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Uncertainties in chemical risk assessment: Results of a European benchmark exercise

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Abstract

The paper describes an European Community (EC) project (*Benchmark Exercise on Major Hazards Analysis*) aimed at assessing the state of the art of chemical risk analysis and the associated uncertainties. The same reference subject (an ammonia storage facility) was analysed by 11 teams representing control authorities, research organizations, engineering companies and industries. In the first phase, a complete risk assessment was performed and the results were compared with respect to methodologies, data and models employed. In the second working phase, a set of selected partial exercises with predefined boundary conditions was carried out in an attempt to identify the sources of the overall spread of the results obtained from phase one. The project resulted in a comprehensive overview of currently available methodologies for chemical risk assessment in Europe, and triggered an important common learning process towards sound analytical procedures.

1. Introduction

Despite their increasing use, risk assessment procedures for chemical processes and storage plants are not yet well established. Decision makers are confronted with a variety of approaches, methodologies and forms of presentation of the results, which make it difficult to compare studies performed by different analysts. Furthermore, a comprehensive investigation of the uncertainties linked with the results of a risk assessment, as well as the causes for their variability, is lacking.

Benchmark exercises have been shown to be highly successful in establishing consolidated consensus procedures for the probabilistic assessment of safe performance of nuclear power plants (NPP) [1–3]. Indeed, independent analyses of a reference subject performed by different teams with different backgrounds, have proven to be an effective tool for gaining an understanding of

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TABLE 1

Composition of the participating teams

TNO (NL)
Demokritos, Athens University, Ministry for the Environment (GR)
Health and Safety Executive (UK)
Risø, Oil Consult, Cowiconsult (DK)
Tecnimont, EDRA, Rohm and Haas Italia (I), CEP (F), IGC (E)
ENEA-DISP, Snamprogetti, NIER, Fiat Engineering (I)
Technica (UK), Ansaldo (I)
Vincotte (B), Solvay (B–I)
GRS, Battelle (FRG)
VROM (Ministry for the Environment) (NL)
VTT (Technical Research Centre of Finland) (SF)

Note: For confidentiality reasons, there is no correspondence between the order of teams in the table and the team numbers given in the graphs.

the available methods, their strengths and weaknesses, the uncertainties involved, their origins and their impacts on the results.

Based on this experience, the Joint Research Centre (JRC) in Italy managed, during the period 1988–1990, a benchmark exercise on major hazard analysis (MHA-BE) for a chemical plant. The objectives of the study were to evaluate the state of the art and to obtain estimates of the degree of uncertainty in risk studies. The project was partly funded by the Shared Cost Action Program of the EC and by the Directorate for the Environment responsible for the EC Major Accident Hazards Directives. The exercise was performed by 11 teams representing 25 organizations (research institutes, engineering companies, authorities and industries) from different European countries. The participants are shown in Table 1. An ammonia storage facility was taken as reference plant for the project.

The project was subdivided into two phases. The first phase was aimed at a comparison of the existing approaches to risk analysis, from hazard identification up to and including the calculation of the individual risk contours. The objective of the second phase was to identify the single factors contributing to the overall difference in the results, and this phase was designed on the basis of the results of the first phase.

Whereas an extensive description of the results was given in the final report [4], this paper summarizes the main steps and findings of the project.

2. Objectives and structure of the MHA-BE project

2.1 Objectives of the project

The main objectives were:

(1) to identify the state of the art on major hazards analysis; and

(2) to obtain estimates of the overall degree of uncertainty.
These in turn include:
(1) the comparison of the different methods, models and procedures;
(2) the assessment of their relative advantages and limitations;
(3) the state of the art of available data bases;
(4) the assessment of the variability of the results obtained by independent teams, together with the origin and nature of the uncertainties;
(5) the identification of problem areas, possibly worthy of separate investigations; and
(6) the possible achievement of a common awareness on the problems associated with all the above-mentioned items.

2.2 Reference plant

The project was performed with reference to an existing ammonia storage plant, but supposed to be located on a hypothetical site. The plant included the following facilities:
(1) an ammonia sea terminal;
(2) an undersea pipeline connecting the sea terminal to a sea-side refrigerated storage tank;
(3) a refrigerated storage tank with a capacity of 15,000 tonnes;

