the frequencies of hazardous events is primarily based upon logic structures such as event trees and fault trees, that identify the different combinations of more elementary events, called intermediate events for event trees and basic events for fault trees, that could lead to undesired system states. The types of basic events in PRA (Probabilistic Risk Assessment) include events such as: the failure of a pump to start, the failure of a pump to run for 24 hours, the occurrence of an initiating event such as overpressure in a vessel or pipe, failure of an operator to take the appropriate actions to prevent system damage. The majority of these basic events is regarded as resulting from random processes (aleatory uncertainty) and are described by probabilistic models.

As discussed at Section 2 the “operational” variability applies to all components of uncertainties and is difficult to single out from the other factors. However by following the more traditional way of dealing with the uncertainties, specifically for this stage it can be stated that modelling uncertainty

<sup>2</sup> J.C. Helton, and D.E. Burmaster, Eds., Special Issue on "Treatment of Aleatory and Epistemic Uncertainty". Reliability Engineering & System Safety 54, Nos. 2-3 (1996)



results from the use of different models (fault trees, event trees and simplified generic-based models). Completeness uncertainty is due to differences in the number and nomenclature of basic/intermediate and initiating events included in the modelling. And parameter uncertainty is due to different numerical inputs (basic/initiating event frequencies, in particular) used to assess the net frequency of a hazard.

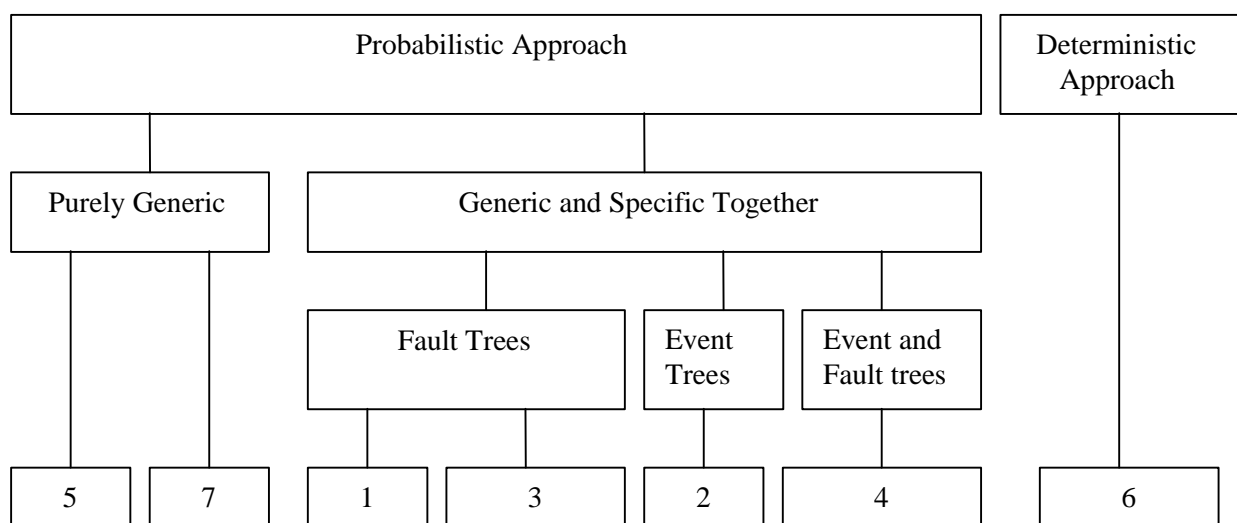
Completeness uncertainty can hardly be qualified quantitatively but only in a descriptive way like listing all basic/initiating events for each of the scenarios included in the analysis and diagramming event and fault trees developed by each of the partners.

Modelling uncertainty does allow quantification in principle, in case the input data are the same. Having the same inputs for modelling would reveal the variability in outputs that in turn could be measured (as the roughest case by stating lower and upper bounds). If inputs cannot be made the same, it is impossible to distinguish whether the variability in final assessments is caused by different inputs or models themselves. As it will be seen further in the current report, the inputs cannot be made the same for the models used by the teams. It is because the sets of basic and initiating events are very different and they overlap only to some extent and it is impossible to have the same inputs even for two specific models developed by different partners. In practice it is hardly possible to split up completeness and modelling uncertainty analysis and such a categorisation is mainly of academic interest.

Understanding such a picture of the state of affairs in uncertainty analysis, modelling-completeness uncertainty will be represented in a descriptive way through the review of different methodologies and stating kind of models employed by different teams. More promising with respect to uncertainty quantification is parameter uncertainty. It is possible to allocate common events among all the models used by different partners and, as a consequence, common parameters that will be subject to scrutiny with the purpose of identifying the root causes of their variability. In order to have the set of common events pre-definably representative enough to get possibly maximum insight, it was decided to make up a set of common scenarios which each of the partners has to include in their risk analysis.

### 5.1.2 Approaches employed

Approaches adopted by the research teams can be classified as shown in Figure 5.



**Figure 5 Approaches used by the partners for the frequency assessment of hazards**

The ‘Purely generic’ approach to assess the frequencies of hazards can be summarised as follows.

The plant and equipment are split into several plant sections like ‘ship loading’, ‘import pipeline’ and ‘import by trucks’. For each of these sections possible LOC events are identified, and generic data are used to assess the frequencies of the LOCs. The teams use neither any specific plant data nor safety measures mitigating the consequences of releases.

As seen from Figure 5, most of the teams are in favour of combining generic and specific approaches. Any of the approaches used (Fault Trees, Event Trees and their combination) enable to take into account plant specific particularities (safety measures, external events, human errors etc.) which are often a subject of expert judgement.

Partner 6 employed a drastically different approach (deterministic). The frequency of the occurrences of hazardous scenarios are not assessed numerically but qualitatively. The probability of an event judged as unacceptable to occur has been evaluated in function of the number of independent events of faults necessary for the undesired event to occur. Classifying the events identified by the preliminary analysis has been realised by gathering them into 4 levels of probability defined as follows :

1. *one barrier* : one single event is enough to trigger off the occurrence of the unacceptable event (equipment fault, human error, external aggression, etc.);
2. *two barriers* : The combination of two independent events is necessary to trigger off the occurrence of the unacceptable event;
3. *improbable – three barriers* : The combination of three independent events is necessary to initiate the occurrence of the unacceptable event;
4. *the event is highly improbable* : The occurrence of the unacceptable event requires the combination of more than three independent events.

### 5.1.3 Exhibition of the frequencies

It is seen from the previous section that the methodologies employed by the partners for frequency assessments of the scenarios’ top events vary. Even though the methodologies in general are the same, the sets of events (basic events in fault trees, initiating and intermediate in event trees) included in the analyses are different. Partners 5 and 7 have used the minimal set of events compared to the other teams and, as a consequence, the number of frequencies involved is minimal. In their analyses only LOC events are used to characterise the frequencies of the scenarios. The other partners include in the analyses a number of basic and initiating events that are different in general. The common intersecting set, which can be attributed to each partner, is the set of top events (LOC events) of the common scenarios. Therefore, these events have been taken to compare possible variability in the frequencies.

Table 1 summarises the frequencies of the common scenarios’ top events modelled or elicited from a generic data source by each partner. A set of plots (Figure 6 - Figure 8) diagrams the data presented in Table 1. All the data were grouped into three sets as related to pipelines, loading arms and tanks for a better overview.

As it is known, in risk management one of analyst’s tasks is to rank hazards identified in accordance with their likelihood and severity. In order to draw preliminary conclusions one could rank the hazards according to only the likelihood. In looking over Table 1, the hazardous events are ranked as appears below.

	Partner number						
	3	4	1	5	7	2	6*
Most probable scenarios	<b>4</b> 17	<b>4</b> 2	<b>4</b> 2	<b>7</b> 1,2,14,17	<b>2</b> 7	<b>4</b> 2	<b>17,18</b>
Least probable scenarios	<b>18</b> 9	<b>18</b> 14	<b>18</b> 7	<b>18</b> 9	<b>18</b> 9,10,15	<b>18</b> 9,15	<b>4,9</b>

\* Partner 6 used a deterministic approach; the other partners used a probabilistic one.

The numbers in the above table are scenario numbers. Those in bold have absolute maximal or minimal frequency/likelihood. The other numbers exhibited in normal font have the magnitudes of the frequencies of the same order and may be regarded as hardly distinguished from each other due to uncertainties present in the assessments. From this, despite a large spread in the frequency assessments nearly all the partners among the adherents of probabilistic approach are unanimous over the most probable and least probable scenarios (least probable scenarios – full agreement). The apparent conclusions based on deterministic approach (partner 6) cannot be compared with the other ones: the indication of the number of barriers is not sufficient to characterise the risk if not accompanied by a judgement on the quality of the barrier.

