Probabilistic analysis of gas explosion loads

J.R. Bakke and O.R. Hansen, GexCon AS, Norway

Published in FABIG Newsletter , Issue No. 34, January 2003

1 ABSTRACT

The paper gives an outline of the history of probabilistic explosion analyses from a Norwegian viewpoint, with focus on offshore oil and gas production. The relevance of probabilistic analyses is argued, and examples show how a probabilistic analysis compares with other, more traditional analysis methods.

2 HISTORY

In the North Sea region design against gas explosion loads was not really an issue before well into the 1980's. Predictive tools available earlier were typically venting guidelines which did not account for the effect of scale nor of geometrical congestion on explosion propagation.

The first detailed analysis tool for gas explosions that became available was FLACS-86 in 1986. At that time the programme could account for – and was indeed validated for - the effect of a limited number of relatively large obstacles on gas explosions. Hence the geometries that were analysed with FLACS were coarsely modelled, resulting in low overpressures. It was not appreciated at the time that smaller geometry details had the potential to increase overpressures significantly, sometimes by an order of magnitude. As a consequence, analyses performed at that time were worst case type analyses. Simulated overpressures were not prohibitively high and sensitivity analyses varying e.g. confinement often brought pressures within acceptable limits.

In the early 1990's DNV pioneered the use of probabilistic analyses for gas explosions, however still in a very simplistic format. Through the large-scale, high-congestion explosion tests managed by the Steel Construction Institute and performed by British Gas (now Advantica) at Spadeadam (as part of the Blast & Fire Engineering for Topside Structures project – BFETS) [1], it became clear that it was necessary to include smaller geometry details in explosion analyses to a far greater extent than previously assumed. This was supported by similarity tests in medium-scale performed by Christian Michelsen Research (now GexCon). As part of BFETS, an explosion model evaluation exercise was also performed. This exercise showed that special-purpose CFD explosion simulators were capable of and indeed the best suited tools for reproducing the main results of the experiments, i.e. that increasing scale and congestion led to a significant increase in overpressure (for an example see Figure 1).

With the observed increases in explosion overpressures the probabilistic techniques previously assumed to be satisfactory, were shown to be inadequate in the sense that too conservative results were produced. Hence, the techniques did not form an appropriate basis for decisions with regard to design and mitigation of estimated explosion risk.

The BFETS concluded that high explosion pressures were indeed possible, but did not address nor solve the question of how to design barriers against explosion risk (i.e. determine required structural strength and other risk-reducing measures). The UK Health and Safety Executive later performed more tests (Phase 3A) studying less confined situations and the risk-reducing potential of water deluge.

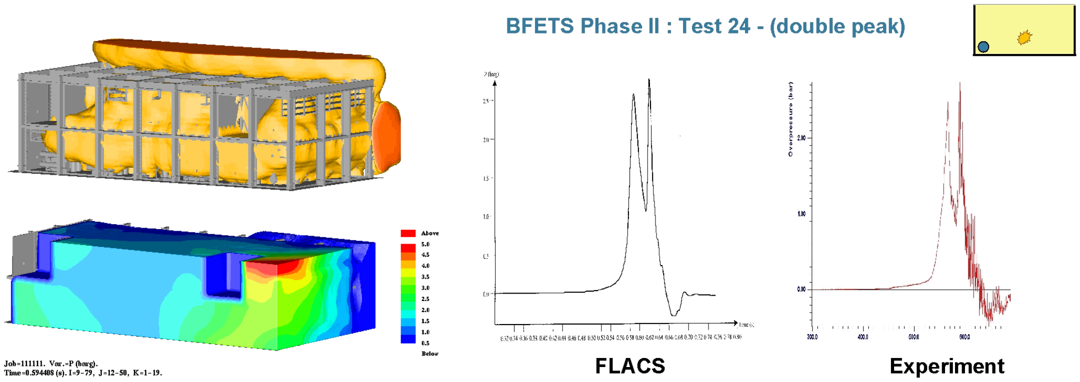

Figure 1 *FLACS simulation results submitted prior to BFETS full-scale test 24, flame (upper left) and pressure contours (lower left) at time of maximum pressure. Predicted pressure curve compared with test result (center versus right).*

In 1997 the NPD formally approached operators on the Norwegian continental shelf to ask how the results of BFETS were implemented in safety work. As one result of this Norsk Hydro, Statoil and Saga Petroleum formed a working group which in the end produced the document “Procedure for probabilistic explosion simulation”, now Annex G to NORSOK Z-013 Risk and Emergency Preparedness Analysis [2]. It is required by Norwegian operators that all explosion analyses adhere to the requirements set out in this standard.