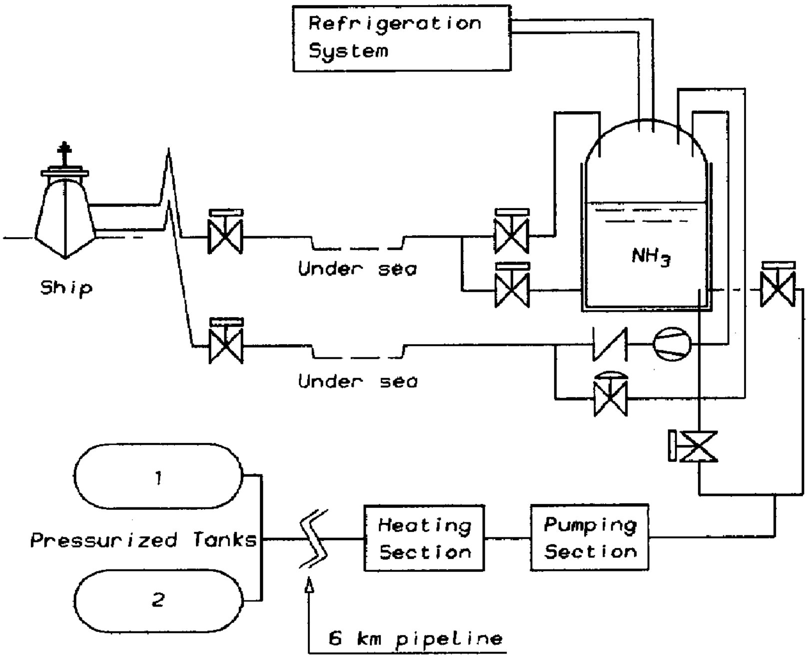

Fig. 1. Simplified reference ammonia storage plant.

(4) an underground pipeline connecting the refrigerated tank to two pressurized vessels within a fertilized plant; and
(5) two pressurized vessels.

A simplified scheme of the reference plant is shown in Fig. 1.

Marine shipments arrive directly at the offshore sea terminal (ship manoeuvering incidents were not part of the study). One ammonia vessel arrives every other month. The unloading capacity is 600 t/h, and ammonia is unloaded at −33 °C. During unloading, ammonia gas is displaced from the refrigerated storage tank as it fills up with liquefied ammonia, and it is sent to the ship where it replaces the liquefied ammonia. The refrigerated storage tank, which consists of a single steel plate wall, is cylindrical with a curved roof. The steel tank is located within an outer concrete tank, and is designed for storing 15,000 tonnes of ammonia at −33 °C (temperature determined by the atmospheric boiling point of ammonia). To maintain a temperature of −33 °C, a refrigeration system is needed that is made up of three compressors. During normal service one compressor is sufficient to maintain the pressure in the tank. During tanking operations all three compressors are in operation.

Liquefied ammonia from the storage tank is drawn from the base of the tank and pumped 6 km to the process plant after heating at −20 °C. These tanks, surrounded by a low bound, have a normal inventory of 60 t (50% capacity).

2.3 Outline of the project

The project was subdivided into a documentation phase and two working phases.

2.3.1 Documentation phase (January–August, 1988)

A first set of documents was distributed to the participants before the first project meeting, which included a visit to the plant (May 1988). After the meeting, the documentation was completed and time was made available for the participants to ask questions to the plant experts. All questions and the corresponding answers were circulated among each team in order to ensure participants had uniform information on the plant. Furthermore all the project meetings were attended by a plant expert, thus allowing a further exchange of information.

2.3.2 Working Phase I (May 1988–January 1989)

In the first working phase the participants were asked to perform a complete risk analysis of the plant, ranging from hazard identification to the evaluation of the individual risk contours. In order to examine the current procedures for risk analysis without biasing the works by assigning contents and formats, the teams were left free to apply their own methodologies and to include any types of procedural steps and estimations that they considered to be appropriate.

Working Phase II (February–September, 1989)

The results of the first working phase were incorporated into the content of the second phase. The need to identify the main differences in the results of the risk calculations meant that Phase II was defined as a set of partial exercises based on stricter common boundary conditions. These exercises were as follows:

1. A system reliability analysis for the event "over-pressurization in the refrigerated storage tank".
2. A human action analysis concerning the isolation of a pipe break.
3. Four ammonia release cases:

(a) a guillotine break of a pipe downstream of the pressurised storage tank;
(b) a guillotine break of a feedline to a pressurized tank;
(c) an isolatable break in a pipe connected with the refrigerated tank;
(d) a failure of a known dimension of the roof of the refrigerated tank.

In this analysis, both the vulnerability model used in the first working phase, and a common vulnerability model, had to be applied.

3. Main indications from the results

The MHA-BE results have confirmed the usefulness of, and the need for, the project. For the first time, analysts with different cultural backgrounds (strictly linked to national approaches to the problem) had the opportunity to compare their methodologies, experiences and procedures on a wide-ranging project, which touched on the different facets of a risk assessment procedure for a chemical storage facility.

In the main indications derived from the whole project are presented in general terms, whereas a more detailed discussion is given in Section 4 by focusing on the pressurized part of the reference plant.

3.1 Approach to risk analysis

Any comparison of multiple studies should attempt to outline the main tendencies and common factors against divergences among the guiding principles. This, of course, may result in oversimplifications and losses of particular aspects, which also contribute to the differences in the overall results. With this warning in mind, the approaches adopted can be basically classified into two main different categories.

