APPLICATION OF A CFD-BASED PROBABILISTIC EXPLOSION RISK ASSESSMENT TO A GAS-HANDLING PLANT

O. Talberg, O.R. Hansen, J.R. Bakke and K. van Wingerden
GexCon AS, Bergen, Norway

ABSTRACT

Until few years ago worst case studies dominated gas explosion risk assessments for big industrial facilities offshore and they often still do for similar facilities onshore. However, full-scale gas explosion experiments carried out in the UK demonstrated that design against worst case explosions is unacceptable (the necessary investments would be too high) even for moderate size facilities and/or facilities with moderate levels of congestion.

To tackle this problem for offshore facilities probabilistic approaches have become more and more common. Probabilistic approaches have a challenge with an infinite number of possible accident scenarios, and a lot of non-linear physics to describe. Various approaches with reduced precision of the physical description, and conservative estimates when in doubt have been popular. There are several problems with such approaches:

- Results vary with assumptions; different companies give different results
- Physics are not described properly; effect of risk reduction measures will be wrong
- Predicted risk level may be too high; perhaps caused by the use of uncontrolled conservatism

GexCon has developed a methodology based on good understanding of underlying physics, where CFD-calculations on ventilation, dispersion and explosion play an important role. This methodology also fits the requirements mentioned above. Recent developments include:

- The use of a Time Dependent Ignition Probability Model, where both constant and intermittent ignition intensities are coupled with transient cloud size from dispersion simulations,
- “Frozen Cloud” assumptions and symmetry approximations are used in a responsible way to reduce the number of dispersion simulations,
- A dispersion “library” is developed, where any set of transient leak profiles can be used,
- Effect of mitigation measures like isolation, pressure relief, reduction of ignition probabilities, application of water deluge at detection, changed wall configuration, etc. are easy to evaluate in a physically realistic way.

A recent study performed for an offshore-based gas-handling plant is used to illustrate the methodology, where a few hundred ventilation, dispersion and explosion calculations were carried out. The major advantage with the current approach is a higher precision level describing the physics, and thus a reduced uncontrolled conservatism.

Although the method is developed and demonstrated for offshore applications it can easily be applied for onshore industrial facilities to decide on e.g. control room strength and location.

1 INTRODUCTION

Throughout the last years there have been many different ways to quantify the risk from gas explosions, where the overall aim is either to identify the “correct” risk level or that the risk level is acceptable. Because of uncertainties in methodologies, models, data sources and more, it has been common practice to include conservatism in order not to underestimate the risk.

The results from recent full-scale explosion experiments [1, 2] revealed that very high explosion loads can be expected in congested industrial facilities, and also that geometry details are important for the explosion development. Thus installations to be considered in explosion risk analyses would have to be represented down to the finer geometry details. Explosion loads from simulated worst case scenarios are often very high, and it is generally both unpractical and expensive, sometimes impossible, to design against such loads.

The main idea behind the methodology described in this paper is to bring more accurate CFD-calculations into Quantitative Risk Analysis (QRA) in a consistent way and to obtain a reduction of uncontrolled conservatism compared to general practise when applying QRA. The method is still under development and compared to the introduction of the methodology [3], some important improvements are described in this paper. The changes are first of all related to the dispersion simulations and the post-processing of these. Further a time dependent ignition probability model is included in the study. One of the strengths with the proposed methodology is full transparency of intermediate assumptions and results. This is believed to aid in accelerating the development into an even better methodology.

2 GAS EXPLOSIONS IN CONGESTED ENVIRONMENTS

The methodology has been developed for accident scenarios where a gas cloud is formed resulting from a leakage in industrial facilities such as refineries, chemical plants, offshore platforms, etc. Upon ignition of such a gas cloud an interaction arises between expansion flow generated turbulence at piping, vessels, cable racks, etc. and combustion. The resulting positive feedback mechanism can cause very high combustion rates and thereby very high explosion overpressures, which on its turn may result in serious damage to the facility itself [4]. Resulting blast waves may be very asymmetric resulting in local much higher blast overpressures than predicted by more commonly used methods such as the Multi-Energy method [5]. A comparison of a priori performed predictions of overpressures and experimental results of the full-scale experiments showed that only CFD-based techniques were able to predict the consequences of explosions in congested environments in a satisfactory way [1].

The analysis presented in this paper has been carried out with the CFD-code FLACS. FLACS is a dedicated CFD-based method developed for prediction of the consequences of gas explosions. FLACS can be used for analysis of ventilation, dispersion and explosion processes [6]. Moreover FLACS can be used to study the effects application of water deluge can have on explosion effects. The effect of water deluge can sometimes reduce explosion pressures by a factor of 20 [2, 7].