**Table 1 Frequencies of the top events of the common scenarios used by the partners (events per year)**

#	Top Event*	Partner number							Range of deviation
		3	4	1	5	7	2	6	
1	Major ammonia leak from 8'' feeding pipe	2.1 10 <sup>-4</sup>	5.0 10 <sup>-6</sup>	9.5 10 <sup>-5</sup>	1.6 10 <sup>-5</sup>	2.0 10 <sup>-5</sup>	7.7 10 <sup>-6</sup>	3	5.0 10 <sup>-6</sup> - 2.1 10 <sup>-4</sup>
2	Breakage of 4'' pipe 241P-067-P1349	3.9 10 <sup>-4</sup>	1.0 10 <sup>-4</sup>	2.0 10 <sup>-4</sup>	5.9 10 <sup>-5</sup>	7.3 10 <sup>-4</sup>	4.5 10 <sup>-4</sup>	2	5.9 10 <sup>-5</sup> - 7.3 10 <sup>-4</sup>
4	Rupture or disconnection between ammonia ship and unloading arm 241-ME1	5.8 10 <sup>-3</sup>	5.0 10 <sup>-3</sup>	4.8 10 <sup>-4</sup>	4.1 10 <sup>-6</sup>	1.0 10 <sup>-5</sup>	4.8 10 <sup>-4</sup>	4	4.1 10 <sup>-6</sup> - 5.8 10 <sup>-3</sup>
7	Rupture of 10'' pipe 241P-089-P1283	4.0 10 <sup>-4</sup>	2.0 10 <sup>-8</sup>	3.9 10 <sup>-8</sup>	7.0 10 <sup>-5</sup>	1.7 10 <sup>-4</sup>	-----	2	2.0 10 <sup>-8</sup> - 4.0 10 <sup>-4</sup>
7*	Rupture of a ship tank	5.7 10 <sup>-5</sup>	-----	2.3 10 <sup>-7</sup>	2.3 10 <sup>-6</sup>	4.9 10 <sup>-6</sup>	2.3 10 <sup>-7</sup>	-----	2.3 10 <sup>-7</sup> - 5.7 10 <sup>-5</sup>
9	Rupture of cryogenic tank 241-S1	Contained leak: 1.0 10 <sup>-6</sup> Uncontain leak: 4.0 10 <sup>-8</sup>	-----	5.0 10 <sup>-7</sup>	5.0 10 <sup>-8</sup>	5.0 10 <sup>-7</sup>	1.0 10 <sup>-8</sup>	4	1.0 10 <sup>-8</sup> - 1.0 10 <sup>-6</sup>
10	Rupture of 20'' pipe 241P-015-P1284	9.0 10 <sup>-5</sup>	1.0 10 <sup>-6</sup>	7.6 10 <sup>-6</sup>	8.8 10 <sup>-7</sup>	9.7 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	2	8.7 10 <sup>-7</sup> - 9.0 10 <sup>-5</sup>
14	Rupture of one of the ten pressurised tanks	2.5 10 <sup>-6</sup>	5.0 10 <sup>-7</sup>	1.6 10 <sup>-6</sup>	1.3 10 <sup>-5</sup>	2.0 10 <sup>-6</sup>	5.0 10 <sup>-7</sup>	3	5.0 10 <sup>-7</sup> - 1.3 10 <sup>-5</sup>
15	Rupture of 4'' pipe on the distribution line of tank 241-V1	2.3 10 <sup>-4</sup>	2.0 10 <sup>-5</sup>	6.0 10 <sup>-5</sup>	1.1 10 <sup>-5</sup>	4.9 10 <sup>-7</sup>	3.4 10 <sup>-8</sup>	2	3.4 10 <sup>-8</sup> - 2.3 10 <sup>-4</sup>
17	Rupture or disconnection between ammonia truck and unloading arm	3.7 10 <sup>-3</sup>	6.0 10 <sup>-5</sup>	4.7 10 <sup>-6</sup>	6.8 10 <sup>-5</sup>	1.0 10 <sup>-6</sup>	1.5 10 <sup>-7</sup>	1	1.5 10 <sup>-7</sup> - 3.7 10 <sup>-3</sup>
18	Catastrophic rupture of a truck tank	2.3 10 <sup>-7</sup>	1.2 10 <sup>-7</sup>	1.1 10 <sup>-8</sup>	7.4 10 <sup>-9</sup>	2.7 10 <sup>-8</sup>	1.5 10 <sup>-9</sup>	1-2	1.5 10 <sup>-9</sup> - 2.3 10 <sup>-7</sup>

- Grey tanned cells contain the lower assessments. Black tanned cells contain the upper assessments

\* More detailed definition of top events for the common scenarios can be found in ANNEX I

