Deluge and gas explosion risk management: A decision support framework

Rasmus Nilsson

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik
Lunds tekniska högskola
Lunds universitet

Report 5219, Lund 2006

The report has been financed by Norsk Hydro AS and Det Norske Veritas

Deluge and gas explosion risk management: A decision support framework.

Rasmus Nilsson

Lund 2006

Brandvattensystem och riskhantering av gas explosioner: Ett ramverk för beslutsstöd.
Deluge and gas explosion risk management: A decision support framwork.

Rasmus Nilsson

Report 5219
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--5219--SE

Number of pages: 136
Figures: 58

Keywords
Explosion, deluge, decision making, CFD, FLACS. offshore

Sökord
Explosion, brandvatten, sprinkler. Beslutsfattande, CFD, FLACS, offshore

Abstract
On offshore installations for oil- and gas exploration, fire-water deluge systems are often installed to mitigate the effect in case of fires. Recent research has shown that the deluge can also be used to mitigate explosion consequences by activating deluge on gas detection. The effect of deluge on the explosion risk is however very complex and could in some cases lead to increased explosion risk instead of risk reduction.

This thesis puts the problem of explosion risk management and deluge into a decision making context and investigates different aspects of relevance to the decision on if deluge should be used as explosion risk reduction measure or not. A framework has been derived on how to produce a decision support which reflects both the decision makers preferences and the scientific sound methods of calculating the explosion risk with and with-out deluge. The four most important features of the framework include a course decision analysis, the use of computational fluid dynamics to quantify the consequences, Monte Carlo analysis and the application of the NORSOK Z-013 standard. The framework also includes a cost-benefit analysis model and a model to estimate the time from start of leakage to efficiently activated deluge.

The framework was then tested practically by applying it in a case study of an installation in the North Sea. During this exercise, problems and opportunities of improving the framework became obvious. Based on this hindsight knowledge, the framework was improved. A recommendation for the case study object is also presented.

Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Department of Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se/english

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Acknowledgement

The report is a cooperation project between Norsk Hydro, Det Norske Veritas and the University of Lund. The thesis embraces the interests of Hydro, DNV and the requirements of Lund University for a Bachelor degree in Fire Protection Engineering and a Master degree in Risk Management and Safety Engineering.

The author would like to take the opportunity to thank all the people who has contributed to the report in different ways, including family, friends, fellow students, teachers and colleagues. In fear of forgetting someone, I will not even try to list all of you; you know who you are. To mention some of the most important by name, I would like to thank:

Henrik Johansson
Göran Holmstedt
Arve Kvien
Geir Stener Jakobsen
Hans-Tore Johannessen

for guiding me through the work of this thesis, helping me in times of troubles and adding a lot of value through your comments and our discussions. Thanks also to Rolf K. Eckhoff for being an incredibly inspiring personality and for introducing me to scientific study of explosions.

This is also the proper place to thank Norsk Hydro for helping me economically with housing, and GEXCON for the generosity of allowing me to attend the FLACS user course. DNV has been very generous in many ways such as with computer power, office space, social events and the large amounts of coffee needed to finish this thesis on schedule.

Last but most importantly I would like to thank Helene Trymander for all her love, patience and invaluable support. Without you this thesis would never have been the same.

Sammanfattning

Inom processindustrier med stora brand- och explosionsrisker finns ofta brandvattensystem installerade för att reducera brandrisken. Medan de positiva effekterna av sådana system i förhållande till bränder har varit välkända en lång tid har motsvarande effekter på explosioner varit svårare att förutsäga. De komplicerade fysiska sambanden och de experimentella svårigheterna förbundna med explosioner har begränsat möjligheterna att modellera och kvantifiera explosionsrisken. Beslut om när och hur brandvattensystem ska användas som en riskreducerande åtgärd för explosioner är följaktligen komplexa och kräver ett gediget beslutsunderlag.

Det huvudsakliga syftet med detta examensarbete har var varit att härleda ett ramverk som beskriver hur ett lämpligt beslutsunderlag kan tas fram baserat på beslutsfattarens preferenser och de bästa tillgängliga metoderna. För att lyckas härleda ett sådant ramverk har först en bred litteraturstudie genomförts av olika aspekter med anknytning till beslutet i fråga.
En konklusion av litteraturstudien är att den bäst lämpade metoden för att kvantifiera explosionsrisken är att kombinera CFD med Monte Carlo simuleringstekniker.
Genom att kombinera ett hybridkriterium med ett diagram över den kumulativa explosionslasten kan lagkrav, beslutsfattarens preferenser och explosionsrisken för de olika beslutsalternativen presenteras på ett överskådligt sätt för beslutsfattaren. Diagram med den kumulativa explosionslasten kan även användas som utgångspunkt för vidare analyser som till exempel kostnad-nytta analyser eller andra riskmått. I ramverket finns även en modell för att beräkna tiden från det att läckaget startar tills att brandvattnet aktiverats.

Syftet med detta examensarbete var även att testa det framtagna ramverket genom att utföra en fallstudie av en offshore-installation i Nordsjön. På en övergripande nivå visade fallstudien att ramverket fungerar som ett bra stöd för att utföra analysen. Tre huvudsakliga problem med ramverket identifierades dock: det är mycket resurskrävande, brist på indata och stora osäkerheter i resultaten från riskanalysen. Baserat på erfarenheterna från fallstudien kunde ramverket förbättras ytterligare och förslag till vidare forskning ges.