In 1998 Statoil, Norsk Hydro and Saga challenged 5 Norwegian safety consultants to use the principles outlined in the procedure document referred to above to improve QRA-methodology for explosion risk. One major objective was to standardize explosion risk assessments to reduce variation in results between the different providers of explosion safety studies. The current status is that these consultants now have a probabilistic QRA-method for explosion risk following principles as outlined in Annex G to NORSOK Z-013, such as:

Good physical descriptions of ventilation, dispersion and explosion:

- Validated CFD-tools must be used for explosion and dispersion
- Dispersion analyses must be transient
- Assumptions can limit number of CFD-simulations if validity is documented
- A large number of scenarios must be considered with regard to different ventilation regimes, leak sizes and leak locations and directions
- Time dependent ignition modelling must be applied

Transparency must be ensured by presentation of intermediate results:

- Leak frequencies and classes, leak durations
- Ignition probabilities
- Ventilation conditions
- Frequency of ignited and unignited gas cloud sizes, total ignition frequency
- Explosion pressures as function of gas cloud sizes

The remaining part of the present paper presents arguments for why probabilistic analyses form a better basis for decision making and gives examples of results of their use as well as how they compare to other methods.

3 WHY PERFORM PROBABILISTIC ANALYSES

Explosion loads are determined by several parameters, some of which are hard to represent realistically or accurately in an analysis. The three perhaps most important ones are

- Congestion – piping, structure, equipment, cabling, HVAC (see Figure 6 for an example)
- Confinement - walls, decks, larger equipment
- Gas cloud size (i.e. size of part of cloud at near-stoichiometric conditions)

The BFETS gave us a necessary reminder of the importance of correct or realistic representation of all of these parameters. If in an analysis of semi-confined gas explosions congestion is underrepresented, overpressures will be severely underpredicted. Wrong confinement configurations will lead to wrong ventilation, dispersion and explosion venting conditions. Unrealistic or non-representative gas cloud sizes will give wrong overpressures. All three parameters may each lead to order of magnitude errors in predicted overpressure if incorrectly represented.

It is fair to say that in present gas explosion analyses, gas cloud size assessment is at least as great a challenge as is the explosion prediction itself. Hence ventilation and gas dispersion simulations have become a very important part of the explosion analysis. Figure 2 shows an example of the effect of gas cloud size on explosion overpressure on the production deck of an FPSO. 10%, 25% and 50% sizes are shown, and pressures range from less than 0.1 barg for the smallest cloud (right figure) to more than 2 barg for the large one (left figure).

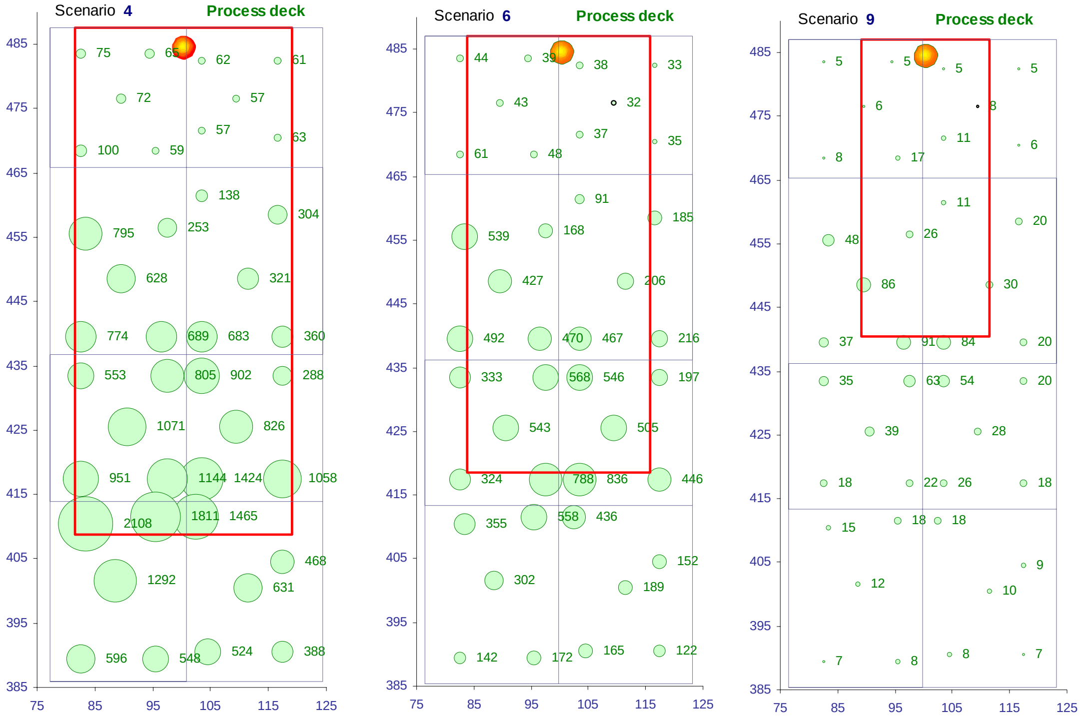

Figure 2 Overpressure as function of gas cloud size. Gas clouds are outlined in red, overpressures are indicated with "bubble" sizes. Ignition is shown by the orange circle.

Implications of this are that when gas explosion risk is analysed, it is necessary to cover the entire chain of events from the onset of a leak, via dispersion and mixing (incl. the effect of ventilation), ignition, the explosion itself to the structural response following the explosion. The obvious way to integrate these processes is through a probabilistic analysis, starting with weather statistics and leak frequencies and ending with probabilities for exceeding loads and for unacceptable structural response.