## Pipeline-related scenarios

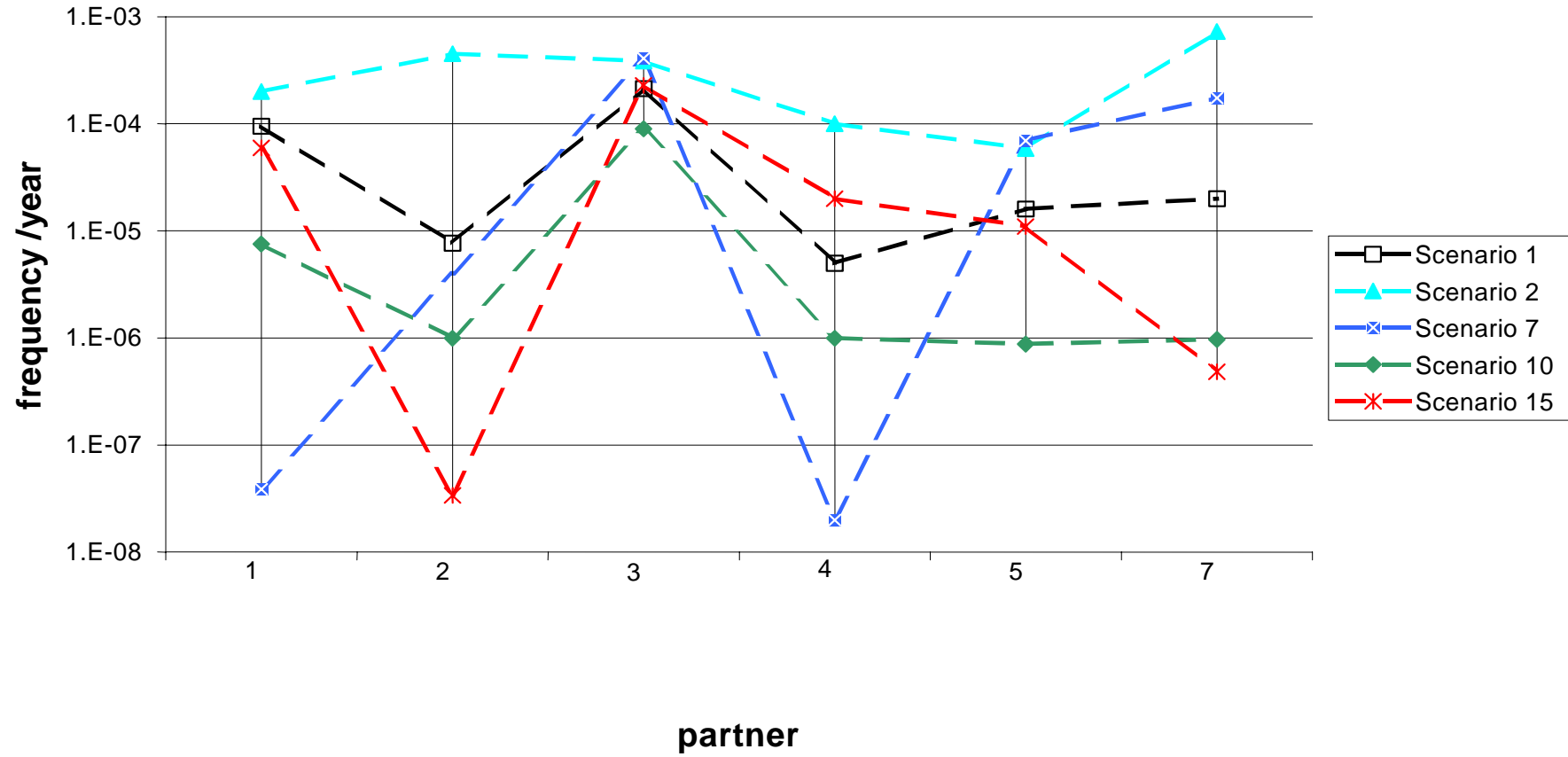


Figure 6 Frequencies of LOC events for pipe-related scenarios

# Loading arm-related scenarios

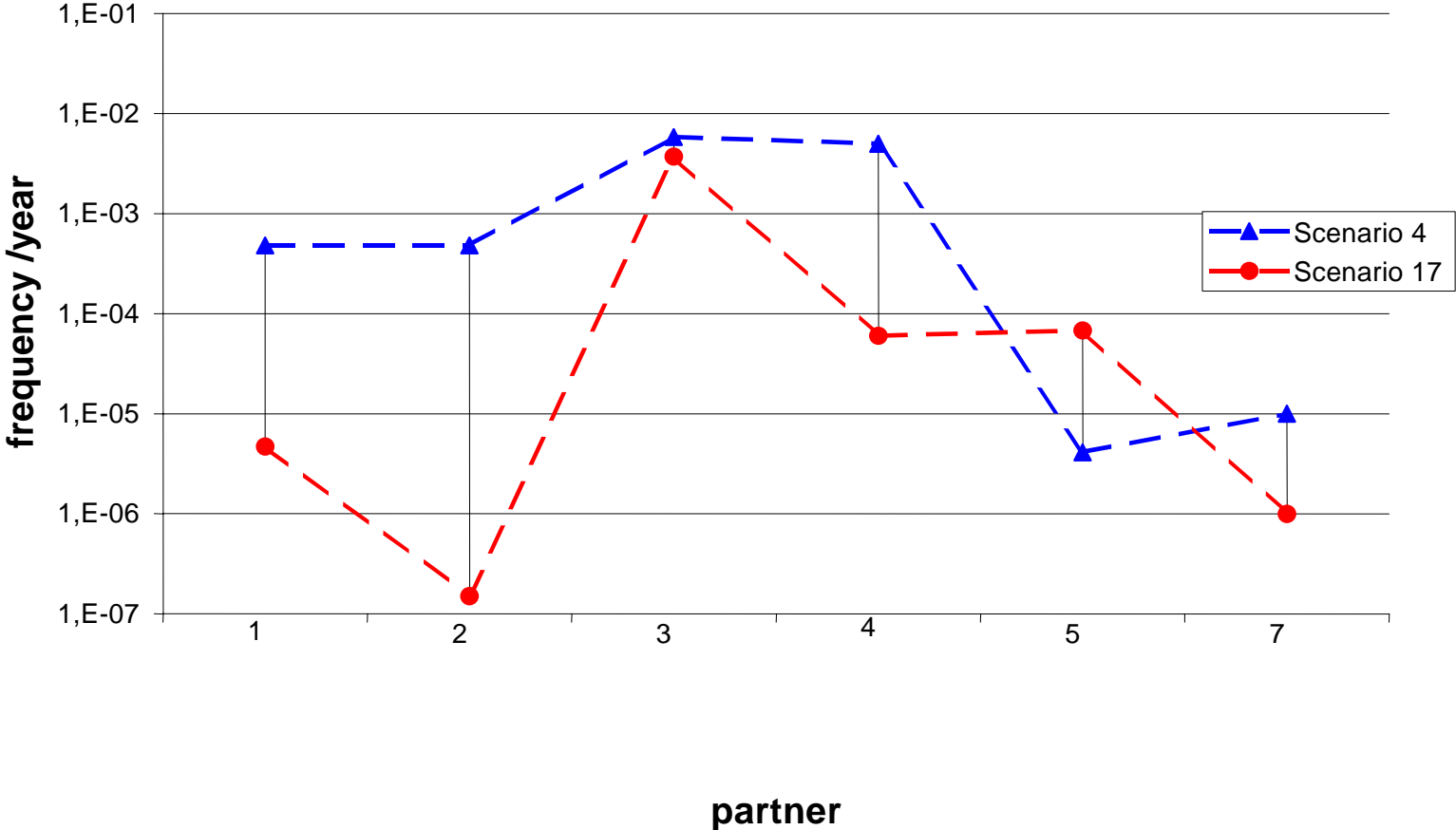
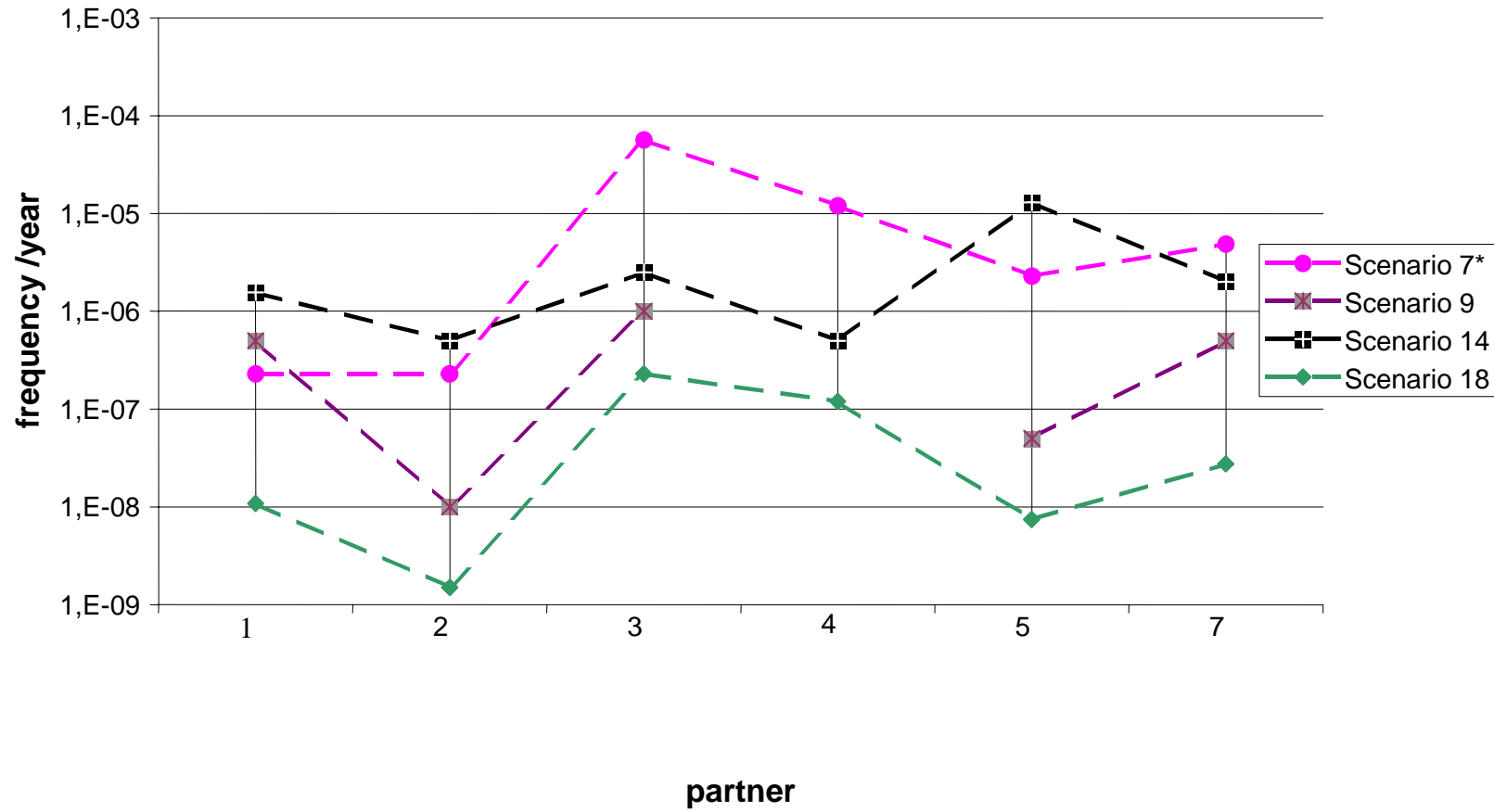


Figure 7 Frequencies of LOC events for loading arm-related scenarios

## Tank-related scenarios



**Figure 8** Frequencies of LOC events for tank-related scenarios

#### 5.1.4 Analysis of the causes of deviation

In order to penetrate the very causes of the deviations, possible assumptions made by the analysts were extracted, grouped and summarised in Table 2 - Table 4. As it was done above, the scenarios were grouped into three sets: scenarios related to (1) pipelines, (2) loading arms, and (3) tanks.

The following possible causes of uncertainty have been considered:

##### (1) scenarios related to pipelines

1. Length of a pipeline to be analysed
2. Utilisation factor (fraction of time when a pipeline is in use)
3. Including piping-related components (flanges, valves and pumps)

Failure causes:

1. Mechanical
2. Overpressure
3. External impact

##### (2) scenarios related to loading arms

1. Number of transhipments

Failure causes:

1. Mechanical
2. Overpressure
3. Other (e.g. "excessive movement of the arm, leading to its rupture")

##### (3) scenarios related to tanks

Failure causes:

1. Mechanical
2. Overpressure
3. Other (e.g. fires and explosions)

The analysis of Table 2 - Table 4 resulted in conclusions summarised in the sections below.



**Table 2 Assumptions related to the frequency assessments of pipelines**

#	Top Event	Assumptions	Partner 3	Partner 4	Partner 1	Partner 5	Partner 7	Partner 2
1	Major ammonia leak from 8'' feeding pipe	Length (m)	10 (above ground)	50	966	850 (800 underground, 50 above)	1000	966
		Utilisation factor	8000/8760	1	1	1	1	1
		Piping-related components		valves	valves	None	Valves	valve
		Failure causes: 1. Mechanical (m.y) <sup>-1</sup>	1.0 E-7	} 1.0 E-7	9.85 E-8	} 1.1 E-7, above	} 2.0 E-8	} 1.0 E-7
		2. Overpressure			Not quantifiable			
3. Extern. impact	⊗ (dominates)		Included in 1					
2	Breakage of 4'' pipe 241P-067-P1349	Length (m)	5	1000	500	800	1500	1500
		Utilisation factor	8000/8760	1		1	1	1
		Piping-related components				1 valve (7.3 E-8)	Valves included	valve
		Failure causes: 1. Mechanical (m.y) <sup>-1</sup>	1.0 E-7	} 1.0 E-7	3.0 E-7	} 7.3 E-8	} 5.0 E-7	} 3.0 E-7
		2. Overpressure			E-4 (both sides)			
3. Extern. impact	⊗ (dominates)		Included in 1					
7	Rupture of 10'' pipe 241P-089-P1283	Length (m)	10	100	900	800	900	Not provided
		Utilisation factor	8000/8760	20/8760	1/100 ev/y, duration 24 h	1	1	
		Piping-related components	Flanges included			None	Valves included	
		Failure causes: 1. Mechanical (m.y) <sup>-1</sup>	1.0 E-7	1.0 E-7	1.0 E-7	} 8.8E-8	} 2.0 E-7	}
		2. Overpressure			⊗			
3. Extern. impact	⊗ (dominates)		Included in 1					
10	Rupture of 20'' pipe 241P-015-P1284	Length (m)	20	10	25	20	25	10
		Utilisation factor	1	1	1	1	1	1
		Piping-related components				None	Valves included	valve
		Failure causes: 1. Mechanical (m.y) <sup>-1</sup>	1.0 E-7	} 1.0 E-7	1.0 E-7	} 4.4E-8	} 4.0 E-8	} 1.0 E-7
		2. Overpressure			⊗			
3. Extern. impact	⊗		Included in 1					
	Rupture of 4'' pipe on the distribution line of tank 241-V1	Length (m)	20	200	200	50	6	200
		Utilisation factor	1	1	1	1	1	5/8760
		Piping-related components				None	Valves included	valve
		Failure causes: 1. Mechanical (m.y) <sup>-1</sup>	1.0 E-7	} 1.0 E-7	3.0 E-7 (=)	} 2.2E-7	} 8.0 E-8	} 3.4 E-8 (=)
		2. Overpressure						
3. Extern. Impact	⊗		Included in 1					
		Factor 5 to adapt generic frequenc						

Notation "(=)" means that the source of the frequencies was the same but different numbers were taken, "⊗" means that a failure cause was considered and its frequency quantified

**Table 3 Assumptions related to the frequency assessments of loading arms**

#	Top Event	Assumptions	Partner 3	Partner 4	Partner 1	Partner 5	Partner 7	Partner 2
4	Rupture or disconnection between ammonia ship and unloading arm 241-ME1	Number of transshipments (yr <sup>-1</sup> ) Failure causes: 1. Mechanical (trship <sup>-1</sup> ) 2. Overpressure 3. Other	5		8	6	6	8
			1.0 E-5 yr <sup>-1</sup>		6.0 E-5 (extr incl.)	} 6.8E-6 per cargo	1.0 E-5 yr <sup>-1</sup> (1.6 E-6/operation/yr)	} 6.0 E-5
			4.0 E-4 yr <sup>-1</sup> (judg)	5.0 E-3	⊗			
			⊗ (dominates)					
17	Rupture or disconnection between ammonia truck and unloading arm	Number of transshipments (yr <sup>-1</sup> ) Failure causes: 1. Mechanical 2. Overpressure 3. Other	10	10	20	10	20	10
			1.0 E-6 (pipe 2", 5 m)	} 6.0 E-5	3.0 E-8 (1/h)	} 6.8E-6 per delivery	1.0 E-6 yr <sup>-1</sup> (5.0 E-8/operation/yr)	} 3.0 E-8
			⊗ (dominates)		⊗ (from truck)			