3 DESCRIPTION OF THE QRA-METHOD

Last year GexCon performed an explosion risk analysis for a module on an existing offshore gas handling facility. New piping inside the module was assumed to influence on the explosion risk, therefore a QRA-study was required. The methodology applied in this project is described in this chapter.

The methodology is based on a high number of CFD-simulations and accurate description of the geometry. The first step of the study is to carry out a ventilation study. Frequency of ventilation conditions prevailing are taken from the results of the ventilation study and the wind distribution. Then, based on a leak distribution CFD dispersion simulations are performed which will result in a gas cloud distribution used as input for gas explosion calculations. The choice of the gas cloud distribution is partly determined by the type of ignition sources (intermittent or continuous) and its probability of occurrence. The gas explosion effects, normally measured in form of a maximum pressure, resulting from the explosion simulations are then together with the various probabilities (ignition probability and occurrence of gas cloud size) used to arrive at a so-called exceedance curve showing the likelihood that a certain explosion overpressure is reached. These exceedance curves are often used to decide on structural measures to take to protect the plant. Figure 1 shows the method in a graphical manner.

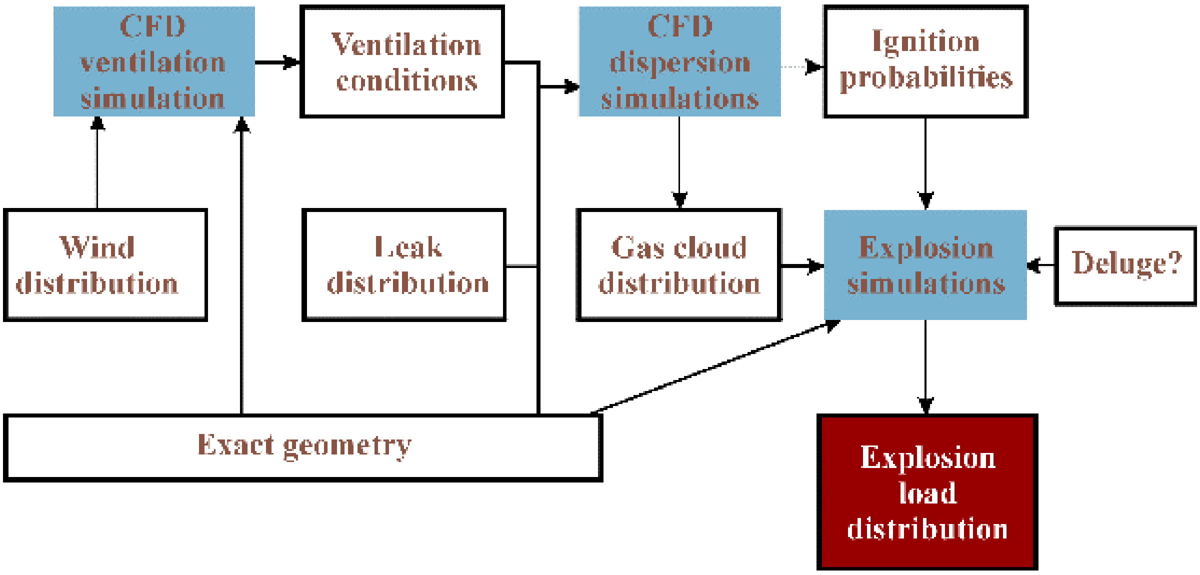

FIGURE 1 Graphical illustration of methodology.

3.1 Geometry

A detailed representation of the geometry must be prepared before simulations can be performed. Because all equipment present will influence the explosion development, and to some extent also the dispersion, even minor details should be included. The particular areas where gas explosion analyses are carried out must be modelled with a high degree of accuracy. Adjacent areas are modelled because of their influence on the ventilation and as targets for blast loads, hence minor equipment can be ignored.

Newer offshore facilities are often modelled in CAD. Then the geometry information may be converted into FLACS directly from CAD format. In early design stages, where no accurate descriptions of the geometry exist, "anticipated" congestion is applied to obtain the final expected object density and distribution, previous experiences using such techniques are convincing.

No CAD-database was available for the offshore facility considered, therefore the geometry was represented both by existing geometry information from available drawings and by inserting "anticipated" congestion where equipment density otherwise was expected to be too low. This was done in a consistent manner, based on experiences from several similar offshore projects.

The considered module is between two solid decks and have two long firewalls located in the south and north. Between the solid decks there is a grated deck. The outer walls located in the eastern and western part of the module consisted of a combination of louvers, explosion relief panels and open areas. The model of the module is shown in Figure 2.