Det viktigaste resultatet av detta examensarbete är det förbättrade ramverket. Det består av en iterativ och stegvis process där värderingar och vetenskapliga bevis separeras så långt som möjligt. Efter varje steg i explosionsriskanalysen utvärderas resultaten för att avgöra om tillräckligt stöd finns för att fatta beslutet eller om mer djupgående analyser är nödvändiga.
Om beslutstödet inte är tillräckligt fortsätter analysen på nästa nivå. Det förbättrade ramverket består av följande steg: uppdatering av nya forskningsresultat, grov beslutsanalys, explosionskonsekvensanalys, tidsstudie, explosionsriskanalys, kostnad-nytta analys och kvantitativ analys av osäkerheterna.

Resultatet av fallstudien, baserat på det totala mängden bevis, är att rekommendera användandet av automatiskt aktivering av brandvattensystemet **om** droppstorleken, uttryckt som Sauter medeldiameter, är större än 0,5 mm. En mer detaljerad analys med bättre, objektspecifik indata och ett större antal simuleringar och full probabilistisk explosionsanalys är dessutom att rekommendera.

Summary

In process industries with extraordinary fire and explosion hazards, deluge systems are installed to reduce the fire risk. While the benefits of deluge in case of fire have been known for a long time, the effects on the explosion risk have been harder to predict. The complicated physics and experimental difficulties attached to accidental gas explosions put strict limits on the ability to model and quantify explosion risk. Decisions on when and how deluge should be used as an explosion risk reduction measure are complex and requires a solid decision support.

The main purpose of this study has been to derive a framework describing how such a decision support should be produced based on the decision-makers preferences and the best available scientifically methods. To be able to derive such a framework a broad literature study of aspects related to the decision problem in question has been conducted. It was concluded that the most suitable method for quantifying the explosion risk is to combine computational fluid dynamics with response surface and Monte Carlo simulation techniques. A hybrid criteria combined with a cumulative explosion load diagram was seen as a good way of combining the legal requirements and the decision-makers preferences with an illustrative risk estimate in a single diagram. The cumulative explosion load was also shown to be useful as a departure point to further analyse the effect of deluge on explosion risk, for example by translating the results into a cost-benefit analysis or fatality risk index. A time analysis model to calculate the time from the start of the leakage until deluge is efficiently activated.

The purpose of this master thesis was also to test the suggested framework in reality by applying it in a case study of an offshore installation. In general, the framework methodology was found to be a valuable when conducting the analysis. Three main problems were identified with the framework: large resource demand, lack of good input and large uncertainties in the risk analysis results. Based on this hindsight experience the framework was improved and suggestions for future research pointed out.

The most important result of this master thesis is the improved framework. It consists of as an iterative stage by stage process where judgement and evidence are separated as far as possible. For each stage in the explosion risk analysis, the results are subjected to a managerial review to evaluate if more evidence is needed before the decision can be made. If the decision support is not sufficient the analysis continues with the next stage. The improved framework includes the following stages: recent research update, coarse decision analysis, explosion consequence analysis, time study, probabilistic explosion risk analysis, cost-benefit analysis and quantitative uncertainties analysis.

The main result of the case study is that based on the total amount of evidence it is recommended to implement deluge on automatically activated deluge **if** it the Sauter mean diameter can be confirmed to be larger than 0,5 mm. A more detailed analysis with better installation specific input, a larger amount of simulations and full probabilistic explosion risk analysis is nevertheless recommended.

1 Introduction

In process industries with extraordinary fire and explosion hazards, deluge systems are installed to reduce the fire risk. This is particularly true for offshore oil and gas-platforms where safety is essential for company survival. The waste consequences of failing safety offshore have taken its toll throughout the last century: most notorious might be the Piper Alpha catastrophe in 1988. The lessons learned from these tragic accidents have paved the way for the modern risk management and offshore safety culture. Risk analysis and management has slowly taken a more important role in decision making within this area.

The benefits of deluge in case of fire have been known for a long time, while the effects on explosions have been harder to predict. The complicated physics and experimental difficulties attached to this area have put strict limits that are now being challenged by computational fluid dynamic (CFD) tools. This comparatively new technique has been developing with a tremendous speed during the last decades and has shown good results in comparison to practical experiments.

1.1 Background

In order to introduce the reader to offshore explosions, four examples of historical accidents together with a coarse historical review on explosion research is presented in this section. A more detailed discussion of explosion physics and modelling will be presented in later chapters.

1.1.1 Four historical accidents

To give a brief background and high-light the hazard of offshore gas explosions four historical accidents have been described. The events have been chosen of particularly interest to the present study, but also to show that serious gas accidents are still a real threat on the Norwegian shelf. The most important lessons to be learned in relation to the present study are presented.