**Table 4 Assumptions related to the frequency assessments of tanks**

#	Top Event	Assumptions	Partner 3	Partner 4	Partner 1	Partner 5	Partner 7	Partner 2
9	Rupture of cryogenic tank 241-S1	Failure causes: 1. Mechanical (yr <sup>-1</sup> ) 2. Overpressure 3. Extern. impact	Insignificant (double wall structure)		5.0 E-7 (=)	5.0 E-8	5.0 E-7	} 1.0 E-8 (=)
			1.0 E-6	1.5 E-4	✗			
			Spilling outside the concrete wall 0.04	Rupture only of Tank roof	Tank with protective outer shell	Double containment tank	Tnk with outer containment	Full containment tank
						No breach of bund		
14	Rupture of one of the ten pressurised tanks	Failure causes: 1. Mechanical (yr <sup>-1</sup> ) 2. Overpressure 3. Extern. impact Utilisation factor	5.0 E-7		5.0 E-7	1.3 E-5	} 2.0 E-6	} 5.0 E-7
				5.0 E-7	✗	} 6.5E-6 per vessel		
			✗		Included in 1			
			2 tanks in use	1 tank in use	3 tanks in use	2 tanks in use		1 tank in use
			Estimate for a single tank					
18	Catastrophic rupture of a truck tank	Number of transhipments (yr <sup>-1</sup> ) Failure causes: 1. Mechanical (yr <sup>-1</sup> ) 2. Overpressure 3. Extern. impact	20 (0.4% of time, i.e. 30 hrs/yr)	10 (15 hrs/yr)	2.28 E-3 (20 transh per yr, 8 h each transhipment)	10	20 (60 hours per year)	10 (truck is 45 min on-site)
			8.6 E-9		5.7 E-11 (1/h)	} 6.5E-6	2.7 E-8/yr (1.4 E-9/delivery)	} 1.5 E-9
			✗	1.2 E-7	✗			
			✗		Included in 1			Including traffic acc
7*	Rupture of a ship tank	Number of transhipments (yr <sup>-1</sup> ) Failure causes: 1. Ship-Jetty 2. Ship-ship collision 3. Fires and explosion	5.4 (average)	Not provided	8	5	6	8
						2.1 E-7 per cargo	5.0 E-6/yr (8.3 E-7/operation)	} 3.0 E-8 per cargo
			5.0 E-7 per cargo		3.0 E-8 per cargo	2.6 E-7 per cargo		
			1.0 E-5 per cargo			0		

Notation “(=)” means that the source of the frequencies was the same but different numbers were taken

### 5.1.5 Conclusions concerning frequency assessments

#### *Pipelines (Scenarios 1, 2, 7, 10 and 15)*

The range of deviation in the frequency assessments of pipelines' failures reaches up to 4 orders of magnitude (Scenario 7 and 15). Causes of the deviation revealed are:

1. *Different length of pipe sections considered in the frequency calculations.*
2. *Ignoring the utilisation factor taking into account a part-time involvement of some of the plant parts.*
3. *The use of different generic data sets for the assessments of failure frequencies.*
4. *Disagreement on what failure frequency is more relevant as a generic reference data (the same data source but different numbers).*
5. *Different failure causes considered.*
6. *Ignoring piping-related components (valves, flanges and pumps).*
7. *The use of a correction factor to allow for vibration, corrosion, thermal stresses etc. (some partners use the factor, the other does not).*

#### *Loading arms (Scenario 4 and 17)*

The range of deviation in the frequency assessments of loading arms' failures reaches up to 4 orders of magnitude (Scenario 17). Causes of the deviation revealed are:

1. *Slight difference in the number of transshipments (least contribution to uncertainty)*
2. *Different failure causes considered.*
3. *The use of different generic data sets for the assessments of failure frequencies.*

#### *Tanks (Scenario 7\*, 9, 14 and 18)*

The range of deviation in the frequency assessments of tanks' failures reaches up to 2 orders of magnitude (Scenario 7\*). Causes of deviation revealed are:

1. *Slight difference in the number of transshipments (least contribution to uncertainty)*
2. *Different failure causes considered.*
3. *Different understanding or interpretation of the design applied.*
4. *Disagreement on what failure frequency is more relevant as a generic reference data (the same data source but different numbers).*
5. *The use of different generic data sets for the assessments of failure frequencies.*

It should appear clear that most of these causes can be considered as "operational" related since they derive from use of judgement, bias from current national approaches, limitation in the access to the data sources, etc.

### 5.1.6 A case study

After having analysed the causes of uncertainty in the frequency assessments it became clear that some of them could be regarded as shortcomings of the current particular exercise and might not be attributed to risk analysis as a whole. Those resulted from the limited involvement of the plant personnel in the risk analysis process and, as a consequence, entailed the use of different interpretations of the in-site characteristics like the number of transshipments, utilisation factor, length of pipelines and some others. The use of different lengths of pipelines was aggravated by ambiguous statement of the common scenarios. The set of common scenarios was constituted based on the reference scenarios borrowed from the deterministic approach taken by partner 6. In the course of scrutiny it was disclosed that the formulation of the scenarios was hardly compatible with the probabilistic view.

After these findings had been disclosed, a case study purifying the benchmarking exercise was performed. The idea was to eliminate the causes of deviation which were introduced due to the lack of knowledge of in-site characteristics and ambiguous formulations of the common scenarios.

The following characteristics common for all the partners were defined:

1. for all pipeline-related scenarios (1, 2, 7, 10 and 15) the length of the pipes to be analysed is 10 m, and assuming that this is the aerial part of the pipelines,
2. the utilisation factor for scenarios 1, 2 and 7 is equal to 8000/8760 meaning that the pipelines are in use 8000 hours per year,
3. for loading arms: scenario 4, the number of transshipments to be considered by each team is 8 per year; scenario 17, the number of transshipments per year is 10,
4. for tank-related scenarios: scenario 14, the utilisation factor to be considered by each team is 2 out of 10 tanks in use; scenario 18, the number of transshipments per year is 10 or the exposure is 15 hours per year.

The recalculated frequencies of the top events of the common scenarios are presented in Table 5.

It is seen from the table that the range of deviation was considerably reduced and is now basically of 1-2 orders of magnitude, except for scenario 17, where the deviation is nearly in the same range as previously; the outlier here is the assessment by partner 3. The reason for this was that the LOC event "Rupture or disconnection between ammonia truck and unloading arm" was broken down into four constituents: (1) mechanical rupture of the arm, (2) truck accidental movement, (3) defective flange and (4) faulty connection of flanges. Generic failure data can be found only for the first event "mechanical rupture of the arm", whereas the other events can only be assessed by analysts guessing. The team judgements on the other three events turned out to dominate the first one and resulted in an exceptionally pessimistic frequency assessment compared to the other assessments. In case this pessimistic assessment had been discarded, the range of deviation for scenario 17 would also have remained within the 1-2 orders of magnitude.

**Table 5 Recalculated frequencies according to the assumptions common for all research teams**

#	Top Event*	Partner number							Range of deviation
		3	4	1	5	7	2	6	
1	Major ammonia leak from 8'' feeding pipe	4.6 10 <sup>-6</sup>	9.0 10 <sup>-7</sup>	9.0 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	1.8 10 <sup>-7</sup>	9.0 10 <sup>-7</sup>	3	1.8 10 <sup>-7</sup> - 4.6 x 10 <sup>-6</sup>
2	Breakage of 4'' pipe 241P-067-P1349	1.4 10 <sup>-5</sup>	9.0 10 <sup>-7</sup>	1.0 10 <sup>-5</sup>	7.3 10 <sup>-7</sup>	4.6 10 <sup>-6</sup>	2.7 10 <sup>-6</sup>	2	7.3 10 <sup>-7</sup> - 1.4 10 <sup>-5</sup>
4	Rupture or disconnection between ammonia ship and unloading arm 241-ME1	8.0 10 <sup>-3</sup>	5.0 10 <sup>-3</sup>	4.8 10 <sup>-4</sup>	5.4 10 <sup>-5</sup>	1.3 10 <sup>-5</sup>	4.8 10 <sup>-4</sup>	4	1.3 10 <sup>-5</sup> - 8.0 10 <sup>-3</sup>
7	Rupture of 10'' pipe 241P-089-P1283	4.6 10 <sup>-6</sup>	9.0 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	8.0 10 <sup>-7</sup>	1.8 10 <sup>-6</sup>	-----	2	8.0 10 <sup>-7</sup> - 4.6 10 <sup>-6</sup>
7*	Rupture of a ship tank	5.7 10 <sup>-5</sup>	-----	2.3 10 <sup>-7</sup>	2.3 10 <sup>-6</sup>	4.9 10 <sup>-6</sup>	2.3 10 <sup>-7</sup>	-----	2.3 10 <sup>-7</sup> - 5.7 10 <sup>-5</sup>
9	Rupture of cryogenic tank 241-S1	4.0 10 <sup>-8</sup>	-----	5.0 10 <sup>-7</sup>	5.0 10 <sup>-8</sup>	5.0 10 <sup>-7</sup>	1.0 10 <sup>-8</sup>	4	1.0 10 <sup>-8</sup> - 5.0 10 <sup>-7</sup>
10	Rupture of 20'' pipe 241P-015-P1284	5.0 10 <sup>-6</sup>	9.0 10 <sup>-7</sup>	6.0 10 <sup>-6</sup>	4.0 10 <sup>-7</sup>	4.0 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	2	4.0 10 <sup>-7</sup> - 6.0 10 <sup>-6</sup>
14	Rupture of one of the ten pressurised tanks	1.0 10 <sup>-6</sup>	4.5 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	1.3 10 <sup>-5</sup>	4.0 10 <sup>-7</sup>	1.0 10 <sup>-6</sup>	3	4.5 10 <sup>-7</sup> - 1.3 10 <sup>-5</sup>
15	Rupture of 4'' pipe on the distribution line of tank 241-V1	1.5 10 <sup>-5</sup>	9.0 10 <sup>-7</sup>	3.0 10 <sup>-6</sup>	2.2 10 <sup>-6</sup>	8.0 10 <sup>-7</sup>	3.4 10 <sup>-7</sup>	2	3.4 10 <sup>-7</sup> - 1.5 10 <sup>-5</sup>
17	Rupture or disconnection between ammonia truck and unloading arm	2.1 10 <sup>-3</sup>	2.7 10 <sup>-6</sup>	2.4 10 <sup>-6</sup>	6.0 10 <sup>-6</sup>	5.0 10 <sup>-7</sup>	1.5 10 <sup>-7</sup>	1	1.5 10 <sup>-7</sup> - 2.1 10 <sup>-3</sup>
18	Catastrophic rupture of a truck tank	1.2 10 <sup>-7</sup>	1.2 10 <sup>-7</sup>	5.5 10 <sup>-9</sup>	4.7 10 <sup>-6</sup>	1.4 10 <sup>-8</sup>	1.5 10 <sup>-9</sup>	1-2	1.5 10 <sup>-9</sup> - 4.7 10 <sup>-6</sup>

• Grey tanned cells contain the lower assessments. Black tanned cells contain the upper assessments