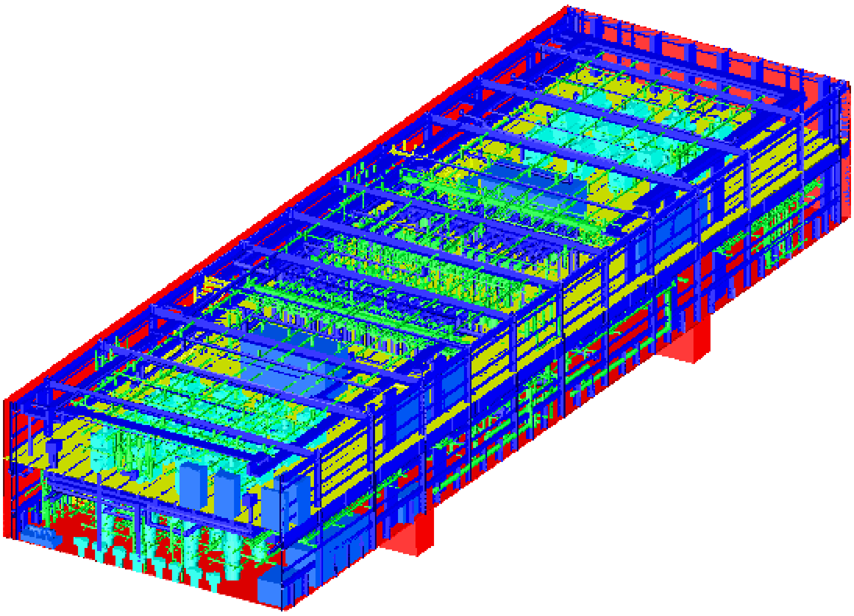

FIGURE 2 Offshore module seen from SW, wall (south) and louver (west) are removed for better view

3.2 Ventilation

The objective of performing the ventilation simulations is to generate a ventilation distribution in terms of rate, direction and probability. Based on this information representative wind conditions are selected to be used in the dispersion simulations.

Ventilation simulations with average wind speeds of 10 m/s from 12 different sectors were carried out, and the internal ventilation rate and wind flow pattern was noticed. These internal ventilation rates were then scaled linearly with the lower and higher wind speeds. It is assumed that internal wind speeds scale linearly with external wind speeds, for most wind directions this is a fair assumption. Using the conversion factors from external wind speed to internal wind speed, the internal wind speed was calculated. The internal wind speed inside the module is shown in Table 1.

TABLE 1 Internal wind speed distribution

External Wind Direction	30	60	90	120	150	180	210	240	270	300	330	360
External Wind Speed	Internal **Western** Wind Directions						Internal **Eastern** Wind Directions					
< 1.9 [m/s]	0.05	0.09	0.10	0.09	0.04	0.02	0.04	0.09	0.09	0.05	0.03	0.02
2.0 - 3.9 [m/s]	0.14	0.27	0.31	0.27	0.12	0.07	0.12	0.26	0.28	0.15	0.10	0.05
4.0 - 5.9 [m/s]	0.23	0.45	0.51	0.46	0.20	0.11	0.20	0.44	0.46	0.25	0.17	0.09
6.0 - 7.9 [m/s]	0.32	0.63	0.72	0.64	0.27	0.16	0.28	0.62	0.65	0.36	0.24	0.12
8.0 - 9.9 [m/s]	0.41	0.81	0.93	0.82	0.35	0.20	0.37	0.79	0.83	0.46	0.30	0.16
10.0 - 11.9 [m/s]	0.51	0.99	1.13	1.00	0.43	0.25	0.45	0.97	1.02	0.56	0.37	0.19
12.0 - 13.9 [m/s]	0.60	1.17	1.34	1.19	0.51	0.29	0.53	1.14	1.20	0.66	0.44	0.23
14.0 - 15.9 [m/s]	0.69	1.35	1.54	1.37	0.59	0.33	0.61	1.32	1.39	0.76	0.51	0.26
16.0 - 17.9 [m/s]	0.78	1.53	1.75	1.55	0.67	0.38	0.69	1.49	1.58	0.86	0.57	0.30
18.0 - 19.9 [m/s]	0.87	1.71	1.95	1.73	0.75	0.42	0.77	1.67	1.76	0.96	0.64	0.33
20.0 - 21.9 [m/s]	0.97	1.89	2.16	1.92	0.82	0.47	0.85	1.85	1.95	1.07	0.71	0.37
22.0 - 23.9 [m/s]	1.06	2.07	2.36	2.10	0.90	0.51	0.93	2.02	2.13	1.17	0.78	0.40
24.0 - 25.9 [m/s]	1.15	2.25	2.57	2.28	0.98	0.56	1.01	2.20	2.32	1.27	0.85	0.44
26.0 - 27.9 [m/s]	1.24	2.43	2.78	2.47	1.06	0.60	1.10	2.37	2.50	1.37	0.91	0.47
28.0 - 29.9 [m/s]	1.33	2.61	2.98	2.65	1.14	0.65	1.18	2.55	2.69	1.47	0.98	0.51

As seen in Table 1 the wind inside the module either had a western or an eastern direction. Based on the internal wind speed distribution and the frequency for each of these wind speeds, 7 internal wind/probability classes were established (3 in each direction and a calm situation), these were to be used in dispersion simulations, see Table 2.