Piper Alpha, 1988

The Piper Alpha catastrophe from 1988 is one of the most notorious and tragic events in the history of offshore exploration, leading to the death of 167 people and the complete devastation of a whole installation. It is often cited as a classical example of a worst-case scenario in reality and there are many lessons to learn from it.[1] HSE has estimated the incurred costs of the Piper Alpha catastrophe to be over £2 billion.[2]

The accident started as a rather small explosion which escalated into fires. The initial explosion over-pressure has been estimated to be only 0,3 bar. The fire-walls were destroyed, which made it possible for the fires to spread and grow. Eventually a riser ruptured creating a giant jet-flame which destroyed the platform.[1]

One important lesson to be learned from Piper Alpha is how a domino effect escalation can lead to a disaster. Even though the installation survived the initial explosion, it led to fires that in turn led to the rupture of a riser that eventually destroyed the platform. The goal of a successful explosion risk management is thus not only for the mere structure to survive, but also to avoid dangerous escalation.

Snorre A, 2004

The PTIL report[3] of the Snorre A event gives a good description of the situation which is considered to be one of the most serious on the Norwegian shelf ever. On the 29th November 2004, problems with the well operations on Snorre A initiated an uncontrolled chain of events that eventually led to a natural gas blow-out. Explosive gas was spread onboard, and it was reported that the water under the installation was ‘boiling’ with gas. The mass flux has been estimated to 20-30 kg/s. Fortunately, no ignition occurred and the consequences of the event were limited to the economic losses of production stop and downtime costs. Under slightly different conditions the event could have developed into a disaster with explosion, escalation and even total collapse. Besides the loss of large number of lives, the environmental and economic consequences could have been enormous. [3]

[1] HSL, (2002) *“A Review of the State-of-the-art in Gas Explosion Modelling”*
[2] www.hse.gov.uk/costs, 2006-11-13
[3] PTIL (2005) *“Gransking av gassutblåsning på Snorre A, brønn 34/7-P31 A 28.11.2004”*

A complicating fact of special interest to the present study is that natural gas entered the fire water intake, which made a number of fire water pumps was unable to work properly. This in turn led to a pressure drop in the deluge system. There were also concerns that gas could enter into the reserve power diesel engines and ignite the gas, or that an explosive cloud might reach the flare.[4]

Lessons learned from the incident are that deviations from the recommended procedures and standards can lead to extremely dangerous situations. The PTIL report concludes that the Snorre A blow-out was not caused by bad luck, but rather it was caused by deficiencies in risk management and well operations in conflict with basic safety requirements.[3] The fact that the fire water supply could not function properly during the event shows the possibility of safety system failure for one reason or another.

Jotun A, 2004

A PTIL report of the event on Jotun A has been used a reference source for this section.[5] On the 20th August 2004 a sudden pressure drop on a 6’’ gas export pipeline was recorded. Later it turned out that the pipeline had been broken 10 km from Jotun A, probably due to the external forces of a fish trawler. When the pressure had dropped from 140 bar(g) to 70 bar(g) an automatic alarm shut down the production on Jotun A. Although a leakage was suspected, it was decided to override the alarm and restart the production.[5]

This shows a lack of risk awareness, but also the complexity of decision making and communication in situations of deficient information. The leak was finally identified and localized as a giant gas bubble on the surface with approximate 100 meter in diameter. From the pressure drop to finishing the reparation it took more than 48 hours. During that time 1,3 million m^3 of gas were lost to the atmosphere. This was still only 1% the worst possible case. Thanks to the fortunate fact that the fracture of the pipeline was deformed the leak area became rather small. If the gas had been released in the vicinity of an installation or ship and ignited, the event could have led to serious explosions.

Lessons learned from Jotun A are that it is difficult to assess and make decisions in situations of incomplete information, and that external factors (in this case a fishing trawler) can lead to dangerous gas releases. The PTIL report emphasises the need of proper emergencies preparedness, procedures and documentation to ensure safe operations.

Visund, 2006

The PTIL report[6] together with a DNV investigation[7] describes the event on the oil platform Visund have been used as references of this section. During the flaring on the 19th January 2006, a circular piece of metal from the knock-out drum was ripped off and sucked into the high-pressure flare system. At the first 90 degree bend it penetrated the high-pressure flare pipe, creating a large 53x42 cm hole. Gas and flame detectors went off in a number of modules which led to activation of deluge and shutting down possible ignition sources. The initial gas leak rate has been estimated by Statoil to be 900 kg/s and during the 50 minutes of depressurization that followed approximately 26 tonnes of gas escaped through the hole. This is an extremely large leakage rate. As a comparison the categories for reporting leakages to the authorities stretches from 0.1 kg/s to >10kg/s, where >10kg/s represents the largest and most serious category. The crew was evacuated with helicopter to surrounding platforms.[6,7]

During the event, the flare however continued to burn, which could have ignited leakage. Fortunately the leak never ignited and no persons were hurt during the accident. The consequences were mostly economic due to the loss of production. In the investigation that followed the accident it was found that the leakage had caused severe damage to the passive fire protection of process equipment. The explanation of the accident was the poor design of the knock-out drum, insufficient validation of the design and inadequate maintenance. It should be noted that the safety systems such as detection, deluge and ignition source shut down was satisfactory according to PTIL.[6,7]

One lesson to be learned from Visund is that the risk of a large gas leakage and explosion is still present despite all the efforts made to eliminate and reduce the risk. This does not mean the efforts have been in vain, but rather that it is important to continue working with explosion risk management. It should be noted that the successful use of safety systems such as detection, ignition source control and deluge, especially the ignition source shut down, may have played an important role in avoiding a mayor disaster. Further, the risk of escalation should be