\* More detailed definition of top events for the common scenarios can be found in ANNEX I

### 5.1.7 Common list of data sources

1. Data tables from the “*Risk analysis of six potentially hazardous industrial objects in the Rijnmond area, a pilot study*” – D. Reidel Publishing Company – 1982
2. *Guidelines... 1989b*. Guidelines for Process Equipment Reliability Data with Data Tables. New York, Center for Chemical Process Safety of the American Institute of Chemical Engineers. 303 p.
3. *Guidelines for Quantitative Risk Assessment*. “Purple Book”. Report CPR 18E. Committee for the Prevention of Disasters. First edition. Sdu Uitgevers Den Haag, 1999. ISBN 90 12 08796 1
4. *TNO memorandum... 1999*. Information QRA. TNO Institute of Environmental Sciences, Energy Research and Process Innovation, Cees M. A. Jansen, 5 July 1999. 21 p.
5. Data tables from the “*Gas pipelines incidents, Report 1970/1992 – A report of the EGIG*” –EGIG October 1993
6. *HSE 1978*. Canvey: an investigation of potential hazards from operations in the Canvey Island/Thurrock area. London: Health and Safety Executive. Appendix 11. pp. 146–152.
7. *HSE 1981*. Canvey: a second report. A review of potential hazards from operations in the Canvey Island/Thurrock area three years after publication of the Canvey Report. London: Health and Safety Executive. pp. 22–25.
8. *IEEE Std 500-1984*. IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear Power Generating Stations. New York, The Institute of Electrical and Electronic Engineers, Inc. 1424 p.
9. *OREDA-92, 1992*. Offshore Reliability Data Handbook, 2<sup>nd</sup> Edition. Hovik, OREDA Participants. 614 p.
10. *Science Applications Inc., 1975*. LNG terminal risk assessment study for Oxnard, California, USA.
11. OREDA (1997) Offshore Reliability Data, Det Norske Veritas, Veritasveien 1, N1322 Høvik, Norway.
12. Papazoglou, I.A. et al. “Probabilistic Safety Analysis Procedures Guides”, BNL Report, NUREG/CR-2815, 1984.
13. Hawksley J L. *Some social technical and economic aspects of the risks of large plants*. Chemrawn III, 1984.
14. Lees F P. *Loss Prevention in the Process Industries*. Second Edition 1996. Butterworth Heinmann.
15. HSE, ‘*Offshore Hydrocarbon Release Statistics 1997*’, Offshore Technology Report OTO 97 950, 1997.
16. Smith T A and Warwick R G. ‘*The Second Survey of Defects in Pressure Vessels Built to High Standards of Construction and its Relevance to Nuclear Primary Circuits*’ Safety and Reliability Directorate – Report No SRD R 30, UKAEA, 1974.
17. Health and Safety Commission. ‘Major hazard aspects of the transport of dangerous substances’ HMSO 1991.
18. HSE database 'FRED' (Failure rate and event database)

## 5.2 Uncertainties related to the assessment of consequences

In general, the sources of uncertainty in the consequence assessment can be divided into the following categories:

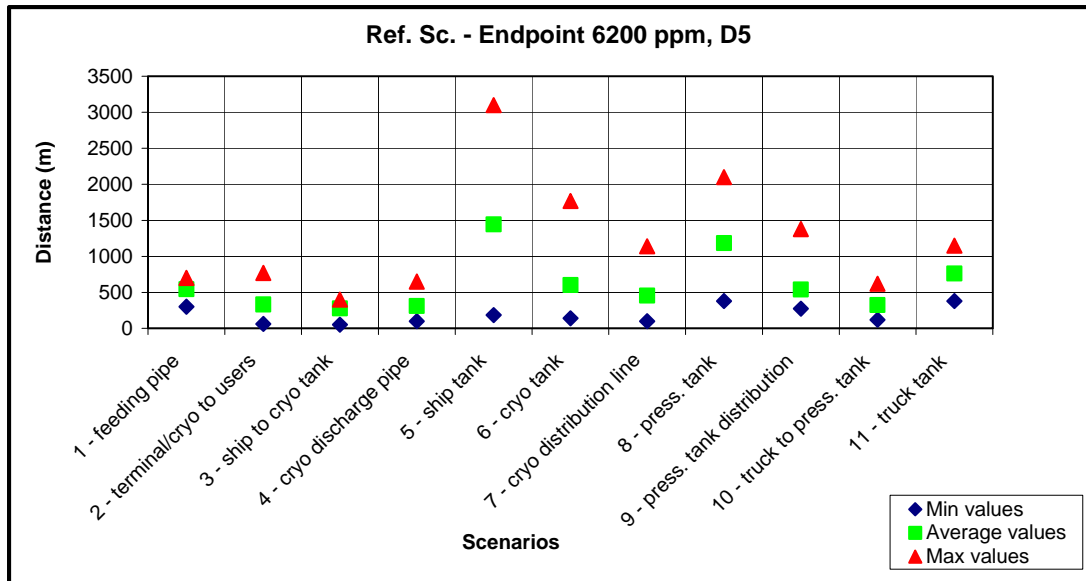
1. Scenario completeness and correctness;
2. Uncertainty in definition of scenarios / ambiguity;
3. Modelling uncertainty, including the description of physical phenomena and the detailed model characteristics, constants and parameters;
4. Input assumptions / boundary conditions / Interface between models;
5. Simplifications made throughout the analysis; and
6. Overall level of “conservatism” of the analyst.

Again most of the sources of uncertainty are depending on judgement and the “operational” approach to the problem.

Concerning the first source, it should be noted that the partners’ assessments contained all the scenarios contributing to risk outside the establishment, thus this source is excluded from our exercise. In certain cases, however, there has been significant discrepancy in the definition of scenarios, especially concerning the catastrophic ruptures of tanks. Given the importance of the analysis of these scenarios as input to a number of risk-informed decisions (e.g. Land Use Planning), this source of uncertainty is highlighted and a careful and precise definition of these catastrophic ruptures is strongly recommended.

Figure 9 presents the minimum, maximum and the mean values of the assessed endpoints. A careful examination of these findings reveals also our “state-of-knowledge” for the various physical phenomena. Thus, the greater discrepancy in the results appeared in the assessment of scenario 5 - Rupture of a ship tank and release of refrigerated ammonia on the sea surface. In fact, our knowledge on this particular scenario seems not to be consolidated yet: Although all partners foresee a partial dilution of ammonia into the water and partial evaporation, the relevant percentages vary significantly. Based on bibliographical sources and experimental data, the partners assess the amount of evaporated ammonia from a small percentage (8%) of the total release up to as large as 60% of the total release. Consequently, the variation in the final results is large (ranges from 185 to 3100m).





**Figure 9 Variation of results for the consequence assessment of the reference scenarios. Minimum, maximum and average values for concentration endpoint of 6200 ppm (LC1%)**

Another source of uncertainty affects the scenarios related to the catastrophic rupture of storage tanks, i.e. scenarios 6 and 8, which present the second largest variation in the results: It is the *uncertainty in definition of scenarios* (or ambiguity). This is the main source of uncertainty for the catastrophic rupture of the cryogenic tank, and one of the sources in the rupture of the pressurised tank. Especially for the cryogenic tank, some partners defined “catastrophic rupture” as instantaneous release of the complete content of the tank into the air (as if the tank disappears instantaneously), others defined it as rupture of the internal steel tank but the released ammonia remains contained in the external concrete wall (therefore only evaporation from the damaged roof is foreseen), and one partner defined it as partial rupture (40%) of the roof. Obviously, the different definitions resulted in different source terms and large variation in the assessed endpoints. For the catastrophic rupture of the pressurised tank definition uncertainty was only one of the sources, others being initial conditions (different pressure and temperature) and dispersion modelling.

Less variation in the results was observed for the scenarios referring to pipeline ruptures – with the exception of the feeding pipeline. For the feeding pipeline, as well as for other pipeline scenarios, detailed case studies were performed with common data, especially concerning the initial conditions and the duration of outflow (time of reaction and closure of the relevant isolation valve). A “state-of-knowledge” problem was also present here, since the pipeline is a very long one and the models usually employed do not apply in this particular case. The variation in the assessed outflow rate in this case should be compared to the outflow rate in a case corresponding to scenario 7 (rupture of a pipe connected to the cryogenic tank). Indeed, in the second case the partners simply applied the Bernoulli equation, and any discrepancy in the outflow rate is due to different discharge factor ( $C_d$ ) values. The results in this case where knowledge of the physical phenomena was more consolidated are definitely more uniform than in the former case.

In more detail, the main sources of uncertainty within each phase of the consequence assessment are the following:

### **Calculation of outflow for pipes connected to pumps:**

1. Assumptions related to the characteristic curve of the pump and pumping against zero pressure
2. Use of models not-tailored to model the particular release (e.g. hypothetical tank with constant pressure)
3. Simplifications related to the consideration of release from one or from two sides of the ruptured pipe.
4. Length of the pipe
5. Time of reaction (closure of valves)

It is worth noticing an agreement in the calculation of flash fraction (for releases of pressurised ammonia) among the partners.

### **Calculation of outflow for pipes connected to tanks:**

1. Level of liquid in the tank
2. Discharge factor  $C_d$
3. Length of the pipe
4. Time of reaction (closure of valves)

### **Calculation of outflow rate for tanks**

1. Definition of the scenario
2. Level of liquid in the tank
3. Dimensions and position of the rupture
4. Initial conditions (overpressure)
5. Instantaneous release of the initial vapour, for refrigerated ammonia

### **Pool formation and evaporation**

1. Assumptions related to the violence of the phenomenon. These assumptions determine the percentage of droplets in the cloud and its overall behaviour in the dispersion phase.
2. Percentage of droplets
3. Type of ground assumed. Especially in the case of release on water the variation in the results is very large.
4. Structure and characteristics of the models applied, both for pool formation and for evaporation (whether they take into consideration heat exchange from sun, air, etc.)

In general, a pool is assumed to be formed in all releases of cryogenic ammonia.

### **Dispersion**

1. Source terms.
2. Interface between models. This is a very important source of uncertainty and refers to cases where the evaporation or release rate vary significantly over time, for the period of

interest, this variation, however, not being possible to be inserted in the dispersion model. Thus, there is doubt whether the dispersion model should be fed with average values of source terms or with maximum or minimum, or with a 'corrected' average value. This gives rise to variation in source terms, which is then translated into variation in the end results. It should be highlighted that some integrated computer programs used by the partners make this 'transition' automatically.