This is recognized in ISO 13702 “Petroleum and natural gas industries – Control and mitigation of fires and explosions on offshore production installations – Requirements and guidelines”. Chapter 13 “Explosion mitigation and protection systems” states the following objective for such systems:

“To reduce to an acceptable level the probability of an explosion leading to unacceptable consequences”

and later states in 13.2 Functional requirements:

“As input to the FES (Fire and Explosion Strategy) an evaluation of explosion loads and the associated probabilities of exceeding those loads, shall be performed. “

A theoretical worst case analysis will normally result in overpressures far exceeding what one can design against. On the other hand an assessment based on vent curves like NFPA68 will often result in loads far below normal strength of barriers, structure and equipment. A third method is to choose “representative” leak scenarios or explosion scenarios for dimensioning. The selection of scenarios depends completely on the user and may result in any load being produced. There is no way of determining whether the loads are high or low.

None of these methods are really suitable as decision-making tools.

A probabilistic assessment will result in loads between the two extremes, where loads are assigned a probability of exceedance for different levels. Such analyses are routinely based on CFD simulations of ventilation, dispersion and explosion. It is possible to perform a probabilistic analysis in many ways, with different levels of conservatism. In particular the amount of gas close to stoichiometric concentration is very sensitive to small variations in leak direction, rate, location and type. As an example, one case showed that by changing the leak direction by 90 degrees, the volume of gas close to stoichiometric changed from filling 10% of the module to 65%.

Overpressures will vary significantly depending on cloud size (see Figure 2 above) and ignition location, therefore it is necessary to account for the variation in these parameters. Hence, if a probabilistic analysis is based on a small (~10-20) number of dispersion simulations, it may be necessary to include conservatism in the analysis to ensure that underprediction does not become a problem. In the end, results can vary significantly, hence decisions based on the results can differ depending on the choice of method. It is recommended to base the analysis on as large a number of CFD simulations as is feasible economically and time-wise.

Figure 3 outlines the main parts of a probabilistic assessment. The numbers shown in the figure are indicative only. For detailed information on how to perform a probabilistic explosion analysis, see [3], [4], [5]. Detailed information including these papers (in pdf format) can also be found on www.gexcon.com.

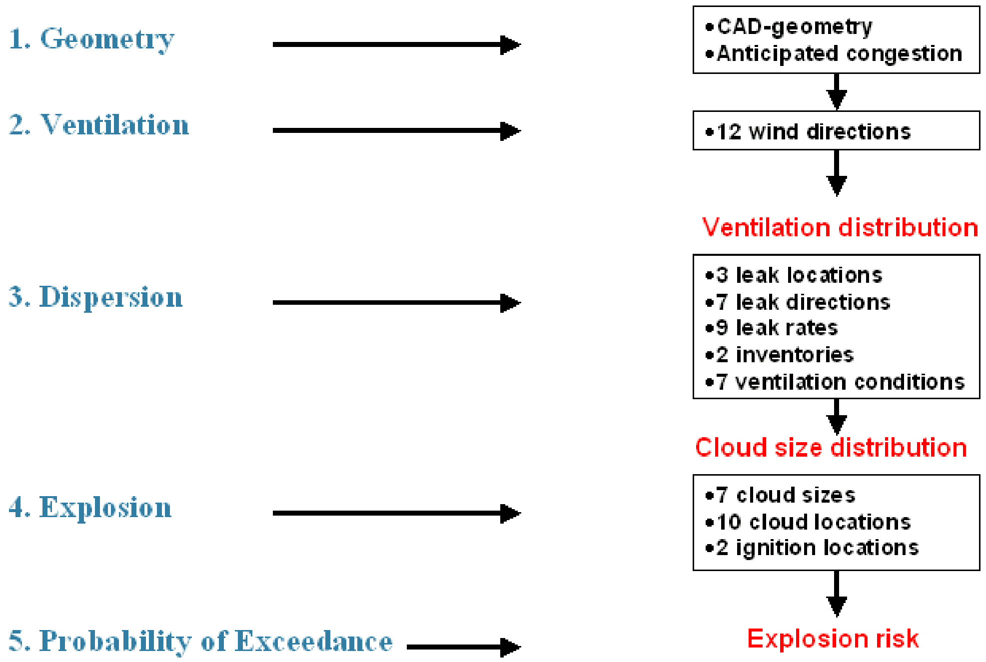

Figure 3 Outline of a probabilistic explosion risk analysis

An illustration of the effects discussed above will be presented in the next chapter.

4 EXAMPLES OF DIFFERENT ANALYSIS METHODS

In the following an attempt will be made to compare different methods for explosion risk assessment on an offshore platform. These methods have been applied over the last 20 years, however, some of them with earlier and less accurate models for explosion prediction. In the comparison, FLACS-99r2, the newest and most accurate version of FLACS, has been used. Several of the older methods presented are still used to some extent. The methods to be compared are:

A) Full probabilistic explosion risk analysis according to NORSOK requirements
B) Probabilistic explosion risk analysis, non-transient dispersion
C) Probabilistic risk analysis, simplified dispersion (i.e. balloon / stirred reactor models)
D) Realistic worst-case approach, CFD-dispersion to select worst-case cloud
E) Theoretical worst-case explosion simulations
F) Worst-case explosion with too low congestion (1990 type approach)
G) NFPA-68 estimate of necessary explosion strength

The reported overpressures apply to a fire wall in the module and for the probabilistic methods (A-C) correspond to the 10^{-4}-value in the exceedance curve. A picture of the module is shown in Figure 4.