[4] PTIL (2005) *“Gransking av gassutblåsning på Snorre A, brønn 34/7-P31 A 28.11.2004”*
[5] PTIL (2004) *”Granskingsrapport etter hendelse knyttet til gasslekkasje fra 6” eksport rørledning fra Jotun A”*
[6] PTIL (2006) *“Granskning av alvorlig gasslekkasje fra trykkavlastningssystemet på Visund den 19.1.2006”*
[7] DNV (2006) *“Teknisk undersøkelse i forbindelse med gasslekkasje fra fakkelrøret på Visund 2006-01-19”*

underlined as the passive fire protection was damaged due to the leakage. The conclusion is that there needs to be several safety barriers and systems to control and mitigate an accident so that in case one of the systems fail or is damaged, some other barrier may stop the dangerous chain of events.

1.1.2 Brief historical overview of experimental research

This section presents a brief historical overview of the progresses in experimental explosion research. Focus has been put on the most important large research programs. For the sake of clarity this section has been divided the following parts:

i. Early research
ii. Joint industry projects (JIP)
iii. Modelling and Experimental Research into Gas Explosion program (MERGE)
iv. Recent and present areas of studies

Early research
During 1970-1980 the main research focus was put on super-sonic explosions, so-called detonations. Research however soon ruled out detonations as the main industrial explosion hazard as detonations were found to be quite difficult to initiate and thus deemed to have rather low probabilities. The more probable, subsonic explosion mode deflagration became the main research topic in around 1980. During the following decade a number of research program on accidental explosions were launched.[8] As an example, the large national research program 'Sikkerhet på sokkeln' was conducted in Norway, which at that time was emerging as an important offshore oil and gas nation. The mentioned project led to the development of the flame acceleration simulation CFD code, often referred to as FLACS. [9]

One of the most important world-wide progresses during the eighties was the recognition of the importance of turbulence in congested deflagrations. This is often referred to as the Schelkin mechanism after a Russian researcher, and will be explained in detail in later chapters.[8]

A new era of explosion research began after the Piper Alpha disaster in 1988, with a marked increase in explosion research. Important research on the effect of deluge on deflagration was conducted by a number of researches in the beginning of the nineties. These small- and medium-scale experiments revealed that deluge had two effects on explosion; a mitigating effect due to water evaporation and an increased turbulence effect leading to increased burning velocities and possibly to more severe explosion loads. For details and further references, see for example Wingerden[10,11] and Thomas[12].

Joint Industry Projects
The United Kingdom and Norwegian regulators together with concerned individual companies, interest groups and research communities launched the joint industry project (JIP) 'Blast and Fire Engineering on Topside Structures' in 1990, often referred to as 'JIP Phase 1'. One of the key findings in Phase 1 was that the understanding and modelling of explosions in large structure were insufficient and based on small-scale experiments although the parameters were known to scale in different ways. [8]

This urged for full size experiments and more JIP projects were conducted in the end of the millennium, often referred to as JIP Phase 2, 3a and 3b. Phase 2 was completed in 1997 and showed that high overpressures could be generated, typically for certain configurations with high congestion, high confinement and ignition position leading to long explosion paths. Some tests examined the effect of deluge and it concluded that deluge activated before ignition could reduce the overpressures significantly. Phase 3a and 3b further examined the effect of deluge on deflagrations. The results confirmed earlier findings that deluge could reduce the overpressures. Altogether, the full-size experiments in the JIP Phase 1-3 created a wealth of data that could be used for development, calibration and validation of explosion models. Some of the models included sub-models to account for the effects of deluge. Another JIP covered ignition and ignition modelling.

---

8 HSE (2002) *"A critical review of post Piper Alpha developments in the explosion science for the offshore industry"*
9 Bjerkevendt et al (1997) *"Gas explosion handbook"*
10 Van Wingerden, K. (1995) *"Gas explosion in vented enclosures and in the open: mechanisms, prediction methods and mitigation"*
11 Wingerden K. (2000) *"Mitigation of Gas Explosions Using Water Deluge"*
12 Thomas, G.O. (2002) *"On the conditions required for explosion mitigation by water sprays"*

Modelling and Experimental Research into Gas Explosion program
Parallel to the joint industry program, the Commission of European Communities launched the research program 'Modelling and Experimental Research into Gas Explosion' (MERGE) in the mid-nineties. The results from the MERGE program, including small-, medium- and large-scale experiments revealed serious flaws in many of the contemporary explosion models. Unexpectedly high overpressures were produced in the experiments in relation to model predictions. The results were used to incorporate new knowledge to improve the explosion models, and as validation data sets. A presentation of the MERGE results, including a bench-mark test comparing different CFD-models to experimental data, is presented by Popat et. al.[13]

Recent and present areas of research
Recent research has been aimed at further develop and validate the explosion models. This includes efforts to overcome the flaws and limitations of the present CFD models, such as the poor turbulence and combustion models. Efforts are made to include more advance features such as CFD modelling of jet release, dispersion, deluge, two-phase explosion, and coupled explosion load-structure response calculations .[14,15]

Besides CFD modelling, efforts have been put to model the explosion response[16] and the mechanisms of escalation and domino effects[17] more accurately.