3. Initial behaviour of the cloud, i.e. whether a passive dispersion or dense-gas dispersion model should be applied. This decision is based on expert judgement by the analyst and constitutes another source of uncertainty.
4. The detailed characteristics of the dispersion model. Here it should be noted that the principles and basic physics of all the models applied were similar (all of them were 'box models' with similar structure). There were however differences in the way the models deal with certain issues like droplets evaporation (i.e. droplets are evaporated in the beginning and then starts the dispersion, or they are evaporated during the dispersion), air entrainment, or criteria for transition to passive phase. Differences are also present in the values of certain model parameters.

### **Dose/Response calculation**

1. Form and coefficients of the probit function. This is an important issue especially at low doses.

## **6 Implications of uncertainties in risk assessment to risk-informed decisions**

### **6.1 Introduction**

Among the variety of decisions that can and must get a significant input from risk assessment, those related to Land Use Planning (LUP) in the vicinity of hazardous industrial establishments are probably the most important and the most difficult ones. Land-use planning decisions have always been an issue of conflict among various objectives and interests, influenced by different stakeholders, including the plant operators, the authorities and the general public. The role of the latter has been recognised and expanded in the recently issued framework European Directive for control and management of industrial hazards, the Seveso II Directive. In fact, not only land-use planning provisions are included in the Directive, posing a clear obligation to planning authorities to consider major accident hazards in the planning process, but also a requirement is put for consultation of the public in land-use and off-site emergency planning. Moreover, the involvement of many actors and the implications of the relevant decisions on the exploitation of a scarce resource, such as land, make the decisions difficult.

In order to assess the impact of the uncertainties on land-use planning decisions, the results calculated by the partners and the distances/areas corresponding to given threshold levels of consequence, dose or risk, were compared. The variation in the predicted distances/areas clearly shows the effect of uncertainties in land-use planning.

## 6.2 Land-use planning approaches around chemical sites.

From the methodological point of view, two main approaches are followed in the European Union for land use planning purposes<sup>3</sup>: the first focuses on the assessment of consequences of a number of conceivable scenarios and can be typically called “*consequence based*” approach, and the second on the assessment of both consequences and probabilities of occurrence of the possible accident scenarios and can be called “*risk based*” approach<sup>4</sup>. For a given installation, the “consequence based” approach gives the consequence area for lethal effects and serious injuries resulting from the scenarios assessed, while the “risk based” approach gives an area within which there is a given probability of a specified level of harm resulting from a large number of possible accident scenarios. Concerning the risk based methodologies, a further distinction can be done between those using mainly *individual risk based criteria* and those using both individual and *societal risk criteria*.

Various criteria are in use to determine the safety distances/areas: In the “consequence based” approaches, the LC<sub>1%</sub> (concentration lethal to 1% of the general population), AEGL (Acute Exposure Guideline Levels) and IDLH (Immediately Dangerous to Life and Health) concentration levels are used. In the “risk based” approaches, the 10<sup>-6</sup> individual risk level, and a certain line in the F-N curve representing the maximum tolerable societal risk are in use. Table 6 and Table 7 give examples of such criteria according to the Dutch (risk based) and the French (consequence based) LUP system, respectively. Here it should be noted that all methodologies consider indirectly the density of population in the surroundings of the establishments; however, the Dutch approach is the only one using a *formal criterion* in order to express the public aversion against accidents with increased number of casualties.

Furthermore, new approaches have been proposed for taking societal risk into account using a simplified method [3], for taking multiple and conflicting objectives into account [4-7], and for integrating the results from multiple risk sources into overall area risk indices [8, 9]. In the following, three indicative philosophies of LUP are examined, which broadly correspond to the national policies of three EU countries (France, UK, and the Netherlands), and the discrepancies in LUP decisions due to Risk Assessment results are discussed.

**Table 6. Example of probabilistic risk criteria: The Dutch acceptability criteria**

	<b>Individual risk criteria</b>	<b>Societal risk criteria</b>
Existing installations	10 <sup>-5</sup> per year	10 <sup>-3</sup> /N <sup>2</sup>
New installations	10 <sup>-6</sup> per year	10 <sup>-3</sup> /N <sup>2</sup>
Negligible risk	Always ALARA* applied	Always ALARA* applied

\* ALARA : As Low As Reasonably Achievable

<sup>3</sup> For a detailed review of the methodologies for LUP the reader can refer to Ref. 1, 2 and the sources therein.

<sup>4</sup> “Generic” distances, based on the type of the hazardous activity or on a broad estimation of the consequences of typical / “standardised” installations, are also in use; however, their use is restricted in deriving “consultation distances” which provide a first assessment of the compatibility of the installation with the surrounding uses of land.

**Table 7. Example of consequence based criteria: Ammonia concentration levels and corresponding damaging effects, as used in the French planning system.**

Concentration level	Exposure time	Effect on humans
6200ppm	30 min	The LC <sub>1</sub> contour (1% Lethality of the general population or 10 <sup>-2</sup> death risk)
1000ppm	3 min	IDLH (dose equivalent to 500 ppm for 30 minutes)

### 6.3 The Case Study

To illustrate the above-mentioned approaches of LUP, the case study of the ASSURANCE project is used. The seven partners in the benchmark exercise, together with the risk analyses that they produced with their own methodology (at least the ones who have followed a quantitative risk assessment), have also analysed eleven reference scenarios, as these scenarios were set by partner 6 as the most significant for this installation according to his approach.

All teams but partner 6 have performed two types of calculations:

- a) Full Quantitative Risk Analysis for the determination of both individual and societal risk, taking into consideration weather and other types of uncertainty, and
- b) Selected runs (with each partner's toxicological data) for the predefined concentrations (see Table 7) attained in the various scenarios by the released clouds of ammonia under two sets of meteorological conditions, namely wind speed 5m/s and atmospheric stability class D, and wind speed 2m/s and atmospheric stability class F.

#### Calculations supporting a “consequence based” LUP approach

According to a “consequence based” approach, the maximum distances (endpoints) attaining the damaging effects of Table 7 have been calculated by all partners and for all Reference Scenarios. Table 8 presents these endpoints to lethality and irreversible effects thresholds for weather conditions F2 (stability F and wind speed 2m/s, which is the less favourable case), and for Scenario 5 (rupture of a ship tank), as the worst case. However, as it is discussed in the analysis of Reference Scenarios, this scenario represents the maximum discrepancy in the results, since the knowledge of the Risk Assessment community in modelling the release of liquid ammonia onto water surface and the subsequent dispersion is not consolidated yet. Moreover, since this scenario was not analysed by all partners, it seems more appropriate to consider also the “second worst” scenario, which is Reference Scenario 8 (catastrophic rupture of a pressurised tank). The relevant endpoints are then presented in Table 9. Table 8 and Table 9 give also the average distances, the deviation of the assessment of each partner from the average, and the mean square root variation, R.

Table 8 and Table 9 show a great discrepancy in the results and the distances calculated by the partners, ranging for Reference Scenario 8 from –62% up to +156% of the average for the lethal effects endpoint, and from –70% up to +92% for the irreversible effects endpoint. In other words, this discrepancy means that the planner should establish a first (lethal effects) zone of 570 m based on the results of partner P5 or a zone of 3800 m based on the results of

partner P3. It is also worth noting that the variation in the results is reduced for long distances (less variation in the assessment of irreversible effects zone).

**Table 8 Variation in concentration endpoints for Reference Scenario 5**

<b>Partner</b>	<b>6200 ppm endpoint (m)</b> Distance corresponding to criteria for first death	<b>Deviation from Average (%)</b>	<b>1000 ppm endpoint (m)</b> Distance corresponding to criteria for first irreversible effects	<b>Deviation from Average (%)</b>
Partner 1	2845	-39.3	10150	51.0
Partner 2	65	-98.6	68	-99.0
Partner 3	10000	113.2	10000	48.8
Partner 4		/		/
Partner 5	540	-88.5	3390	-49.6
Partner 7	10000	113.2	10000	48.8
<i>Average</i>	<i>4690.0</i>	<i>R=4436.4 (94.6%)</i>	<i>6721.6</i>	<i>R=4210.0 (62.6%)</i>

**Table 9 Variation in concentration endpoints for Reference Scenario 8**

<b>Partner</b>	<b>6200 ppm endpoint (m)</b> Distance corresponding to criteria for first death	<b>Deviation from Average (%)</b>	<b>1000 ppm endpoint (m)</b> Distance corresponding to criteria for first irreversible effects	<b>Deviation from Average (%)</b>
Partner 1	1650	11.2	6350	25.8
Partner 2	820	-44.8	1510	-70.1
Partner 3	3800	156.0	9700	92.2
Partner 4	1360	-8.4	3150	-37.6
Partner 5	570	-61.6	1510	-70.1
Partner 7	705	-52.5	8063	59.8
<i>Average</i>	<i>1484.2</i>	<i>R=1102.3 (74.3%)</i>	<i>5047.2</i>	<i>R=3190.2 (63.2%)</i>

### **Calculations supporting a “risk based” LUP approach employing an individual risk criterion**

The QRA results are summarised in the isorisk curves. Figure 10 gives an example of the discrepancy in individual risk calculations, presenting the “minimum” and “maximum” isorisk curves (those corresponding to minimum and maximum area) for a level of individual risk  $10^{-5}$  per year.

In order to compare the isorisk curves assessed by each partner, the area within each curve has been calculated and the “average” radius, i.e. the radius of a circle equivalent to this area, has also been calculated. Table 10 presents the average radii of the areas covered under isorisk curves  $10^{-5}$  and  $10^{-6}$  per year of QRA results for each partner. Deviation from the average has been calculated and appears in the table, too.