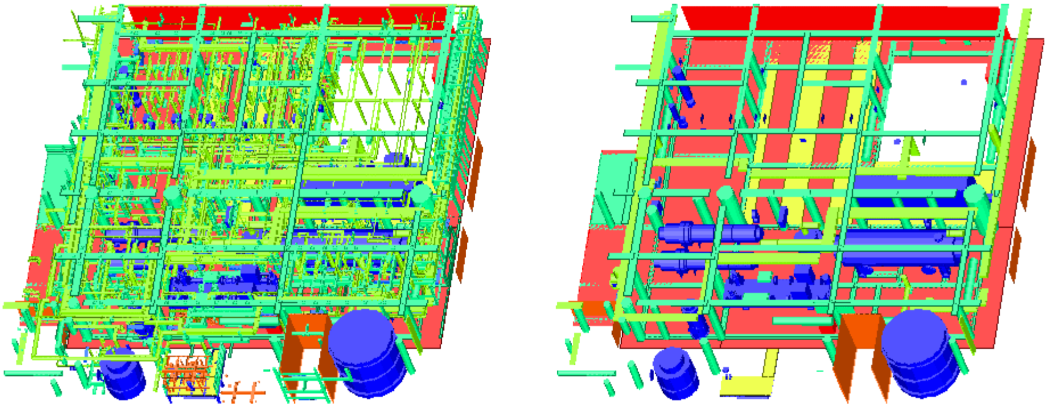

Figure 4 *Geometry model of the platform area considered. To the left the model used for the risk assessment is shown, Anticipated Congestion has been included to compensate for lack of object details in CAD-geometry. To the right a much lower geometry detail level (typical for early simulations with FLACS-86 and FLACS-89) is shown.*

4.1 Method A: Full probabilistic analysis according to NORSOK

The full probabilistic analysis of the platform area (Approach A) is based on FLACS ventilation simulations with wind from 12 different directions, and more than 200 CFD dispersion calculations that due to symmetry considerations and “frozen-cloud” assumptions represent transient gas dispersion results for more than 2000 leak scenarios. These results are used to estimate transient gas clouds from any leak with time varying rate, arbitrary direction, any wind direction and a selected number of leak locations. This is done by automatic processing of results using a time dependent ignition model [6] with both constant and intermittent ignition sources, accounting for reduced intensity after gas detection. Based on local gas concentrations, the realistic non-homogeneous gas cloud is converted to a smaller stoichiometric gas cloud with similar explosion consequences. From this study a gas cloud exposure frequency for different cloud sizes is presented, as well as ignition frequency for each of the gas cloud sizes. An explosion study is performed igniting gas clouds of different sizes and positions. Based on the estimated ignition frequencies, pressure load and impulse distribution is calculated for each wall panel or deck. Similarly, probabilistic drag load on safety critical equipment may also be produced. The calculated pressure exceedance curve on the firewall is shown in Figure 5.

Different companies normally have different acceptance criteria, an example is that a barrier failure that can lead to escalation should happen less than once in 10,000 years on each platform. The design criterion will then be to design walls to withstand pressure loads with cumulative frequency of 10^{-4}/year or less, depending on the number of platform areas with explosion risk. For the present study this would give a wall withstanding explosion pressures of 0.4-0.5 barg (10^{-4}/year) or somewhat higher if there will be more explosion areas that contribute to the risk. The main reason for this low level of estimated explosion risk is the open design, with 3 large open walls, ensuring a much better ventilation than typical for many older North Sea platforms. This reduces the mixing of gas in a leak situation as well as the gas cloud exposure time. In case of ignition, the lower confinement will reduce the general pressure level and duration of overpressure. Further, work to reduce leak frequencies, measures to avoid ignition and depressurization of segments has also contributed to a lower estimated explosion risk than normally seen.