1.2 Project purpose and problem statement

Although a lot of efforts have been made that demonstrate the consequence effects of deluge on explosions, less focus has been put on to demonstrate the overall ***risk*** reduction. Risk is here defined as a combination of probability of the occurrence of harm and the severity of that harm.

The use of deluge to mitigate explosion may lead to practical problems that need to be addressed. Further, the results from an explosion risk analysis need to be incorporated into a risk management framework and decision context to have any practical value. To support the decision on whether to use deluge as an explosion reduction measure, the following questions will be examined in the present study:

What aspects are important to take into consideration when making the decision whether to use deluge as an explosion risk reduction measure?
When and how should deluge be used as an explosion risk reduction measure in the offshore industry?

The attempt to answer these questions requires the latest available knowledge, research results and suitable methods for quantifying relevant risk estimates. Efforts are also put to examine the practical and real problems of automatic deluge on confirmed gas alarm. The aim is also to derive a decision support framework describing how to reach an as good decision support as possible. The results should include a recommendation for the object of the case study concerning decisions of deluge as an explosion mitigation barrier together with a recommendation on how the decision support framework can be used to create decision support for similar decision in the future. For offshore installations, it can generally be assumed that there is already a deluge system installed for fire mitigation. Focus is therefore put on examining to what extent this can be used for explosion mitigation.

---

[13] Popat et. al (1996) *"Investigations to improve and assess the accuracy of computational fluid dynamics explosion models*"
[14] HSE (2002) *"A critical review of post Piper Alpha developments in the explosion science for the offshore industry"*
[15] HSL, (2002) *"A Review of the State-of-the-art in Gas Explosion Modelling"*
[16] Morison (2006) *"Dynamic response of walls and slabs by single-degree-of-freedom analysis – a critical review and revision"*
[17] Salzano, E. et. al. (2005) *"The analysis of domino accidents triggered by vapour cloud explosions"*

1.3 Methodology

1.3.1 General thesis methodology

The work has been dived into three parts as illustrated in figure 1. The aim of the first part is to create a knowledge base of the most relevant aspects of the decision problem. This is done mainly through literature studies and in some cases by mail correspondence to experts within the area. The gathered knowledge is then used to derive a decision support framework of input, models and methods describing how an analysis should be conducted to reach a suitable decision support regarding the use of deluge as an explosion risk mitigation measure.

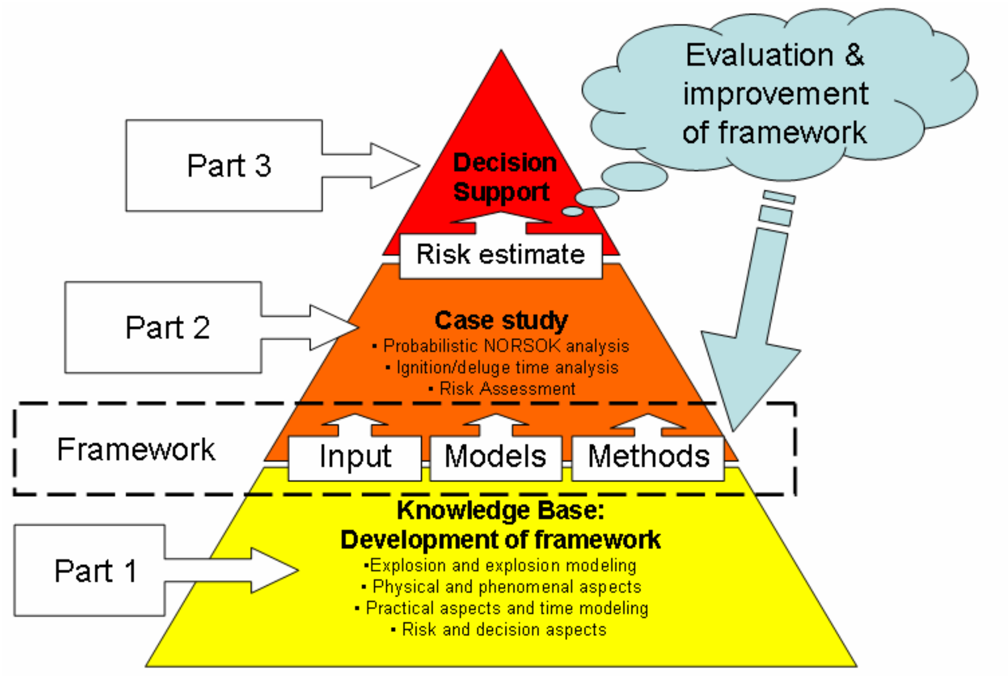


Figure 1: Schematic description of project plan and report structure.

The second part includes chapter 7 and consists of a case study. In the case study the framework of input, models and methods from the first part has tested and used to create a decision support for a Norwegian offshore process module. The preferences of the decision-maker have been included in the analysis through meetings with a company risk expert representing the decision-maker. The second part includes analyses of the effect of deluge on the explosion risk and calculation of risk estimates, which is seen as the most important part of decision support.

In the third part the results, findings and conclusions of the two first parts are discussed. The suggested decision support framework is then revisited, evaluated and improved in the light and experiences from the case study.