TABLE 2 Internal wind/probability distribution

	Eastern Wind Directions				Western Wind Directions			
Class [m/s]	> 0.8	0.8 - 0.4	0.4 - 0.1	0.1 - 0	0 - 0.1	0.1 - 0.4	0.4 - 0.8	0.8 <
Frequency	16.29	12.37	17.45	1.20	1.51	20.00	20.49	10.59
Repr. Speed [m/s]	1.20	0.55	0.25	0.10	0.10	0.25	0.55	1.20

3.3 Dispersion

The main objective of the dispersion simulations is to produce a representative cloud size distribution for the module considered. These representative cloud sizes would be used in the explosion simulations.

3.3.1 Gas Reactivity

The gas cloud reactivity (based on dispersion simulations) is an important factor influencing the explosion overpressure. From the dispersion simulations different variables are monitored inside the modules of interest, these are the total flammable gas volume, the volume obtaining flammable gas for the first time in the current time interval, and the estimated equivalent stoichiometric gas cloud. The two former are used for calculation of ignition probabilities for intermittent and constant ignition sources respectively, the latter is used to characterise the gas cloud size.

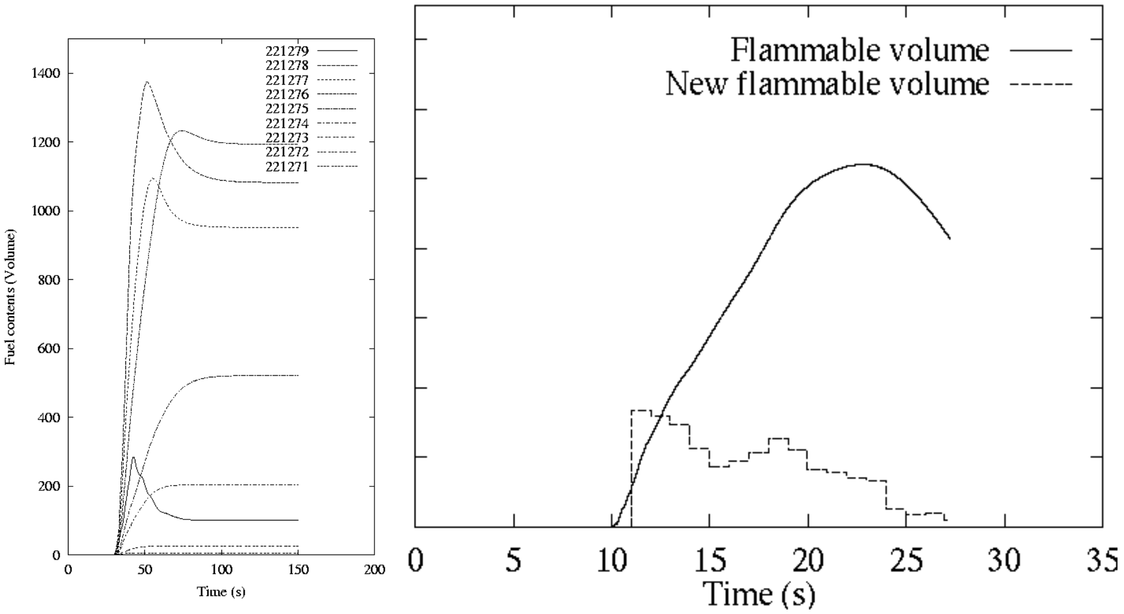

FIGURE 3 Equivalent estimated gas volume as function of time for one leak location, direction, and wind condition, 9 different leak rates plotted together (left). Example of new flammable gas volume last second, and total gas volume, this is important for constant and intermittent ignition source contributions respectively (right).

3.3.2 Scenario parameters

For the leak and dispersion study the number of parameters that can be varied is high (leak locations, -rates, -directions and different wind conditions). It is unrealistic to simulate all possible combinations of these variables with CFD, a selection must therefore be done.