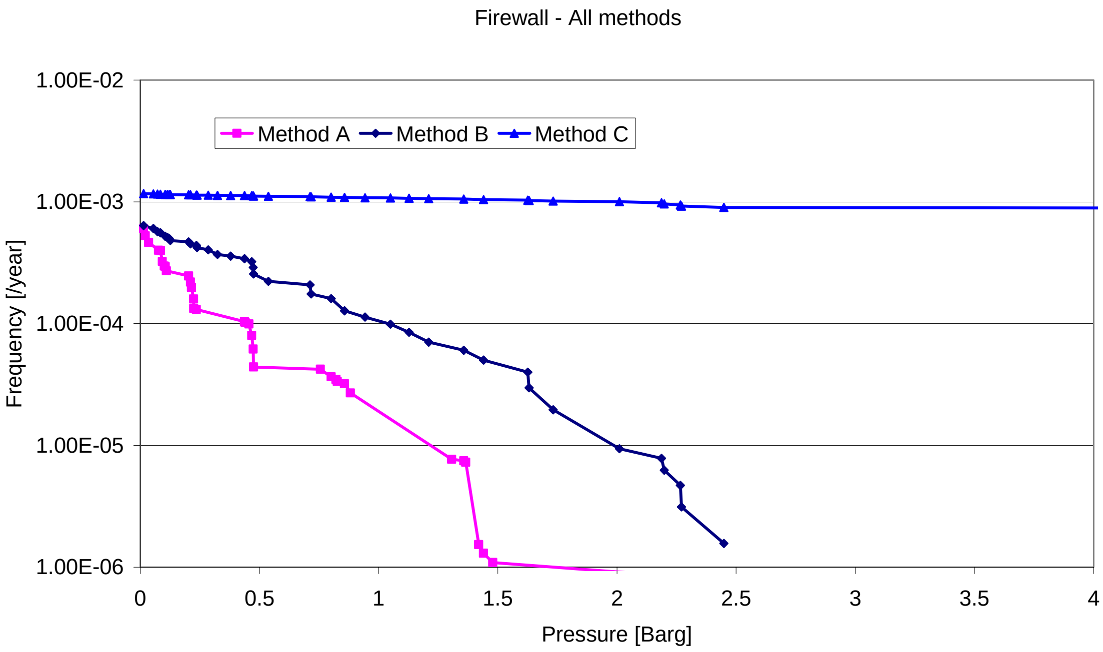

Figure 5 Overpressure exceedance curves for blast wall, approaches A, B and C compared.

GexCon has so far applied the full probabilistic explosion risk assessment to a large number of offshore installations - but no onshore plants. However, in cases where the explosion risk is significant it should be obvious that a better description of the physics will give a better estimate of the risk and a more consistent and cost effective advice on risk reduction measures.

4.2 Method B: Full probabilistic analysis based on steady-state dispersion

Steady-state CFD dispersion calculations may be faster to perform than time dependent transient dispersion calculations due to less strict time step criteria. Problems with this approach include

- Fuel rich clouds (at steady state) may give higher risk contribution in development phase, this is ignored
- Less benefits from time dependent ignition model and short leak duration
- Alternative dispersion tools to provide steady-state solutions may ignore geometry details

In Figure 5 a probability of exceedance curve for pressure at the firewall is shown also for Approach B. The method was applied using neither ignition source reduction nor transient ignition modelling. Ignition source reduction is a risk-reducing measure, e.g. by cutting power to possible electrical ignition sources upon detection. Transient ignition modelling requires calculating the ignition frequency as a function of cloud size during cloud development i.e. also accounting for the smaller cloud sizes very early in a leak situation - normally this reduces the overpressure contribution from small and medium size leaks. It may however increase the contribution from large leaks, which may pass quickly through a large explosive cloud before reaching the rich steady-state cloud. The frequencies for small and medium leaks are however usually much larger than from large leaks, so the net value of this is usually to lower the exceedance curve.

It is possible to use transient ignition modelling based on steady-state dispersion. One then has to produce a (more or less) empirical model for how the near-stoichiometric part of the gas cloud develops towards the CFD-calculated steady-state cloud. The variation of ignition frequency with cloud size increase must then be calculated. This seems to be an unnecessary "simplification" where additional errors can be introduced for the purpose of saving some computing time.

Without the time dependent ignition modelling, the slope of the curve is reduced compared to Approach A. The design pressure will not be influenced by how fast the leak can be stopped, or measures to isolate ignition sources at detection. 10^{-4}/year design pressure corresponding to Approach B is 1.05 barg, while the 10^{-5}/year pressure is estimated at 2 barg.

4.3 Method C: Probabilistic analysis, simplified dispersion tools

An often used approach to explosion risk assessment has been to use a simplified tool for dispersion calculations, and then either a phenomenological tool or a CFD-tool for explosion analysis. Such methods were sometimes applied in Norway until the standardization work for explosion QRA was initiated (see Section 2). At one stage very simple models like the combined balloon and stirred tank reactor models were popular. All gas available is then assumed mixed to be stoichiometric or homogeneous if the volume gets fuel rich.

One major problem with such simplified dispersion models is that they can be extremely conservative at larger scales. In reality, at large scale homogeneous mixing of the gas is close to impossible to achieve, at least for scenarios with low confinement. Applying the simple balloon model, however, one can easily generate a 100% cloud if the leak rate is large enough. And since the ignition frequency for large clouds can be assumed to be larger than for small clouds, a significant fraction of the ignited scenarios will be for large clouds. Using the balloon model on for instance an open, large area like an FPSO process deck can lead to prediction of catastrophic pressures that are completely unrealistic (since one can never get such large stoichiometric clouds there).

The third pressure exceedance curve in Figure 5 illustrates this, as the C curve has a very high likelihood for very high pressures. Since the curve did not cross 10^{-4}, the maximum overpressure of 8.2 bar was used. If the ignition probability was not made dependent on cloud size, somewhat lower frequencies for high explosion loads would be seen. With the low ignition probabilities present offshore (2-5% probability to ignite a very large gas cloud), it should be obvious that a larger cloud will ignite more frequently than a smaller one. With this method, the frequency of the worst-case pressure is higher than a typical acceptance criterion (i.e. 10^{-4}/year).