1.3.2 Report structure

The general thesis methodology described in figure 1 corresponds to the structure of the thesis.

Part 1: Knowledge base and derivation of framework
Chapter 1: Introduction
Chapter 2: Decision making aspects
Chapter 3: Gas explosion basics and modelling aspects
Chapter 4: Simulation aspects
Chapter 5: Other aspects
Chapter 6: Decision support framework

Part 2: Case study of Troll B
Chapter 7: Case study of Troll B

Part 3: Evaluation and improvement of the framework
Chapter 8: Discussion and conclusions

1.3.3 Computer programs used in the thesis

The CFD FLACS code was used to simulate the ventilation, gas dispersion and the consequences of explosions with and without deluge. It was planned to use the CFD results will to construct consequence response surface models of the gas spread and explosion load. Monte Carlo simulations will then be used to combine the consequence response surfaces with probabilities, using the DNV model EXPRESS. A more detailed description of the FLACS and EXPRESS softwares are described in chapter 4. This chapter also includes a description of the methodology for probabilistic explosion analysis according to the NORSOK standard Z-013, which is the suggested methodology. The case study also includes an approximation of the costs associated with deluge as an explosion mitigation measure.

Based on the results of the case study a decision support is presented, including a recommendation for the case study and offshore installations in general.

1.3.4 Probabilistic Explosion Risk Analysis methodology

The methodology for probabilistic explosion risk analysis[18] recommended by NORSOK Z-013 will be briefly described in the following section. The connotation 'probabilistic risk analysis' is not consequent. By definition risk is a combination of consequences and probabilities. A probabilistic combination of consequences and probabilities sounds like a double-dip expression. The expression will nevertheless be used since it is a broadly accepted term. It is a slightly conservative best estimate risk analysis in contrast to a worst-case consequence analysis.

The analysis is divided into a number of different steps, following the chronological development of an explosion from leakage to explosion load and response. First of all, a representative number of leakage scenarios are chosen. The leakages are divided into nine mass flux classes with their respective estimated frequency. Different leakage locations and directions should be taken into account. Normally three different leakage locations combined with the six possible leakage directions and a seventh possibility of diffuse leakages should be simulated with CFD for an offshore module. Different combinations of leakages and wind configurations should be modelled, since this is expected to have a considerable impact on the dispersion and the size of the explosive gas cloud. [18]

The possible combinations of nine leakage classes, three leakage locations, seven leakage directions, eight wind directions and five wind speeds can be calculated using combinatory mathematics as 9x3x7x8x5 = 7560 scenarios. This is obviously to many scenarios to simulate with such a resource demanding tool as CFD. To solve this problem it is suggested to use response surfaces correlations based on a small number of dispersion simulations. Typically 21 CFD dispersion simulations are recommended, but it is acceptable to only conduct 10-15 for each offshore module. The validity of the response surfaces correlations should be documented by independent simulations or calculations.

The most important output from the CFD dispersion simulations is the transient size of the gas clouds for expressed as the total ignitable cloud and equivalent stoichiometric cloud. The stoichiometric cloud equivalent means that the actual concentration distribution from each simulation is approximated with a corresponding stoichiometric cloud volume expected to give similar consequences. This approximation is relating the burning velocities of the gas mixture at different air-fuel concentrations. With the use of correlations, a stoichiometric cloud equivalent is assigned to each of the different to the leakage configurations and their respective probabilities. The use of equivalent stoichiometric clouds is adopted to ease some of the modelling difficulties of explosion propagation in inhomogeneous clouds. It is important to note that this approach may result in a too short duration of the explosion load.[18]

Altogether the result is a frequency distribution of different equivalent stoichiometric clouds based on CFD simulations and the correlations to account for different scenario parameters. For a more detailed analysis, the transient development of the cloud is also taken into account.

[18] NORSOK (2001) *"Z - 013 Risk and Emergency preparedness analysis"*

The next step is to model ignition. The time to ignition and location of ignition sources have to be considered in relation to the dispersion analysis. As the explosive gas cloud grow, the probability of coming into contact with an intermittent ignition source increases. The ignition probability as a function of time may also be used in a transient analysis to account for emergency ignition source shutdown.[19] Together with the dispersion analysis the ignition model results in a frequency distribution for the stoichiometric equivalent cloud size at ignition.

When this is in place, the explosion propagation and load is simulated with CFD software. Since the location of ignition sources have a considerable impact on explosion propagation and load, different ignition locations need to be simulated in the explosion simulations. The explosion loads are then connected to the frequencies of the equivalent stoichiometric cloud at ignition to create a probability distribution of explosion load.[19]

The methodology shows some of the difficulties of modelling accidental explosions. There are many different parameters and transient variables and that influence the outcome. In contrast to modelling experiments, these parameters are inherently unknown in modelling attempts to predict a future accidental explosion load. Theoretically, the possible combinations of continuous variables are infinite. Even with a course representation of parameter 'classes' the number of scenarios is too large. It is therefore necessary to try to choose a representative set of scenarios, estimate the probability of each scenario and to use correlations. All the assumptions, simplifications and different models, including the limitations and uncertainties attached to CFD dispersion and explosion simulations, add uncertainties in the representation of a much more complex reality. For the purpose of practical applications it is the responsibility of the risk analysis to ensure and prove that the final result is conservative, even if the accuracy might be lowered.