3.3.2.1 Leak location and -direction

It is often hard to tell exactly where a leak will take place. In this study it was decided to use 3 different leak locations to represent the different scenarios that could evolve, these were distributed in all parts of the module. 2 of these were placed in the eastern and western part of the module, while the last was placed centrally in the module. Because the eastern and western part of the module is relatively symmetric along the module centreline, it was expected that the leaks coming from the eastern and western location would give similar results with regard to gas cloud sizes and reactivity. For this reason it was decided to let the western leak location represent both the eastern and western location.

Most leaks can have a number of different leak directions, giving different dispersion results. To represent these different leak directions, 6 perpendicular directions (west, east, north, south, up and down) and 1 diffuse leak are used. Because of the particular module orientation considered in this study, with short unblocked distances for a leak pointing to the north, south, up and down, it was assumed that all of these leaks would give similar dispersion profiles. For this reason it was decided to let the leak pointing to the north represent all of these 4 leak scenarios. Similarly centrally located leaks pointing east is represented by the leak pointing west. Thus 21 different leak locations/directions are represented by 7, for two of these symmetry in wind condition reduces the number of scenarios simulated by a factor of two.

3.3.2.2 Leak rates and -profiles

According to the developed methodology for performing explosion risk analysis, 9 leak rates should be evaluated in such a study. For the module considered in this study, each leak rate was also divided into small and large inventories, giving a total of 18 different leak profiles. The leak rates and -frequencies for the module are shown in the table below:

Table 3 Leak rates and frequencies for the module

Leak rates [kg/s]	Representative rate [kg/s]	Annual leak frequency	
		Small Inventory	Large Inventory
0.1 - 0.5	0.24	2.21 E-01	3.87 E-01
0.5 - 1.0	0.70	4.49 E-02	1.46 E-01
1.0 - 2.0	1.40	2.91 E-02	9.48 E-02
2.0 - 4.0	2.77	3.68 E-02	6.15 E-02
4.0 - 8.0	4.92	9.12 E-03	5.96 E-02
8.0 - 16.0	10.80	5.97 E-03	2.94 E-02
16.0 – 32.0	21.82	1.61 E-02	1.33 E-02
32.0 – 64.0	37.49	1.62 E-03	2.10 E-02
64.0 <	181.25	1.58 E-02	4.22 E-02
SUM	**-**	**3.81 E-01**	**8.55 E-01**

3.3.3 Scenarios simulated with FLACS

In order to reduce the number of scenarios to simulate with FLACS only every second leak rate (4) and every second wind condition (4) were simulated with FLACS. This reduced the number of scenarios to simulate with FLACS from a few thousand to 96. The table below shows the scenarios for one combination of leak location and direction, the shaded cells are representing the scenarios simulated with FLACS:

Table 4 Scenarios for 4 leak rates and 4 wind conditions

Wind [m/s] >	1.2	0.55	0.25	-0.1	-0.25	-0.55	-1.2
Rate	Job	Job	Job	Job	Job	Job	Job
181.3 kg/s	220319	220329	220339	220349	220359	220369	220379
37.5 kg/s	220318	220328	220338	220348	220358	220368	220378
21.8 kg/s	220317	220327	220337	220347	220357	220367	220377
10.8 kg/s	220316	220326	220336	220346	220356	220366	220376
4.9 kg/s	220315	220325	220335	220345	220355	220365	220375
2.8 kg/s	220314	220324	220334	220344	220354	220364	220374
1.4 kg/s	220313	220323	220333	220343	220353	220363	220373
0.7 kg/s	220312	220322	220332	220342	220352	220362	220372
0.24 kg/s	220311	220321	220331	220341	220351	220361	220371

All dispersion simulations are performed transiently, from the wind gets stationary, to the leak starts until a stationary gas cloud situation is obtained. The result files for how the gas cloud volume develops is stored in a result library. All the scenarios that are not simulated (white cells in Table 4) are estimated using a “frozen cloud” concept. This is an assumption that gas concentration scales with the inverse of the ventilation rate and with the leak rate. Based on all simulated leak scenarios, result files are also generated for the adjacent scenarios based on such a frozen cloud extrapolation, and stored in the result library. This “frozen cloud” assumption is expected to work better in a ventilation-dominated region than in a region where the leak momentum is low compared to the ventilation. Our experience with this kind of assumptions is not so promising, when a scenario is estimated from four different sides, we see large deviation in estimate, even if the factor of extrapolation is low (3-4 times). To reduce the uncertainty, "frozen cloud" estimates are carried out from simulations from all sides, the average of the different estimates are then used to form the prediction, see Figure 4.