According to the first approach (Approach A), the hazard identification phase consists of studies of the conceivable break of each component and pipe of the plant into a number of "characteristic hole sizes", from which a release of flammable/toxic material can occur, complemented by an engineering review of other failure modes. It can easily be imagined how large the number of such failure cases can be. For each failure case identified, event tree technique is applied to describe possible further development of the accident by considering the behaviour (failure/success) of the safety systems or operator interventions. Hence, the initial number of conceivable accidents increases still further.

Generally, the processing of such a large number of events requires use of automated and integrated computational tools, but even in this case, to keep the number of failure cases within a manageable proportion, some screening criteria must be applied to neglect those failures not presenting a significant risk.

This screening procedure was mostly based on a release rate threshold, $q_{\min}$, below which the effects are considered to be negligible. This value can be obtained by assuming a minimal lethal concentration, at a chosen distance $d_{\min}$, that would result in $x\%$ of fatalities for an assumed exposure time, t, and atmospheric condition. A probit equation is used for this calculation. The release rate, $q_{\min}$, of sufficient magnitude to cause $x\%$ fatalities at distance $d_{\min}$ is then determined.

Once the significant contributors have been selected, the failure frequency calculation is performed by using historical data for the failure events, supplemented, to a minor degree, by the application of the fault tree technique. The calculation of the consequences (for different weather conditions) is generally preceded by a phase in which releases of the same type are grouped together and calculated only once (clustering technique), thus reducing the total amount of computer time needed.

The second approach (Approach B) differs from the previous one, mainly in the hazard identification phase. The failure cases are identified by the application of structured systems analysis techniques (e.g. Hazard and Operability (HAZOP), Failure Mode and Effects Analysis (FMEA), Master Logic Diagram, etc.). In order to reduce the practical complexity in applying these techniques, engineering judgement is continuously applied to stop examining those sequences of events when they are recognized as not being able to give rise to significant accidents, or as having an insignificant probability of occurrence.

From a purely theoretical point of view this approach does not necessarily require any historical review, but in practice the analysts perform a review of past accidents to enhance the completeness of the hazard identification study.

In principle, a consistent application of these approaches should give the same end results. However, in practice the results may differ because of differences in data and models, as well as because the results of the screening process, in both cases, requires a subjective engineering judgement and/or the assignment of cut-off values required by automated procedures.

Whereas the first approach is mostly being adopted by chemical plants to assess external risk for land use planning, the second approach has its origins from the nuclear field, where a large effort is spent in the use of structured techniques for identifying the possible abnormal behaviour of complex redundant systems. However, for practical reasons, the latter approach tends to privilege analysis of high consequence events, whereas the automation normally achieved for the first approach makes it practicable to also consider events with consequences limited to the proximity of the plant.

In the benchmark exercise, the first approach was fully applied by four teams, while all the others used the second approach, with some differences in the techniques applied for hazard identification.

The failure events identified and selected as important by the teams who applied the first approach, show less team-to-team variability than that which resulted from the application of the second approach. This may be due both to the cultural proximity of these teams and to the characteristics of the applied methodology, which results, in practice, in the consideration of a larger number of release events (made possible by using integrated computerized tools) including a large spectrum of possible source terms. Furthermore, this approach mostly implies that historical release rates already include component malfunctions and human errors.

With respect to the second approach, the team-to-team variability seems more affected by the completeness of the hazard identification and by the depth of the analysis. These, in turn, are strongly correlated with the information available on the systems and are sensitive to the assumptions that an analyst is obliged to make when information is uncertain or not available. However, the advantage of this approach is that it allows identification of rare accidents due to multiple failures, with root causes hidden within the specific features of the process/control systems and man–machine interface.

As far as the spread on risk calculation is concerned, it seems that the "degree of robustness" is greater in Approach A because of the larger number of failure events considered, which smooths the results towards the average.

A better familiarization with both approaches will certainly lead analysts to a spontaneous merging of techniques, and this, in turn, should reduce the spread on risk figures and favour the achievement of consensus procedures.

3.2 Other sources of uncertainty and variability of the results

3.2.1 Reliability Data

For a certain number of failures with significant consequences, the spread on component reliability data was of some orders of magnitude: these were the cases for which the unavailability of data significantly affected the spread of the risk figures. Again, for the teams that applied Approach A, commonalities in the data base used were found. Some teams used data essentially derived from nuclear components data banks,but modified by engineering judgement. The fault tree technique was used by some teams for determining the failure frequencies of complex events. When the results from a fault tree analysis were compared with historical data used by other teams for the same event, substantial differences were found. This could be due both to the assumptions made and to the data adopted for the primary events.

All these considerations call for the need to set up data campaigns in existing plants on failure modes and frequencies for components and systems, since the uncertainties due to the data play a role larger than that experienced in Nuclear Power Plant (NPP) projects. Treatment of uncertainties in data and of "common cause failures" is not yet a well established practice among analysts.

3.2.2 Human factors

The application of structured analysis techniques to assess human success probability resulted in the same problems already encountered in NPP projects [5]. Furthermore, this was complicated by the strong correlation that might exist between the judgement of the operator ability to act and the assessment of the release scenarios which required operator intervention; indeed, the operator might be exposed to toxicity risks. However, historical data on the duration of releases may be helpful since these already include human actions.