1.4 Discussion of key concepts

There are many different suggestions on how to define the concepts 'risk', 'probability' and 'uncertainty'. Although the discussion and definition might be seen as merely semantic and of limited practical value, a discussion of different definitions of risk is argued to be necessary to help clarify and avoid misunderstandings.

1.4.1 On the definition of risk

In the article of Klinke[20] et. al. two different perspectives on risk are presented: realism and constructivism. The constructivist perspective states that risk is only a subjective mental construction, representing the analyst opinions and perception of risk. The realist perspective on the other hand argues that technical estimates of risk constitute objective representations of true hazards independent of the analysts' beliefs. Not surprisingly, the constructivist perspective on risk has been dominant among social scientist, while the realist perspective is more accepted among engineers and natural scientists. To solve the conflict between these approaches Klinke et.al. suggest what they call a 'dual strategy for risk', which separate the physical, natural science attributes of risk from the social and psychological attributes of risk. In short terms, this dual strategy means that the setting of priorities and judgement of acceptable risk criteria should be determined by social or political forces based on public values and concerns. It is also seen as useful to further characterise the risk according to the nine following attributes to underline some of the most important dimensions of risk[20]:

i. Extent of damage
ii. Probability of occurrence
iii. Incertitude
iv. Ubiquity
v. Persistency
vi. Reversibility
vii. Delay effects
viii. Violation of equity
ix. Potential of mobilisation

Klinke et. al. argues that the quantification of the magnitude of risk should reflect the technical expertise rather than public values and social concerns. However, their definition of risk includes the whole concept of the dual nature of risk:[20]

[19] NORSOK (2001) *"Z - 013 Risk and Emergency preparedness analysis"*
[20] Klinke, A et. al . (2002) *"A New Approach to Risk Evaluation and Management: Risk-Based, Precaution-Based, and Discource-based Strategies"*

> *"Risk is defined as the possibility that human actions or events lead to consequences that harm aspects of things that human beings value."*

This rather broad definition includes the attributes of perception and evaluation of risk from 'human beings'. Unfortunately, the definition is so broad it becomes ambiguous and vague. The expression 'harm aspects of things that human beings value' needs to be explained and clarified. Who are included in the group 'human beings'? What are the things these 'human beings' value and the harm that threatens these valuable things? The definition however highlights the opinion that risk has a dual nature with both constructive subjective attributes as well as objective realistic attributes. Instead of hiding the underlying human values on which the risk definition is based, the above definition recognises and displays them transparently.

Another formulation of the definition of risk is given by the NORSOK[21] standard Z-013:

> *"the combination of probability of the occurrence of harm and the severity of that harm."*

Note that in NORSOK the risk may be expressed either qualitatively or quantitatively. The NORSOK standard states that risk aversion or perception of risk should not to be included in the quantitative expression of risk. The NORSOK definition of risk is also very similar to the ISO definition of risk. [21]

> *"the combination of the chance that a specified undesired event will occur and the severity of the consequences of that event"*

At first look the NORSOK and Klinke et. al. approaches seem to be contradicting each other. The NORSOK definition does however not necessarily stand in direct conflict with the Klinke et. al. definition, if risk and the quantitative expression of risk can be separated as two different concepts. In fact there seems to be an agreement on the opinion that the quantitative expression of the magnitude of the risk should be based on technical expertise and calculations rather than risk perception and public opinion.

Another, more detailed, discussion on the quantitative definition of risk is found in Kaplan et. al.[22] In their article risk is quantitatively defined as a "set of triplets" using a mathematical formula. Risk can then be explained, somewhat informal, as the answer to the three following three questions:

i. What can go wrong?
ii. How likely is it?
iii. What are the consequences?

The three questions correspond to the components of each triplet and include a specific scenario (S) together with the likelihood (L) and the consequence (S) of that scenario. The idea is that there is an underlying continuum of possible risk scenarios, which can be seen as a risk universe. This underlying risk universe is represented by the set A. To each triplet the index α is attached to represent that it belongs to the set A. The quantitative risk can then be defined according to the following formula:

$$R = \{\langle S_\alpha, L_\alpha, X_\alpha \rangle\} \alpha \in A \quad \textbf{[Eq. 1]}$$

where
R = The quantitative risk
S_α = Scenario corresponding to the point α in the risk universe set A.
L_α = the likelihood of S_α to occur
X_α = the consequences if S_α occurs

This set of scenarios is complete and infinite. This is however problematic: from a practical point of view it is desirable that the scenarios are complete, finite and disjoint. Therefore, the risk R needs to be approximated by a finite set of scenarios. This can be achieved by partitioning, which can be described as cutting up the infinite

[21] NORSOK (2001) Z-013
[22] Kaplan S. et. al. (2001) *"Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and Result Refinement to the Quantitative Definition of Risk"*

continuum into a finite set of scenarios. The finite set of scenarios can be called R_P, where the index P stands for the partitioning. Mathematically this is formulated as[23]:

$$R_P = \{\langle S_i, L_i, X_i \rangle\} \qquad \textbf{[Eq. 2]}$$

where
R = The quantitative risk
S_i = the ith risk scenario
L_i = the likelihood of S_i
X_i = the consequences of S_i