**Figure 10. Discrepancy in the results of individual risk calculations relevant to risk-informed Land Use Planning: Maximum and minimum distances for the isorisk curve  $10^{-5} \text{ yr}^{-1}$  (same figure as Figure 3)**

**Table 10. Variation in the average radius for Isorisk Curves  $10^{-5}$  and  $10^{-6} \text{ yr}^{-1}$**

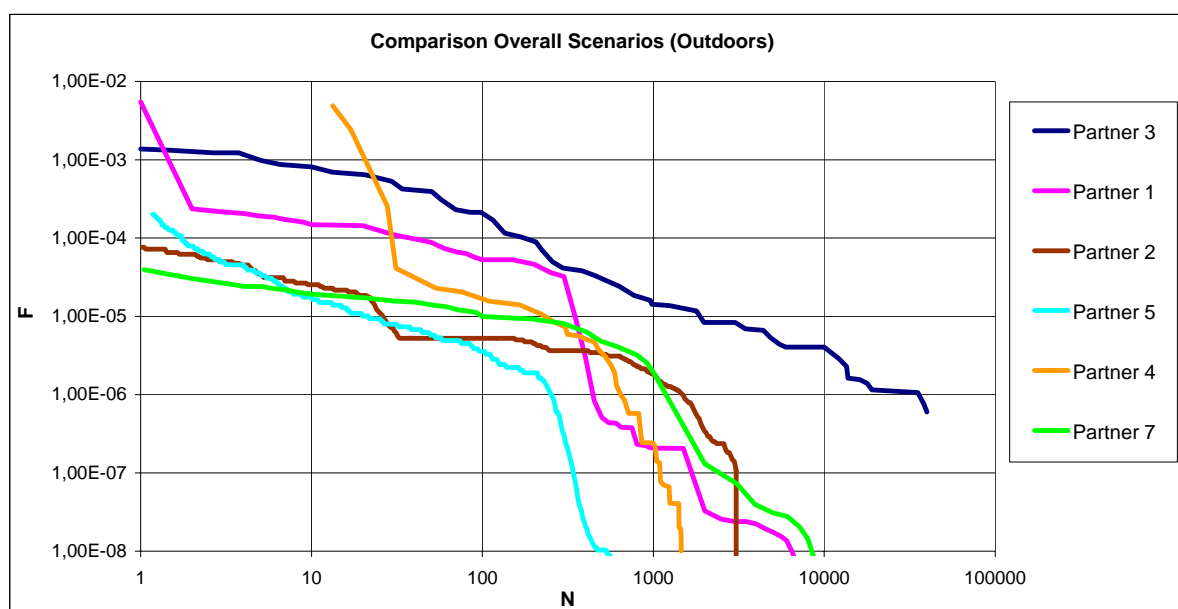
PARTNER	Average radius for $10^{-5} \text{ yr}^{-1}$ Individual Risk Curve		Average radius for $10^{-6} \text{ yr}^{-1}$ Individual Risk Curve	
	Radius(m)	Deviation from Average (%)	Radius(m)	Deviation from Average (%)
Partner 1	565	-8.13	1325	12.36
Partner 2	125	-79.67	925	-21.56
Partner 3	1310	113.01	1676	42.13
Partner 4	545	-11.38	820	-30.46
Partner 5	530	-13.82	1150	-2.48
Partner 7	/*		/*	
Average	615	$R=384$ (62.46%)	1179.2	$R=304$ (25.79%)

\* Results of Partner 7 are not comparable to the others

As previously in the “consequence based” approach, significant variation is reported. The variation is however lower in longer distances (as it was the case with the results of Table 8 and Table 9). More specifically, the equivalent “distance” for  $10^{-6} \text{ yr}^{-1}$  individual risk ranges from 820m to 1676m, i.e. from -30% to +42% of the average. It is thus expected that a planner using the Dutch individual risk criteria (for new installation; for existing installations the  $10^{-5}$  criterion is followed) be confronted with this range of results. The same variation will be present if a planner decides to use the UK criteria and needs to calculate the “middle” zone.

## Calculations supporting a “risk based” LUP approach employing both individual risk and societal risk criteria.

The results of the assessment of societal risk are summarised in Figure 11 (partner P6 did not perform probabilistic calculations). It has to be stressed that the calculations were based on fictitious population data, exaggerating the population density close to the plant, contrary to the practices in all European countries. The purpose for using such data was to reveal differences and variations in the results, which otherwise could remain hidden. Consequently, the societal risk is high, indeed much higher than the criterion F-N curve of  $10^{-3}/N^2$  (see Table 6). All partners therefore agree that the fictitious installation is above the tolerable limits. However, significant discrepancy is again present in the results since, for example, the number of people affected in a single accident at a frequency of  $10^{-5}$  ranges from 20 to 2000 people, according to the calculations of the partners (the “acceptable” value according to the criterion curve would be 10 people). Even if the most conservative assessment of partner P3 is excluded from the data-set, the remaining results would range from 20 to 200 people.



**Figure 11** Discrepancy in societal risk calculations (based on fictitious population data). Same figure as Figure 4.

## 6.4 Conclusions

As the public concern about the protection of human life and the environment increases and the land use planning restrictions remain one of the most important controls for managing major accident hazards, the application of the various approaches for LUP and the comparison between them becomes one of the most widely discussed issues. It is a general impression – and the results herein can demonstrate it – that most often the “consequence based” approach produces longer distances. However, such a comparison in order to be meaningful should take into account the overall application framework: What scenarios are taken into consideration? What restrictions apply? What happens when a criterion is not fulfilled? Which other measures are taken in order to ensure the safety of the citizens and the environment? What is the general philosophy for applying one or the other method?



All these questions have to be addressed and taken seriously into consideration in an overall comparison of the LUP approaches. Such a comparison, however, was out of the scope of this project. What is discussed herein is the effect of uncertainties in risk assessment and modelling on the relevant Land Use Planning decisions. And, as it was demonstrated above, the effect of the uncertainties is very strong, producing great discrepancies in the relevant decisions. In fact, the discrepancy produced by the Risk Assessment results can be greater than the one produced by the type of methodology applied. Finally, it should be underlined that great variations in the results supporting LUP decisions are reported both in the application of the “consequence based” and in the application of the “risk based” approach (see also Ref [10]).

## 6.5 References on land use planning

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## 7 Summary of causes of uncertainty identified

### Findings concerning hazard identification

- Many different approaches / variants for hazard identification have been used
- Hazard identification is done using a combination of complementary approaches

- Three groups of approaches could be distinguished:
  - Methods based on a *top-down analysis*, mainly represented by the Master Logic Diagram, having a form similar to fault trees, starting from a top event and going down to combinations of basic events, capable to provoke accident;
  - Methods based on a *bottom-up analysis*, like HAZOP, SWIFT, HAZSCAN and HCA, which investigate whether deviations of the process variables and failures of individual devices can provoke a major accident; and
  - Methods based on the systematic identification of the possible release events, mostly supported by use of *checklists* or based on *national standards*, after division of the plant in areas.
- For several partners the definition and risk labelling of the categories used in the screening and ranking of identified hazards vary from project to project. No predefined categories are used.
- The understanding of what e.g. “catastrophic event” or “likely event” means differs from partner to partner. Therefore, great care has to be taken not to introduce misunderstandings using labels in discussions among experts or in risk communication to the public.
- The strategies to define consequence categories are rather different ranging from the application of release times, release rates, total releases and consequence lengths. Comparing these, a very good correlation for these categories is found. Nevertheless, only using release rates to categorise may lead to larger differences in the screenings.
- The severity of the scenarios is assessed using an evaluation matrix defined by the categories for the frequencies and the consequences. In order to select the most important scenarios relevant for quantification the risk matrix is reduced. This is in most cases done by cutting off the scenarios in the lowest consequence category regardless the value of the frequency. In the second step, the next lowest consequence category combined with the lowest frequency category is also reduced.
- The scenarios with very low probability are preserved in the highest consequence categories. Some partners, furthermore, emphasise the importance of the consequences using marking.
- The scenarios selected by the partners differ substantially in detail, but the most important hazardous events were identified by all participants.

### **Findings concerning frequency assessments**

#### Pipelines (Scenarios 1, 2, 7, 10 and 15)

The range of deviation in the frequency assessments of pipelines’ failures reaches up to 4 orders of magnitude (Scenario 7 and 15). Causes of the deviation revealed are:

1. Different length of pipe sections considered in the frequency calculations.
2. Ignoring the utilisation factor taking into account a part-time involvement of some of the plant parts.
3. The use of different generic data sets for the assessments of failure frequencies.
4. Disagreement on what failure frequency is more relevant as a generic reference data (the same data source but different numbers).
5. Different failure causes considered.
6. Ignoring piping-related components (valves, flanges and pumps).
7. The use of a correction factor to allow for vibration, corrosion, thermal stresses etc. (some partners use the factor, the other does not).

### Loading arms (Scenario 4 and 17)

The range of deviation in the frequency assessments of loading arms' failures reaches up to 4 orders of magnitude (Scenario 17). Causes of the deviation revealed are:

1. Slight difference in the number of transhipments (least contribution to uncertainty)
2. Different failure causes considered.
3. The use of different generic data sets for the assessments of failure frequencies.

### Tanks (Scenario 7\*, 9, 14 and 18)

The range of deviation in the frequency assessments of tanks' failures reaches up to 2 orders of magnitude (Scenario 7\*). Causes of deviation revealed are:

1. Slight difference in the number of transhipments (least contribution to uncertainty)
2. Different failure causes considered.
3. Different understanding or interpretation of the design applied
4. Disagreement on what failure frequency is more relevant as a generic reference data (the same data source but different numbers).
5. The use of different generic data sets for the assessments of failure frequencies.

## **Findings concerning consequence assessments**

### General sources of uncertainty:

- Knowledge on some scenarios seems not to be consolidated yet (e.g. scenario 5 - Rupture of a ship tank and release of refrigerated ammonia on the sea surface. Although all partners foresee a partial dilution of ammonia into the water and partial evaporation, the relevant percentages vary significantly).
- The uncertainty (or ambiguity) in definition of scenarios is the main source of uncertainty for the catastrophic rupture of the cryogenic tank
- Lower variation in the results was observed for most of the scenarios referring to pipeline ruptures.
- There was a "state-of-knowledge" problem for the feeding pipeline, which is a very long one, and the models usually employed do not apply in this particular case.

In more detail, the main sources of uncertainty within each phase of the consequence assessment are the following:

### Uncertainties in the calculation of outflow for pipes connected to pumps:

- Assumptions related to the characteristic curve of the pump and pumping against zero pressure
- Use of models not-tailored to model the particular release (e.g. hypothetical tank with constant pressure)
- Simplifications related to the consideration of release from one or from two sides of the ruptured pipe.
- Length of the pipe
- Time of reaction (closure of valves)

It is worth noticing an agreement in the calculation of flash fraction (for releases of pressurised ammonia) among the partners.