3.2.3 Source term definition

The variability of the quantity of ammonia released was due to
(1) the extent of the assumed failure events;
(2) the assumed duration of the release event; and
(3) the release rate model.

The size of a break was dimensioned according to the analyst's judgement and to historical data. As far as the duration of the release is concerned, the variability was also related to the assessment of isolation times. A better result can be achieved by considering multiple sizes and times, as was indeed performed by a few of the teams, especially those adopting Approach A.

3.2.4 Dispersion calculation

The major uncertainty found concerned the conditions under which the plume behaves as a heavy or neutral/buoyant gas, especially for releases from refrigerated storage. However, other differences appeared because of the assumptions under which the same model was used. In addition to that, there was a wide consensus of opinion on the need for further R&D activities on:
(1) model dispersion of denser-than-air gases, with the capability of using time-dependent source data (most of the models available to the participants did not have this capability); and
(2) on the linking of passive dispersion occurring in a denser-than-air plume or puff, especially at the edges, with non-passive dispersion at, and near, the central line.

3.2.5 Risk contour calculations

The terms of reference included the calculation of individual risk contours. After the project, a wide consensus was achieved on the fact that the probability of being injured by a toxic cloud versus the distance should be calculated by taking into account the variation of the concentration across the width of the cloud and a systematic consideration of the geometrical effects. The models available to the participants did not always make it possible to reconstruct the total individual risk, by weighting the different atmospheric conditions and wind directions by consideration of such geometrical effects. Therefore, some participants limited their calculations to the cloud centreline. This also resulted in an objective difficulty for the comparison of the final results.

Also the *vulnerability model* played a role, particularly at low risk levels, which was to be expected since the major uncertainty is in the evaluation of the effects of low level doses. With this in mind, some further developments on vulnerability models are needed.

3.3 Final remarks

In both working phases the comparison of the results was not an easy task. This underlines the need of moving towards a harmonization, not only of the content, but also of the presentation formats of the results. The need for a formalized common language also emerged (in some cases, a same term was associated with different meanings, as was the case for the term "individual risk contours"). Since, as described, the numerical results are strongly dependent on the assumptions adopted, the major merit of the presentation of the results should consist in the transparency of the underlying assumptions and in the inclusion of all relevant intermediate quantities.

4. Risk at the pressurized storage site

A simplified P&ID of the pressurized storage area is represented in Fig. 2. On arrival at the process plant, the 6 in. pipeline, from the refrigerated storage tank, splits into two 3 in. lines connected to the two pressurized tanks. These tanks, surrounded by a low bound, are cylindrical 3.5 m diameter and 24.2 m long, with a capacity of 233 m^3. The pressure and temperature of the ammonia is 13 bar and 20°C, respectively. Each tank has a nominal inventory of 60 t (50% capacity). The tanks are connected, at their base, to the 4 in. suction line which run along a trench to the three delivery pumps. The pumps deliver ammonia as required by the process units. The two tanks are continuously in use with varying quantities of ammonia.

4.1 Results of the first working phase (WPh-I)

Figure 3 shows cross sections of the individual risk contours from all sources at the pressurized storage site as they were determined in WPh-I. In this figure,

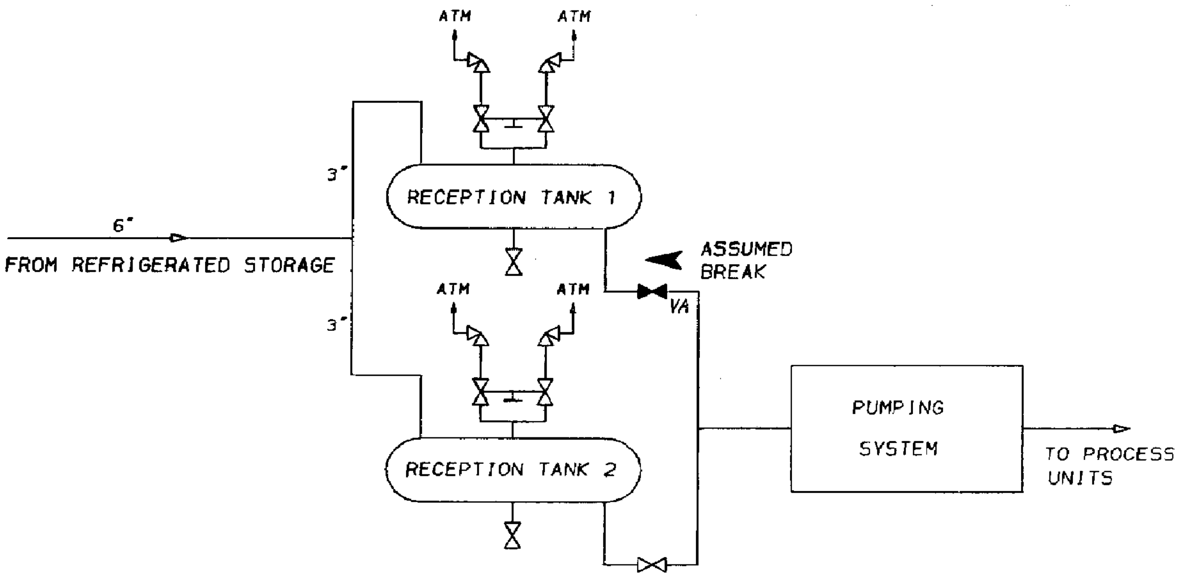

Fig. 2. Simplified diagram of ammonia pressurized tanks.