4.4 Method D: Realistic worst-case approach, CFD-dispersion to select worst-case cloud

In the FLACS dispersion calculations at the installation considered, some of the gas clouds were filling almost the entire module. However, due to non-homogeneities as a result of size and good ventilation, the part of the gas cloud which is close to stoichiometric, and hence will contribute to overpressure generation, only fills about 30-35% of the module volume. In a study of this kind, it is assumed that 5-10 well selected CFD dispersion calculations could identify such a worst-case gas cloud. If the resulting pressure was then applied for design of the firewall a pressure of 2.2 barg would be the resulting design load.

This approach is sometimes used on onshore plants performing a moderate number of dispersion simulations to identify a typical “worst-case” cloud. For calculation of blast pressures in the far field, either with Multi-energy method approach or similar, or with FLACS or other CFD-tools, it can be quite useful to be able to limit the explosion energy for input to the blast calculations. This can be considered conservative, and far more consistent than just assuming a given fraction of fuel to be contributing.

4.5 Method E: Theoretical worst-case explosion (100% stoichiometric gas cloud)

In the North Sea up to around 1994, a typical explosion study would include one or more worst-case explosions with a full stoichiometric explosion cloud. In the early years, only ignition in the centre would typically be considered, later more than one ignition location would be applied. In the table below, maximum pressures are given for four different ignition locations:

Ignition location	**Center**	**Center floor**	**Edge floor**	**Corner floor**
Firewall pressure	5.9 barg	8.2 barg	3.4 barg	4.6 barg
Other locations (P_{max})	8.3 barg	9.9 barg	10.6 barg	12.6 barg

This approach is very seldom used for offshore installations, as the pressures in most cases become unacceptably high. In situations where water deluge will be in place prior to ignition, acceptable pressure levels can still be found with this approach. Acceptable pressure levels can sometimes also be found for far field blast wave propagation on onshore plants.

4.6 Method F: Worst-case explosion with inaccurate (low-congestion) geometry model

The understanding of the importance of geometry details has gradually improved during the 1990s, leading to a successively higher accuracy of geometry representation. With CAD-import possibilities available, a much higher object density is now easily modelled, compared to modelling approaches around 1990. GexCon has also developed the so-called Anticipated Congestion Method, which is a formalised procedure for defining lacking piping based on a large database of as-built CAD geometries. This procedure is actually used in most projects these days.

To illustrate the effect of geometry detail, 5 identical worst-case simulations have been performed, only changing the level of amount of congestion. In Figure 6 firewall pressure curves are shown for the worst-case simulations in the 5 different geometry models. Due to the increased detail level in geometry representation compared to how geometries were represented around 1990, the firewall pressure in a worst-case explosion analysis is increased by a factor of 20. The least detailed geometry results in a maximum overpressure on the fire wall of 0.42 barg. This result is similar to the result from a full probabilistic analysis following NORSOK – bet the result is “correct” for the wrong reasons and one cannot expect this coincidence to carry over to other scenarios.

4.7 Method G: NFPA-68 estimate of explosion pressure

Based on a module dimension of 30m x 30m x 10m, with a full vent area of 3 sides ($900m^2$), NFPA-68 [7] would predict necessary explosion strength of 0.032 barg. Taking into account reduced vent area due to structural beams and some vent panels (yielding at 200 mbarg), and using assumption of hydrogen curves to take initial turbulence into account, 0.048 barg is estimated as necessary design strength. NFPA-68 is not recommended used for vessels containing objects, however, it still seems to be in use onshore for vented industrial rooms. Even a full probabilistic analysis ends up with an order of magnitude higher design overpressure.