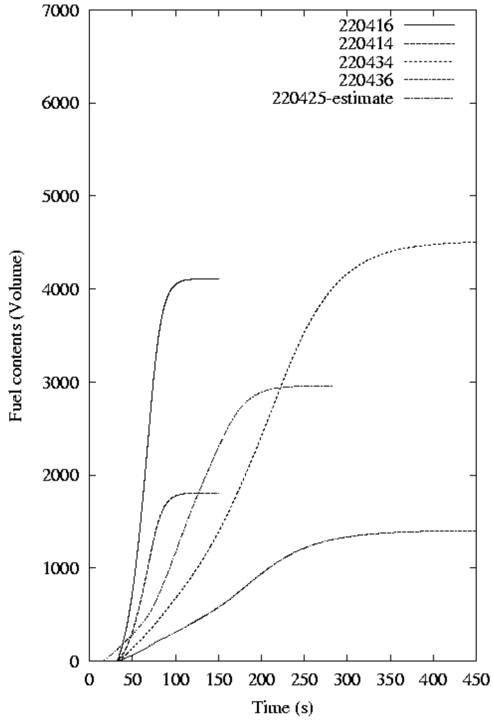

FIGURE 4 Four different frozen cloud extrapolations, and the average of these.

3.3.4 Post-processing

All scenarios considered (9 leak rates x 3 leak locations x 7 wind conditions x 7 leak directions = 1323 scenarios) now have their result file in the result library. For any given leak profile, simulation result files can be generated from interpolations in the result library. With 2 inventory sizes, 1323 x 2 transient dispersion result files are generated.

These 2646 result files all have their distinct probability. During the processing, at each time step of the dispersion, the cloud size is categorised into a cloud size based on the equivalent stoichiometric cloud size, in the study described 5 different cloud sizes were used. The integrated ignition probability for this cloud size then gets a contribution proportional to the flammable volume (intermittent ignition sources) or new flammable volume last time step (constant ignition sources). This was done for every second of all of the 2646 dispersion scenarios.

The results from the dispersion simulations showed that the equivalent stoichiometric cloud size could be large, filling more than 56% of the module. In an average year there will be flammable gas in more than 0.1% of the module for 223 seconds. This based on a total annual leak frequency of 1.24 leaks pr. year. The stoichiometric cloud size distribution became as shown below:

Table 5 Annual cloud size distribution

Cloud Size Category	0% – 7%	7% – 14%	14% – 28%	28% – 56%	56% - >
Representative Cloud Size	5%	10%	20%	40%	80%
Frequency [seconds/year]	195.5	23.0	12.0	2.0	0.03

3.3.5 Time Dependent Ignition Probability Modelling

The ignition probability was calculated based on the contribution from both continuous and discrete ignition sources. The contribution from continuous ignition sources was calculated based on the new volumes exposed to flammable gas in every time interval of the dispersion simulation. The contribution from discrete ignition sources was calculated proportional to the fraction of the module having flammable gas, multiplied by the time of exposure.
The ignition intensities were taken from [8] as a basis for this study.

Ignition probabilities were calculated for 3 different situations:

1. No credit for measures like isolation on gas detection.
2. Ignition intensities are reduced at gas detection, according to recommendations in [8],
3. Measures like isolation and deluge are included. With deluge contribution before deluge can be assumed activated is sorted into dry explosions, contributions at a later stage of the dispersion will be exploded assuming deluge is activated.

3.3.6 Explosion simulations

The purpose with the explosion simulations was to calculate the loads that could occur on the various walls and decks, from the 5 gas cloud sizes found from the dispersion simulations. The loads were presented together with their frequency as ”Probability of exceedance” curves for pressure.

3.3.7 Explosion scenario parameters

Explosion simulations were performed for all of the 5 different cloud sizes, each cloud ignited both at the end of the cloud and centrally. All clouds were also placed at 5 different locations in the module; in the 4 corners and centrally in the module. This made a total of 50 different explosion scenarios.

Pressures were recorded at monitoring panels, which were located at all solid walls and decks inside the module.

3.3.7.1 Water deluge

In order to evaluate the effect of water deluge, the explosion simulations were also simulated with deluge present during the simulations. The deluge system delivered a water flow of 10 liters/min/m^2. Although deluge is activated upon gas detection, there would still be some explosions that could occur after the leak had started but before the deluge was active in the module. In order to establish a sensible fraction of “dry” and “wet” explosions, it was assumed that 20 seconds after gas detection deluge was active. This criterion would then establish the final fractions (frequencies) for “dry” and “wet” explosions.

3.3.8 Results

The ”Probability of exceedance” curves were calculated based on the loads at each wall and deck plate considered. In the curve named ”Constant Ign. Prob.” there was not taken account of a reduction in the ignition probability after gas detection. In the curve named ”Reduced Ign. Prob.” a reduction of ignition intensity is assumed starting at detection (a certain fraction of module volume filled with gas).