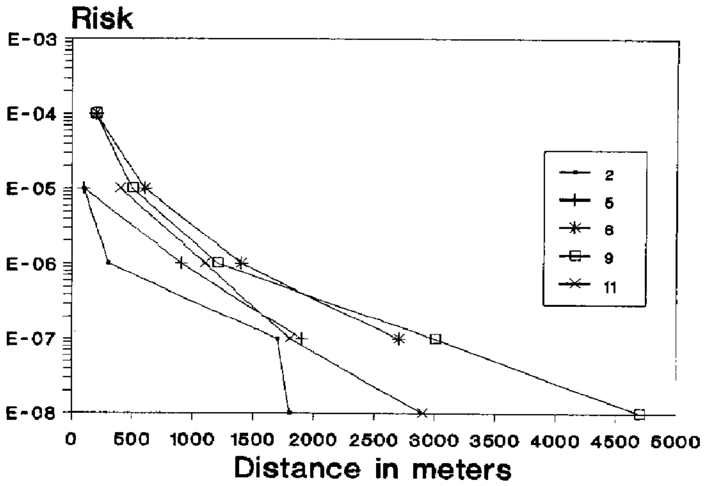

Fig. 3. Individual risk at the pressurized storage site from all contributors (Working Phase I).

only the results of 5 out of the 11 participating teams could be shown, since the other teams supplied results for separated sources, and/or single weather conditions.

As stated before, the differences in the results are due to the various causes described in Section 3. The risk at the pressurized site is, however, practically determined by the hazard sources at that site and by the piping in the vicinity, whereas the risk due to the refrigerated storage (6 km away) is negligible.

Figure 4 shows the cross sections of the risk contours in the same direction as Fig. 3, only from the hazard sources at the pressurized site, as determined

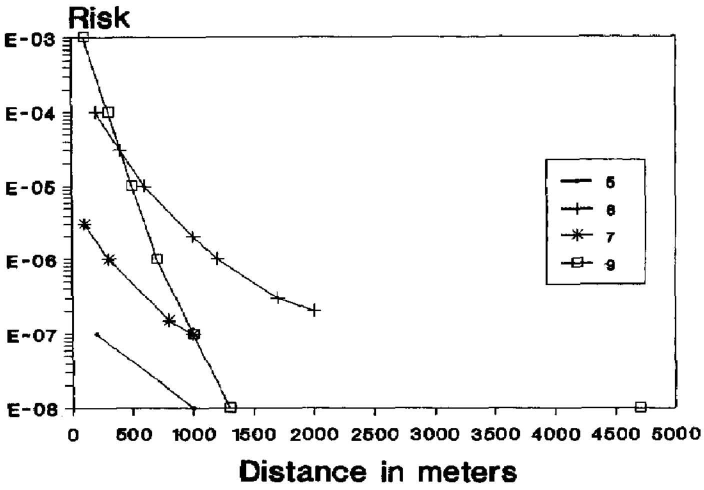

Fig. 4. Individual risk at the pressurized storage site due to accidents occurring inside the defined boundaries of the area (Working Phase I).

by the four teams who presented such separated results. It must be noted that a further source of variability is represented by the boundaries chosen in defining the pressurized site.

For the reasons already given, such curves should not be taken as representative of the uncertainty of a risk assessment. It can be expected that consolidated consensus procedures and definitions would result in more uniform results. They are, however, indicative of the need to continue the work initiated with this project, i.e. to arrive at a common way of thought among risk analysts.

To understand the reasons for the differences, apart from those generically described in Section 3, it is useful to give indications about the main events retained in the hazard identification process and on differences in assumed frequencies. Whereas the teams adopting Approach B tended to concentrate the analysis on the major event "catastrophic failure of a vessel", the others gave account of intermediate leakages in the vessel, pipings and components. Furthermore, someone even considered the possibility of a common cause rupture of both vessels. Consequently, the release source terms varied considerably by a factor of 4. This figure also included the inventory assumed at the time of the release.

In the same way the failure frequency assumed for the pressurized vessel rupture differed by about 3.5 orders of magnitude when using fault tree analysis. A better agreement, a difference of less than 1.5 orders of magnitude, was found among the teams using Approach A.