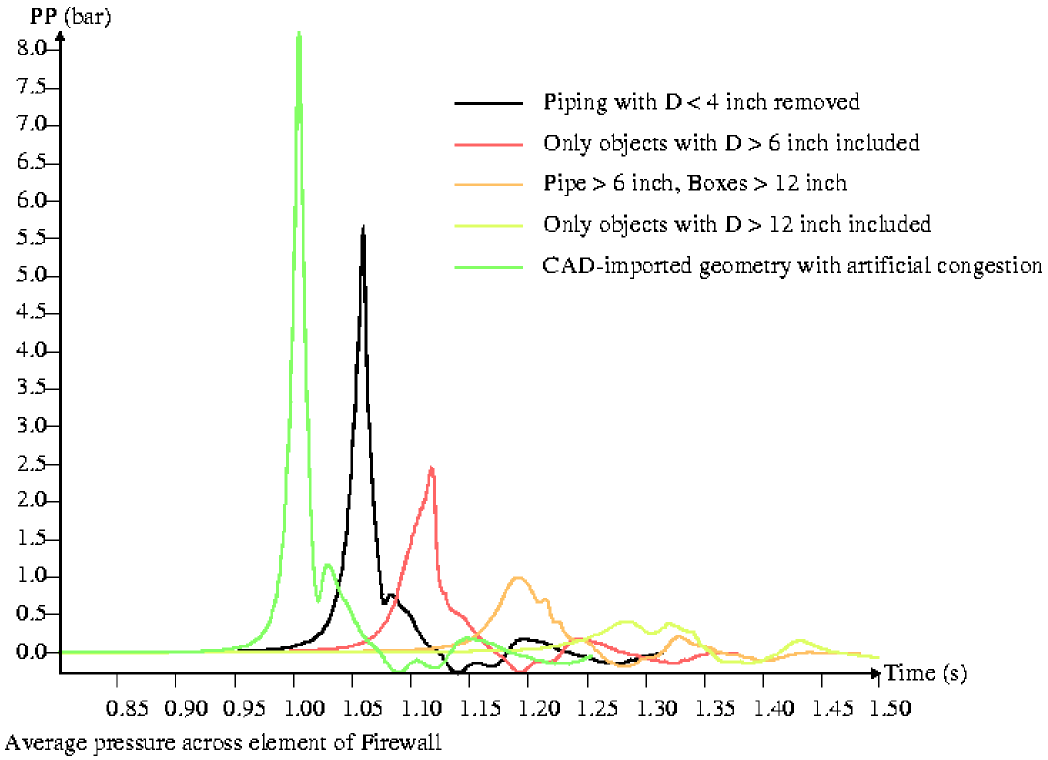

Figure 6 *Worst-case explosion pressures with different level of congestion detail in geometry model*

5 DISCUSSION AND CONCLUSIONS

A probabilistic assessment of explosion risk requires physical processes and input frequencies to be modelled as correctly as possible. One major improvement in recent years has been the ability to model a large number of dispersion scenarios with CFD, this greatly influences the outcome of an explosion study. Results from Phase 3B experiments and FLACS simulations on dispersion and explosions in real clouds (performed by Advantica, GexCon and Shell Global Solutions) were presented at a FABIG meeting in June 2002. Before this, a very limited basis existed for validation of CFD codes for dispersion and explosions in real (partial fill) clouds, both in heavily congested modules. The results were very encouraging, confirming the applicability of CFD to these problem areas. This is seen to be an important confirmation of the validity of several steps in the probabilistic methodology, steps for which validation was previously not addressed.

The study presented in the previous chapter showed that different approaches to risk assessment gave very different answers with regard to necessary design overpressure, varying from 0.048 barg to 8.2 barg (Figure 7). The most accurate (i.e. least conservative) probabilistic analysis is Approach A, which is based on NORSOK and which resulted in a 10^{-4} overpressure of 0.4-0.5 barg. For Methods A and B the 10^{-4} values are used in Figure 7, while for Methods D to G the maximum values were used. Since the curve corresponding to Method C never crosses 10^{-4}, we used the maximum calculated overpressure (i.e. the same as for E).

In this case the probabilistic approach with the best physical description (Method A) gave an acceptable explosion load, this has mainly to do with a good design with high degree of ventilation.

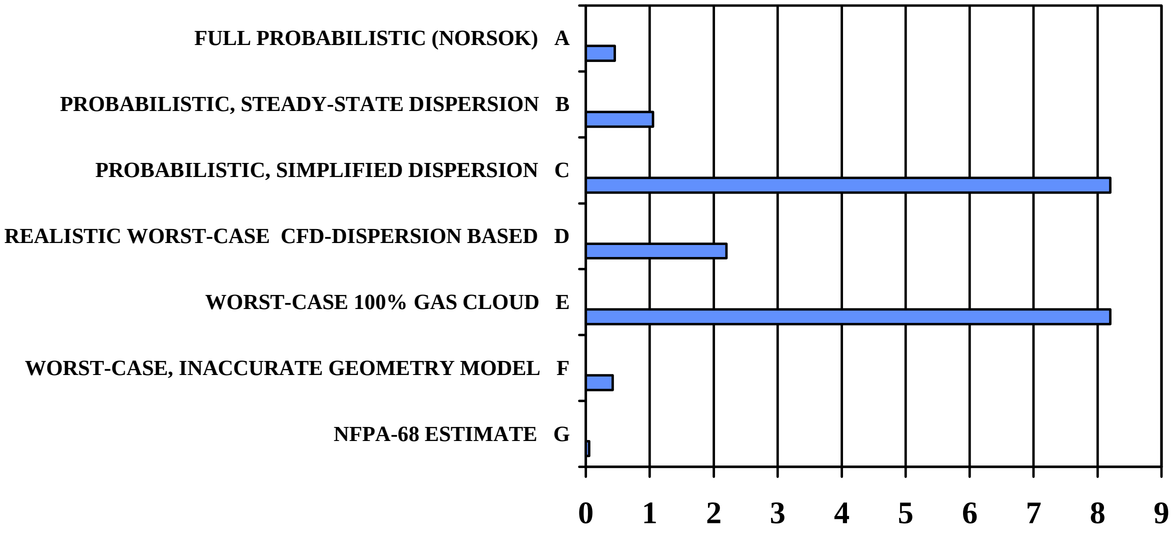

Figure 7 Design load for fire wall derived from different explosion risk analysis methods (overpressure in barg at horizontal axis)

It should be said that several other studies with this approach have resulted in pressures higher than practical wall design strength. In that case the method can be used to assess the effects of mitigation measures like removing walls or applying water deluge on gas detection. Mitigation measures will in many cases influence not only the explosion but ventilation, dispersion and possibility for ignition as well. The effect of removing or adding a wall may not be the same for dispersion and explosions, hence the net effect on explosion risk may only be assessed when the proper balance is calculated in a probabilistic analysis.