The results from the simulations showed that the loads from the explosion simulations without deluge, monitored at each of the walls and decks, varied from 0.1 to 12 barg.

In the figure below, the ”Probability of exceedance” curves for the main deck is shown.

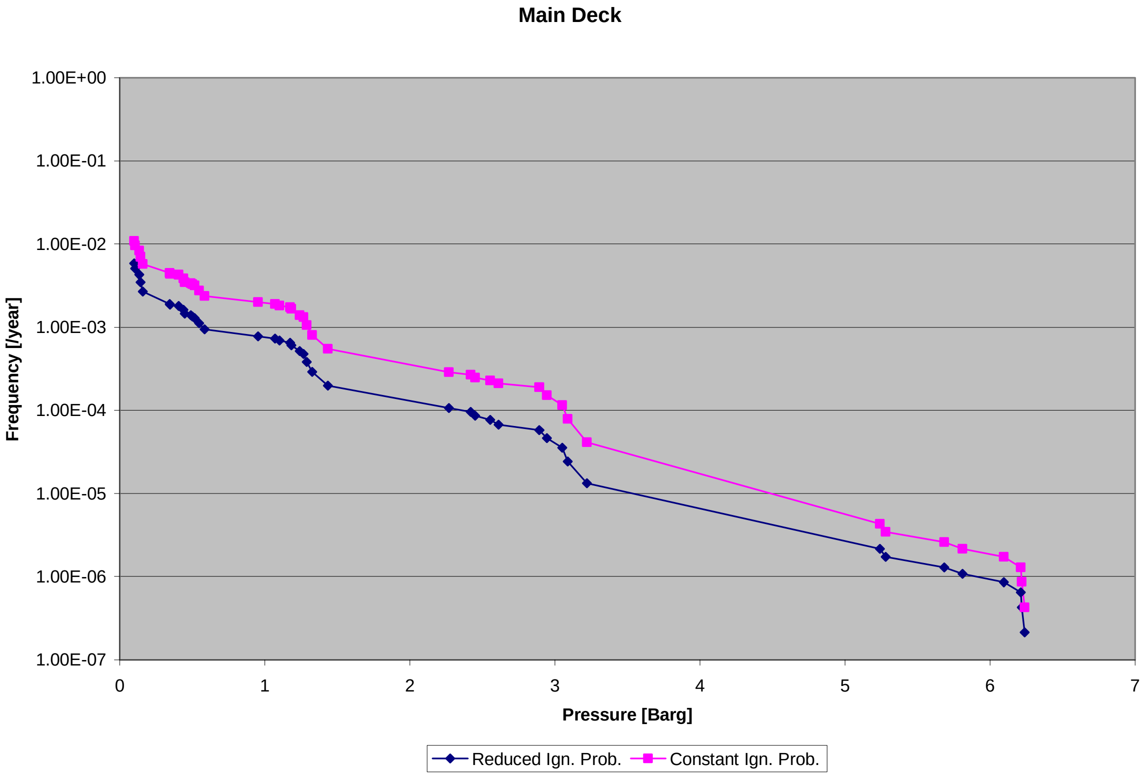

FIGURE 5 Probability of exceedance curves for the module main deck, with and without reduced ignition probability at gas detection.

3.3.8.1 Water deluge

The results from the simulations showed that the loads from the explosion simulations with water deluge were slightly lower than the loads from the simulations without deluge. Due to the limited water application rate of the deluge system (10 liters/min/m^2) and a very confined module, the effect of the deluge was limited.

Below the ”Probability of exceedance” curves for the Main Deck is shown with and without deluge. In the curve named ”Without Deluge” only results from dry explosion simulations are used. There is however a reduced ignition probability, due to isolation of ignition sources. In the curve named ”With Deluge” the explosion pressures represents both the “dry” fraction of scenarios that occurred before deluge was activated and the “wet” fraction of scenarios that occurred after deluge was activated.

The reason for the low mitigating effect of deluge was that the module was very confined with only partly open endwalls. In such a situation a higher water application rate or a reduced confinement will have to be applied. A next step in this study will be to remove confinement at the end walls. This is assumed to increase the natural ventilation, and thus in average reduce cloud sizes and exposure time, reduce the average pressure level, reduce the duration of maximum pressures, and in particular increase the pressure reducing effect of deluge.