Having found such significant discrepancies among the assumptions on events and frequencies, it was questionable whether the differencies found in modelling the releases, the computational tools and vulnerability models could still give further important contributions to the understanding of the overall spread. To clarify such aspects, a particular release event, corresponding to one of the principal failure modes for the pressurized vessel was analysed in the second working phase.

4.2 Results of the second working phase (WPh-II)

In the second phase of the exercise, the failure assumed was a guillotine break of the vertical piping between the pressurized storage tank and the valve VA (see Fig. 2), with the valve assumed to be closed. The break was assumed to occur at the connection point between the pipe and the vessel (80 cm above the ground) at a frequency of 1/y.

In addition to the data described in Table 2, the following boundary conditions were defined:

- Vessel inventory: 100 t at ambient temperature
- Pipe inner diameter: 8 cm
- Surface of the dike: 300 m^2
- Dike height: 70 cm
- Surface type: concrete-dry

The risk had to be assessed by the teams using both the vulnerability model applied in Phase I and a common vulnerability model.

This exercise was performed by all teams. In Figs. 5–7, concentrations versus distance for the three selected meteorological conditions are presented. For the sake of simplicity, all the described results refer to 15 minutes after the starting of the release.

By analysing the intermediate results, the following differences were found:
(1) Almost all teams calculated similar flow rates for the released ammonia from the pressurized tank (from 86 to 105.3 kg/s) and only one calculated a very low flow rate (27.7 kg/s).

TABLE 2

Meteorological conditions assumed in WPh-II

Parameters	Weather class		
	1	2	3
Frequency (%)	40	30	30
Ambient temperature (°C)	20	30	10
Relative humidity (%)	60	60	60
Atmospheric pressure (bar)	1	1	1
Wind speed (m/s)	3.5	5	2
Pasquill stability class	C	D	F
Solar radiation (W/m^2)	35	500	0
Mixing height: 300 m			
Uniform wind direction			

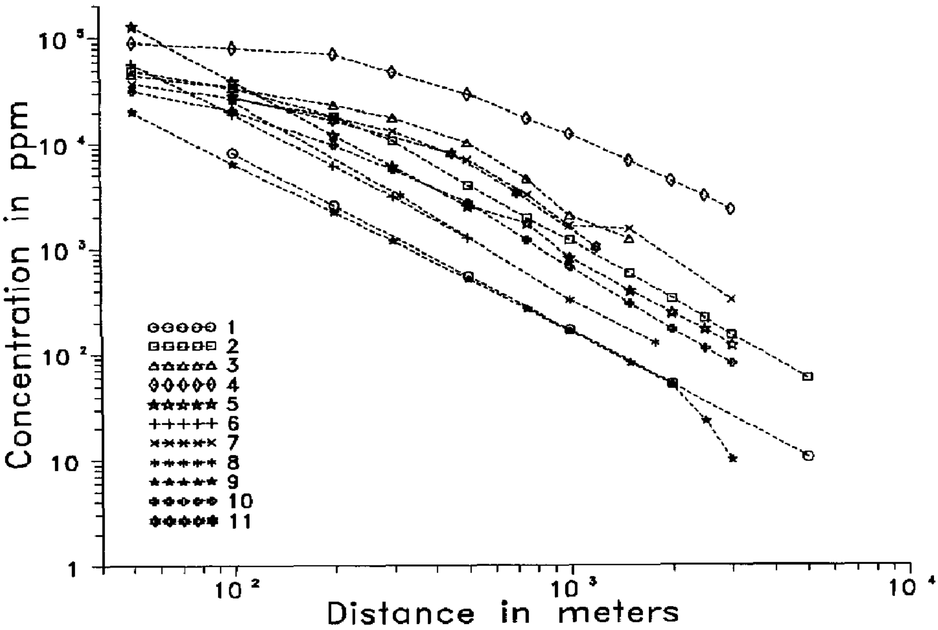

Fig. 5. Ammonia concentration (ppm) versus distance (m) for Weather Class 1, 15 min after the release (Working Phase II).