#### Uncertainties in the calculation of outflow for pipes connected to tanks:

- Level of liquid in the tank
- Discharge factor Cd
- Length of the pipe
- Time of reaction (closure of valves)

#### Uncertainties in the calculation of outflow rate for tanks

- Definition of the scenario
- Level of liquid in the tank
- Dimensions and position of the rupture
- Initial conditions (overpressure)
- Instantaneous release of the initial vapour, for refrigerated ammonia

#### Uncertainties concerning pool formation and evaporation

- Assumptions related to the violence of the phenomenon. These assumptions determine the percentage of droplets in the cloud and its overall behaviour in the dispersion phase.
- Percentage of droplets
- Type of ground assumed. Especially in the case of release on water the variation in the results is very large.
- Structure and characteristics of the models applied, both for pool formation and for evaporation (whether they take into consideration heat exchange from sun, air, etc.)

#### Uncertainties concerning dispersion

- Source terms.
- Interface between models.
- Initial behaviour of the cloud, i.e. whether a passive dispersion or dense-gas dispersion model should be applied.
- The detailed characteristics of the dispersion model.

#### Uncertainties concerning Dose/Response calculation

- Form and coefficients of the probit function.

## **8 General conclusions**

During the course of the benchmarking exercise some findings hardly foreseen beforehand were disclosed. For example, the ranking of hazardous scenarios by probabilistic and deterministic approaches can result in completely different conclusions (this mainly because of the deterministic approach considering only “barriers”, without examining the “strength” of these barriers, i.e. the probability of an accidental sequence surpassing them). On the other hand, despite a large difference in frequency assessments of the same hazardous scenarios among the adherents of the probabilistic approach, there was good consensus on the ranking.

Breaking down the modelling of both frequency and consequence assessments into suitably small elements and conducting case studies allowed identifying root causes of uncertainty in

the final risk assessments. In pursuing uncertainty classification as modelling-, completeness- and parameter uncertainty, it was revealed that, for the given multifarious set of models and approaches employed by the research teams, only parameter uncertainty could be quantified and measured. As a result, a great deal of attention of the researchers was focused on quantifying and measuring the parameter uncertainty. The two other types of uncertainty were assessed qualitatively. Furthermore, it has been shown how hard it is to be satisfied by this kind of classification of the uncertainties, and how the variability of results is depending by judgement, bias, access to models and data, etc. This latter variability has been called here “operational” uncertainty, which permeates the whole process of analysis.

In Table 11 a summary is given of key intermediate results from the reference scenarios, showing the ranges in the results found by the partners for frequency, release rate, released amount and endpoint for the concentration 6200 ppm. As can be seen from the table, in general the largest differences are found in the frequency assessments, in particular for scenarios relating to failure of loading arms. This implies that particular attention must be paid to the quality of failure data when carrying out probabilistic risk analysis. But there are also notable differences in the results for consequences, which are equally important in probabilistic and deterministic risk analysis.

In Table 12 a qualitative assessment is presented of the importance to the final calculated risk of uncertainties in the assumptions made as well as in the data and the calculation methods used. The assessment is based on the findings in the ASSURANCE project and most certainly is not universally valid for all types of risk analysis and plant. But it can serve as a guide to areas where, in particular, caution must be taken when performing risk analyses.

**Table 11 Summary of key results from reference scenarios**

Reference scenario	Frequency range yr <sup>-1</sup>		Ratio between frequencies	Release rate kg/s		Ratio between release rates	Released amount kg		Ratio between released amounts	6200 ppm conc. endpoint, m (F2-weather conditions)		Ratio between endpoints
	Min	Max		Min	Max		Min	Max		Min	Max	
<i>Pressurised pipelines</i>												
1	1,8E-07	4,6E-06	26	25	280	11,2	3000	84900	28	200	1850	9
2	7,3E-07	1,4E-05	19	9,5	150,7	15,9	2412	90000	37	150	1434	10
15	3,4E-07	1,5E-05	44	30	239	8,0	9000	71700	8	400	1275	3
<i>Pressurised tanks</i>												
14	4,00E-07	1,30E-05	33	-	-	-	-	-	-	570	3800	7
18	1,50E-09	4,70E-06	3133	-	-	-	-	-	-	320	2200	7
<i>Refrigerated pipelines</i>												
7	8,00E-07	4,60E-06	6	94	300	3,2	28500	180000	6	80	3466	43
10	4,00E-07	6,00E-06	15	1100	2500	2,3	47400	750000	16	250	3201	13
<i>Refrigerated tanks</i>												
9	1,00E-08	1,00E-06	100	-	-	-	-	-	-	250	4755	19
7*	2,30E-07	5,70E-05	248	-	-	-	-	-	-	65	10000	154
<i>Loading arms</i>												
4	1,30E-05	8,00E-03	615	139	210	1,5	16680	126000	8	118	2300	19
17	1,5E-07	2,1E-03	14000	7	62	8,9	1404	18600	13	200	680	3

**Table 12 Qualitative assessment of the importance of various factors to the uncertainty in the calculated risk (the more stars the more important)**

<b>Factor</b>	<b>Importance</b>
<b>Differences in the qualitative analysis<sup>5</sup></b>	**
<b>Factors relating to frequency assessment:</b>	
Frequency assessments of pipeline failures	***
Frequency assessments of loading arm failures	****
Frequency assessments of pressurised tank failures	****
Frequency assessments of cryogenic tank failures	***
<b>Factors relating to consequence assessment:</b>	
Definition of the scenario	*****
Modelling of release rate from long pipeline	***
Modelling of release rate from short pipeline	*
Release time (i.e. operator or shut-down system reaction time)	***
Choice of light, neutral or heavy gas model for dispersion	****
Differences in dispersion calculation codes	***
<b>"Analyst conservatism" or judgement</b>	***

Without doubt, noteworthy variation in the final results has been revealed. This variation is present both in the assessment of frequencies and in the assessment of consequences. The different results obviously affect the relevant risk-informed decisions, mainly land use planning, emergency planning and acceptability of risk. Therefore, the need to analyse these uncertainties, take measures to reduce them, and inform the other stakeholders of risk-informed decisions about their existence and implications is a principal obligation for the risk assessment community. The outcome of the ASSURANCE project should be seen in this context, i.e. as a contribution to the understanding of the uncertainties.

The exercise also revealed that the level of our knowledge on the phenomena is – with few exceptions – high. In certain cases, like release from long pipelines and release on water, the level of knowledge is being improved. It is, however, apparent that the risk analyst and his/her judgement affect significantly the results of risk studies. Uncertainty in the definition of scenarios and input assumptions/simplifications is probably the most important source. These assumptions should therefore be reported clearly in the risk assessment and the Safety Report, so that they can easily be tracked and evaluated by the competent authority (complete assumptions reporting is, however, a difficult task). Moreover, the scenarios that form the basis for risk-informed decision-making, especially catastrophic scenarios, should be very precisely defined, in order to avoid contradictory conclusions due to ambiguities in definitions.

Furthermore, the outcome of the benchmark exercise confirmed the need that each approach to harmonising procedures be based on similar benchmarking.

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<sup>5</sup> This refers in particular to the outcomes of the quantitative risk analysis; in this case all the partners identified in a similar manner the most relevant scenarios. The statement would be misleading if transferred to the “accident prevention” since the different qualitative techniques have very different ability of identification of possible hazards and corresponding preventive measures.

Finally it should be noted that useful lessons were learned on how to run a benchmarking project. For instance, it is vital that the common assumptions and information about plant data are discussed in depth between the participants in order to make certain that there is a common understanding of these input to the analysis.

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7. Analysis reports produced by the participants in the benchmark (qualitative and quantitative analysis phases and case studies)

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# ANNEX I

## Reference scenarios

From Partner 6's list the following scenarios were agreed on to be assessed by all the partners (numbering below as used in the present report, not identical to the partner's original numbering):

- Scenario 1: Full section rupture of 8'' feeding pipe upstream of valve 09-MOV-01, just after the pipe becomes aerial.
- Scenario 2: Full section rupture of the 4'' pipe 241P-067-P1349 just before tie-in no. 2. (The full section rupture means a pipe split into two parts.)
- Scenario 3: Full section rupture or disconnection of the connecting flange on the liquid phase between ammonia ship and unloading arm 241-ME1
- Scenario 4: Full section rupture of 10'' pipe 241P-089-P1283, on the discharge line downstream of 241-P4
- Scenario 5: Rupture of a ship tank
- Scenario 6: Catastrophic rupture of cryogenic tank 241-S1
- Scenario 7: Full section rupture of 20'' pipe 241P-015-P1284, on the distribution line of tank 241-S1, just downstream of pneumatic valve HV203
- Scenario 8: Catastrophic rupture of one of the ten pressurised tanks 241-V1 to V10.
- Scenario 9: Full section rupture of 4'' pipe 241P-108-413, on the distribution line of tank 241-V1, just downstream of pneumatic valve
- Scenario 10: Full section rupture or disconnection of the connecting flange on the liquid phase between ammonia truck and unloading arm
- Scenario 11: Catastrophic rupture of a truck tank.



## Title and authors

Assessment of Uncertainties in Risk Analysis of Chemical Establishments  
The ASSURANCE project (ENV4-CT95-0627)  
Final summary report

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## Abstract (max. 2000 characters)

This report summarises the results obtained in the ASSURANCE project (EU contract number ENV4-CT97-0627). Seven teams have performed risk analyses for the same chemical facility, an ammonia storage. The EC's Joint Research Centre at Ispra and Risø National Laboratory co-ordinated the exercise and led the comparison of results in order to reveal the causes for differences between the partners' results. The results of the project point to an increased awareness of the potential uncertainties in risk analyses and highlight a number of important sources of such uncertainties. In the hazard identification phase it was revealed that the ranking of hazardous scenarios by probabilistic and deterministic approaches could result in completely different conclusions. On the other hand, despite a large difference in frequency assessments of the same hazardous scenarios, there was good consensus on the ranking among the adherents of the probabilistic approach. Breaking down the modelling of both frequency and consequence assessments into suitably small elements and conducting case studies allowed identifying root causes of uncertainty in the final risk assessments. Large differences were found in both the frequency assessments and in the assessment of consequences. The report gives a qualitative assessment of the importance to the final calculated risk of uncertainties in assumptions made, in the data and the calculation methods used. This assessment can serve as a guide to areas where, in particular, caution must be taken when performing risk analyses.

## Descriptors

BENCHMARK; CHEMICAL FACILITIES; CONSEQUENCE ASSESSMENT; DETERMINISTIC RISK ANALYSIS; FREQUENCY ASSESSMENT; LAND USE PLANNING; PROBABILISTIC RISK ANALYSIS; RISK ANALYSIS; RISK-INFORMED DECISIONS; UNCERTAINTIES



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