To illustrate how important proper modelling is when a study is used as a basis for making decisions, Approaches A and B will be compared with regard to assessing the potential for risk reduction of applying water mitigation at gas detection.

Figure 8 shows that if the less accurate Approach B (steady-state dispersion) is used, activation of water mitigation is expected to reduce the 10^{-4}/year pressures from 1.5 barg to 0.6 barg. To achieve this, upgrading the deluge system may be necessary, but this can be somewhat balanced by reduced strength and design cost of the firewall. Please note that the deluge sensitivity analysis was performed with a subset of the simulations (i.e. only central ignition was used) in the original probabilistic study, hence the values do not correspond directly to those reported in Section 4.2 where the 10^{-4}/year pressure corresponding to Method B was determined to be 1.05 barg.

If the more precise risk assessment methodology (Approach A) was applied, a design pressure of 0.4 barg could be sufficient to withstand the 10^{-4}/year pressures. Only a minor reduction is seen by applying water deluge. Based on this method the risk reduction achieved is marginal and probably not worth the extra effort of upgrading the water deluge systems (unless protection against 10^{-5}/year pressures are required). Please note that the Method A results are actually also slightly changed from those reported in Section 4.2.

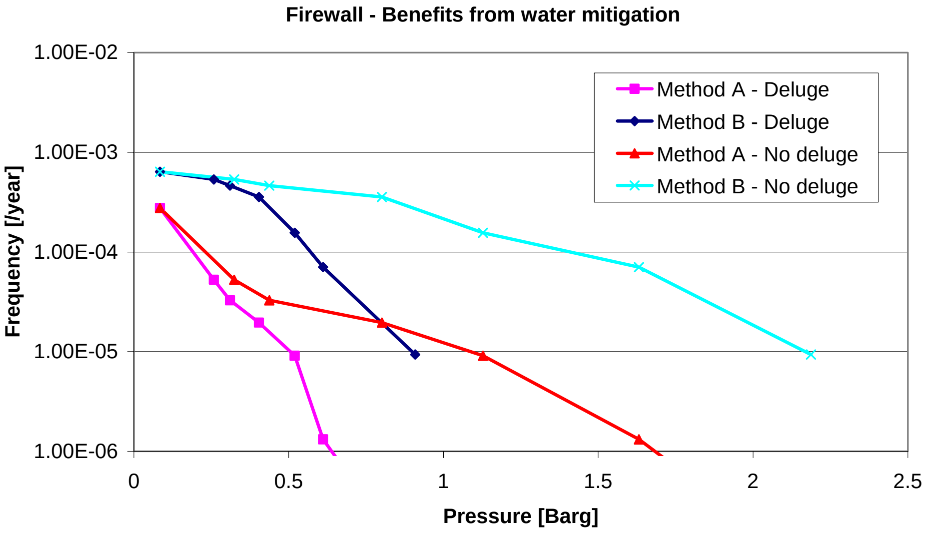

Figure 8 Cumulative overpressure exceedance curves on firewall using Approaches A and B, with and without applying water deluge

In the example presented above a totally different advice on risk reduction expenditure would result from the more precise risk assessment methodology. In some cases it may also be that the advice with a low precision method will involve expensive changes to design or protection systems, and in reality actually increase the explosion risk. This should be considered when choosing an approach for quantitative risk assessment.

For a best possible output from an explosion risk study, it is recommended to model the physics of ventilation, dispersion and explosions as well as possible. Consequence predicting tools and computer power have improved significantly in the last decade. If shortcuts are to be taken, use the realistic worst-case approach (D) or even the worst-case approach (E) if acceptable. Studies assuming relevant gas cloud sizes based on unphysical arguments like experience from unrelated historical accidents should be considered irrelevant.

6 REFERENCES

[1] Selby, C., Burgan, B. “Blast and fire engineering for topside structures, Phase 2, Final summary report”, Steel Construction Institute, UK, Publication number 253, 1998.

[2] NORSOK Z-013, “Risk and emergency preparedness analysis”, 2001.

[3] Talberg, O., Hansen, O.R. and Bakke, J.R.: ‘Explosion Risk Reduction Using CFD’, Major Hazards Offshore, London, November 2001

[4] Talberg, O., Hansen, O.R. and Bakke, J.R.: ‘Recent Advances in CFD-based Probabilistic Explosion Risk Assessment’, Major Hazards Offshore, London, November 2000

[5] Talberg, O., Hansen, O.R. and Bakke, J.R.: ‘Explosion Risk Assessment Using FLACS’, Safety on Offshore Installations, London, November 1999

[6] Ellen M. Berg, Asmund Huser and Erik Skramstad: ‘Ignition Modelling, Time Dependent Ignition Probability Model’, Report No. 96-3629, Rev. No. 04, Det Norske Veritas, 18.02.98

[7] NFPA 68, 1988, “Venting of Deflagrations”, 1998 Edition, National Fire Protection Association, Maryland, USA