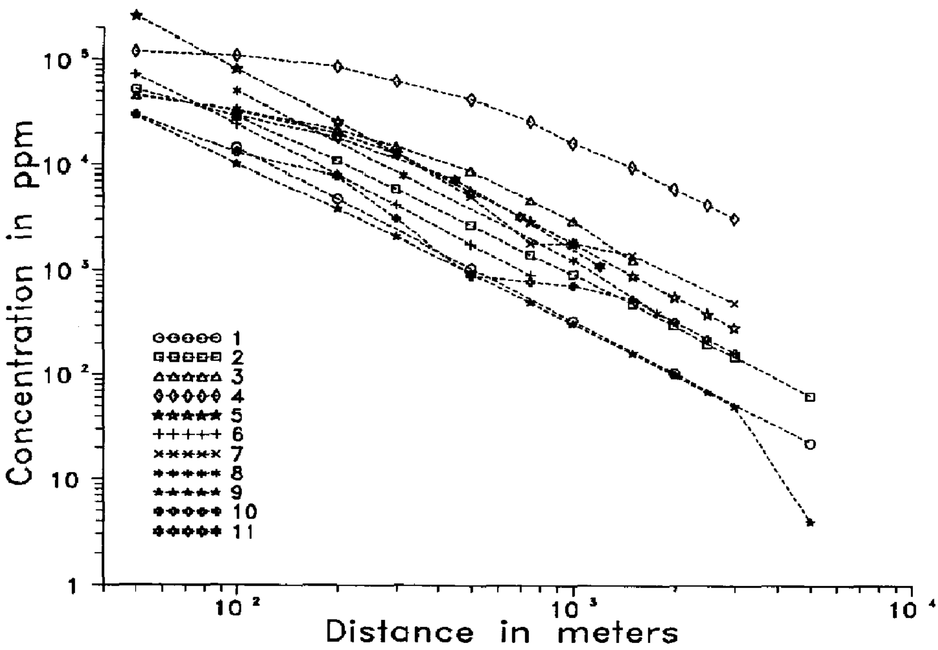

Fig. 6. Ammonia concentration (ppm) versus distance (m) for Weather Class 2, 15 min after the release (Working Phase II).

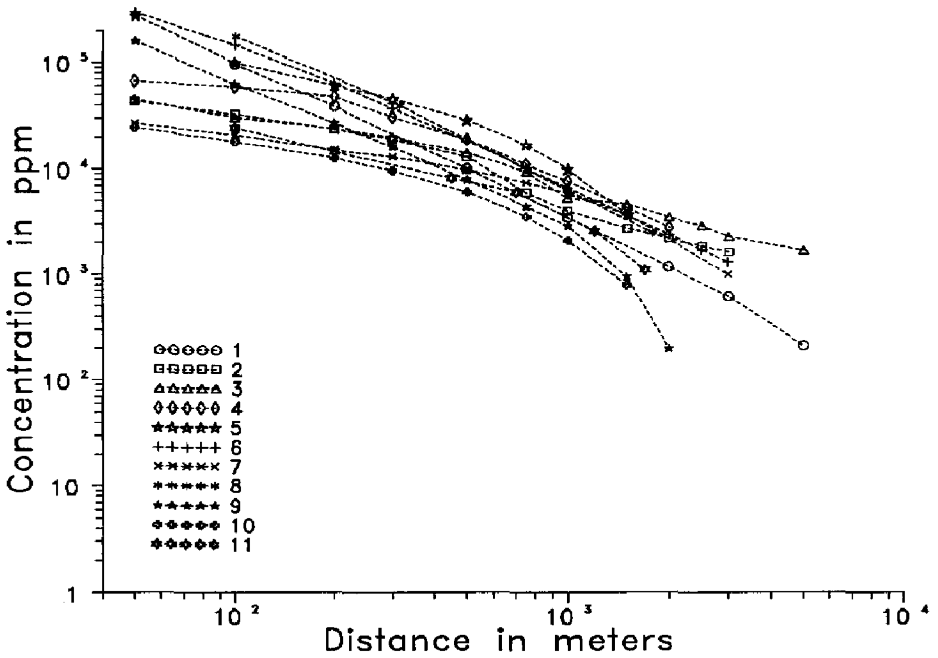

Fig. 7. Ammonia concentration (ppm) versus distance (m) for Weather Class 3, 15 min after the release (Working Phase II).

(2) The calculated total release ranged significantly, from 10.4 kg/s to 96.9 kg/s, i.e. a factor of 9.3. However, the results from nine teams gave a range of between 10.4 and 49 kg/s. (The principal reason lies in the fact that, as the release was towards the ground, there was no consensus as to whether a pool was formed.)

(3) The pool evaporation rate calculated by seven teams is very low (ranging from 0.3 to 1.8 kg/s), while two teams, using the same code, calculated a relatively high pool evaporation rate (5.3 kg/s).

(4) The assumed or calculated rain-out amount of ammonia also had a wide range, from 0 to 83%.

(5) All the teams, except one, used the dense gas dispersion model for the initial plume. For the dispersion of ammonia evaporating from the pool, all the teams used passive dispersion models, except one which used a dense plume model.

(6) The calculated concentrations at the same time (15 min after the release) showed a wide range at various distances. At a distance of 100 m the concentrations range from 6,340 to 80,000 ppm, a factor of 12.6; but excluding the two extreme values, the factor becomes 2. A larger spread was noted at 1,000 m where the concentrations range between 162 to 12,000 ppm, a factor of 73. Also in this case, ignoring the two extreme values, the factor becomes 6.

(7) The differences in the risk values are not only due to different concentrations, as previously described, but also to the different approaches for calcu-

lating the probability that a person be exposed to a certain concentration of ammonia.

Two different techniques were applied by the teams for calculating the risk contours. The first takes into account the probability of being hit by the toxic plume over the whole wind sector, at various distances, while the second technique considers the plume concentration, at different distances, on the central line of each wind sector. Of course the reason why the geometrical aspects have not been considered by some teams is due to the computational models they used, which were derived from dispersion models and not yet finalized to generate risk contours. Therefore, while some teams considered the central line concentration values, all the other teams took into account the geometrical effects but may be using different methods. The risk calculated by these two groups has been described separately in [4].