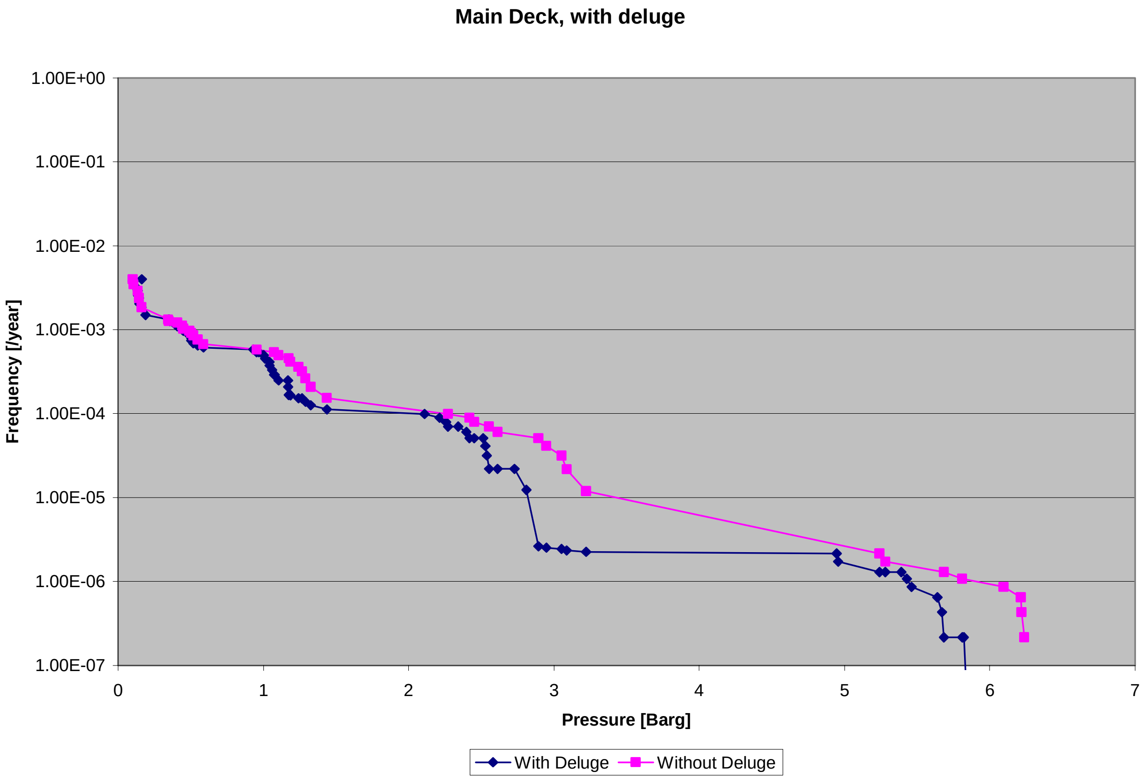

FIGURE 6 Probability of exceedance curves for the module Main Deck, with and without deluge

4 LESSONS LEARNT

4.1 The methodology

A range of non-optimal choices will have to be made, since it is not possible to simulate an infinite number of scenarios. It is believed that most of the choices made in the analysis presented in this paper were reasonable. The methodology has a lot of potential, both for doing physically reliable sensitivity studies, for further development and refinement. A couple of modifications to the methodology are suggested in the section below.

4.1.1 Gas clouds from dispersion or equivalent clouds

One critical step in the procedure is taking a gas cloud distribution into equivalent exploding gas clouds. It has been shown that the methods used will generally give pressures of similar strength for the equivalent quiescent gas clouds as for the non-homogeneous clouds subject to initial turbulence, at least when choosing ignition locations conservatively [3]. With the knowledge from the ongoing full-scale dispersion and explosion tests better validation for simulations of explosions in non-homogeneous clouds can be used to optimise the methods. Possibly, the duration of the equivalent gas cloud explosions may be shorter than for the non-homogeneous ones, giving a different structural impact. This has yet to be studied in detail.

4.1.2 Explosion loads

Depending on the duration and shape of the pressure peak, the importance of the maximum explosion pressure on the structure will vary. For very short pressure peaks, that will often be seen in low confinement situations, the maximum value may not be so important, unless the pressure impulse exceeds a certain limit. Of this reason, it may be worthwhile to include the pressure impulse as a 3rd variable. 3D-surfaces plotting probability of exceeding both a pressure level and an impulse level can be useful for a simplistic structural assessment. Impulse exceedance plots has been included in recent studies by GexCon.

5 CONCLUSIONS AND RECOMMENDATIONS

The methodology presented in this paper is assumed to visualize all risk contributors through the entire analysis in a better way, compared to previous practice.

The quantitative explosion risk assessment concept is still under development. Due to better modelling of physical mechanisms, the concept has significant strengths. It will not be difficult to point at inconsistencies in major QRA-tools handling dispersion/explosion safety. It is believed that faster computers and better understanding and modelling of the physics will lead QRA-methodology in the direction presented in this paper.

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