Figures 8 and 9 represent the risk calculated by those teams that considered the geometrical effects, respectively, with the common assumed model and with the vulnerability model adopted in the first phase. These curves have been determined with the meteorological conditions described in Table 2. Some interesting considerations can easily be made on the uncertainty in the risk due to the vulnerability models used.

One way of showing the importance of the vulnerability model is to look at the different risk curves, determined by a same team, through the use of the common model and the model applied in Phase I.

The comparison of the risk curves calculated using the common vulnerability model and that used in Phase I shows that the vulnerability model becomes important, in explaining the differences of the results, as the risk decreases, i.e. as the distance from the source increases. However, account must be taken of the fact that the risk curves are obtained by assuming a failure frequency

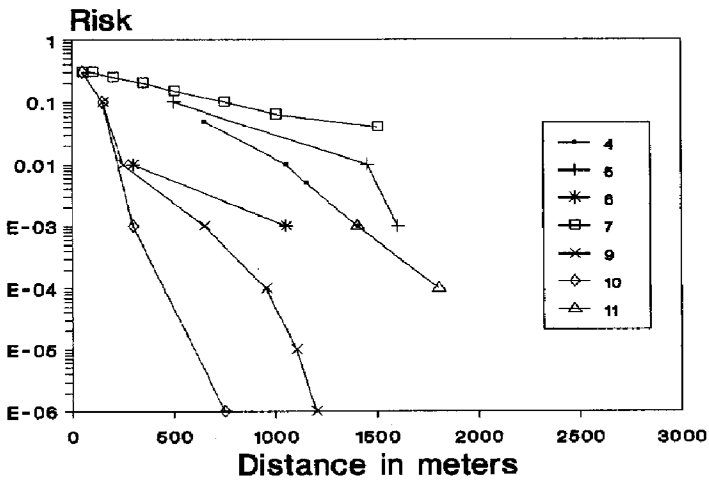

Fig. 8. Risk versus distance for study Case 1. Vulnerability model as applied in Phase I. Geometrical effects considered.

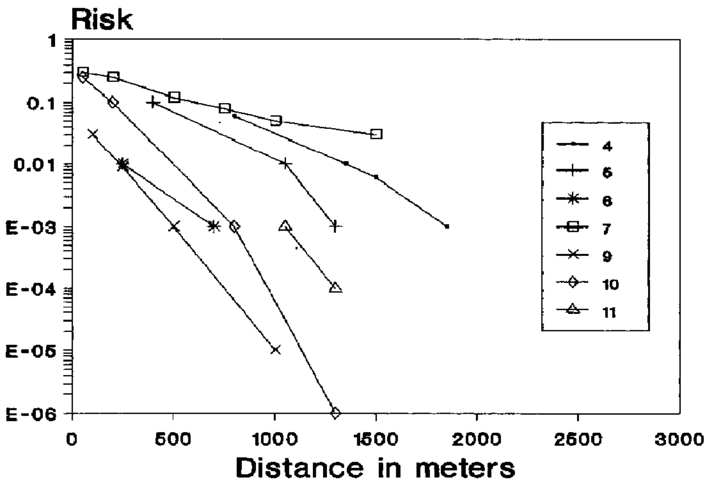

Fig. 9. Risk versus distance for study Case 1. Common vulnerability model. Geometrical effects considered.

equal to 1. In order to give an idea of the weight of uncertainty in the vulnerability model on the overall risk assessment performed for land use planning, assume that the frequency of the event is 10^{-3}, and acceptable individual risk figure is 10^{-6}; then, from Figs. 8 and 9, the difference in the "safety distance" due to the vulnerability model (range 250–700 m) can easily be determined for each team.

Finally, some teams assumed a cut-off limit in determining the concentration versus distance. For concentrations lower than the cut-off value no calculations were performed. This fact explains why not all risk curves cover long distance ranges.

From the above discussion it can be concluded that the main factors responsible for the discrepancy of the results are:

(1) The calculation of the total emission rate, which is mostly the flashing portion of the released ammonia;

(2) The rain-out percentage of the released ammonia;

(3) The dispersion models used;

(4) The vulnerability model and the method of risk calculation.

Furthermore, it must be noted that, although most of the teams calculated time-dependent flow rates, total emission rates and pool evaporation rates, they did not link these calculations with the dispersion models, because the models did not have the capability to accept time-dependent source terms.

5. Conclusions

The findings in WPh-II show that not only do assumptions on failure modes and frequencies contribute to the overall spread, but also the way of modelling the releases, dispersion and toxicity effects have a significant influence on the spread.

As pointed out before, the major outcome of the project does not lie in the numerical differences found in the results, but in the contribution towards identifying the reasons why results can differ. This study should be regarded only as a starting point in the establishment of consolidated consensus procedures.

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