Finally, the relation between R_P and R is described by the following formula:

$$R_P \approx R \qquad \textbf{[Eq. 3]}$$

Hence, R_P is a quantitative approximation of the real underlying risk by partitioning the risk universe into scenarios. The concept is also illustrated in the Figure 2 : [23]

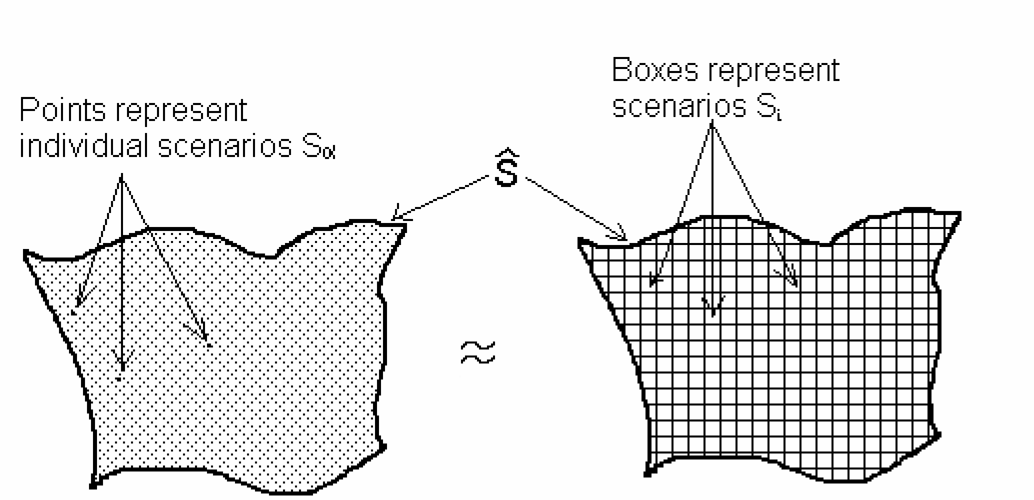


Figure 2: The figure illustrates a geometric representation of the quantitative risk definition used by Kaplan. To the left is a representation of the infinite set of risk scenarios which defines R. To the right is the partitioned, disjoint set representing R_P. From Kaplan S. et. al. (2001) *"Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and Result Refinement to the Quantitative Definition of Risk"*

1.4.2 On the definition of probability

There are two main approaches to probability, often referred to as the classical frequentist approach and the Bayesian approach. In the frequentist school of thought, probabilities are regarded as objective, while in the Bayesian school probabilities are defined as degree of belief, which means they are seen as subjective.[24]

If for example a fair dice is rolled a large number of times, the relative frequency of getting a six will approach 1/6 as the number of rolls increase. The frequentist approach would then be to roll the dice a large number of times. From this large sample a relative frequency can be calculated and used as an objective probability, often described as a 95% or 99% confidence interval.[25]

A problem with the frequency approach to probabilities is that in real risk problems there is often not sufficient data to calculate the frequencies in a satisfying way. There has just not been enough number of rolls with the dice. This is particularly true for extraordinary events, such as offshore explosions which occur very seldom. In

[23] Kaplan S. et. al. (2001) *"Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and Result Refinement to the Quantitative Definition of Risk"*
[24] Pate-Cornel, E. (1996) *"Uncertainties in risk analysis: Six levels of treatment"*
[25] Johansson, H. (2000) *"Osäkerhetshantering i riskanalyser avseende brandskydd"*

these cases, there may be other information such as expert knowledge that needs to be incorporated in the analysis.

To make use of expert knowledge is not possible with the frequentist framework, but it is possible with the Bayesian definition of probability. The drawback with the Bayesian approach is that it is possible for two different persons to have different degrees of belief on what the probability of an event is, depending on their prior experience and knowledge. However, the Bayes theorem allows for the probability estimate to be upgraded as new statistical evidence emerge. This means that even if two experts have different initial estimates of the probability, eventually their estimate will converge as the number of observation increase. As the number of observations and statistical evidence increase, the difference between the subjective Bayesian and objective frequentist probability estimate will also decrease.[26]

Although there has been collision between the two different schools of thought in the past, there now seems to be a broad recognition of the benefits of the Bayesian approach to probabilities in risk management.

1.4.3 On the definition of uncertainty

There are also different approaches to the definition of uncertainty and how the uncertainties should be presented, qualitatively or quantitative. Paté-Cornell discusses two different categories of uncertainties: epistemic and aleatory uncertainties.[27]

The difference between these two categories is that epistemic uncertainty stems from a lack of knowledge, while aleatory uncertainty stems from stochastic randomness. This means it is possible to reduce the epistemic uncertainty by gathering more knowledge, using refined mathematical models to calculate the risk and so on. Often expert judgement and knowledge is required, which can be achieved using the Bayesian definition of probability mentioned above. Epistemic uncertainties include uncertainties caused by the simplifications, assumptions and modelling flaws. Also the difference between the finite set of scenarios used to represent the infinite set of risk scenarios discussed above is a kind of epistemic uncertainty.[27]

Aleatory uncertainty on the other hand stem from stochastic randomness in a well-known population. As an example the wind direction and speed on a random day can be said to be a typically aleatory uncertainty. They can be treated by classical frequentist methods, for example Monte Carlo simulations. In order to treat both kinds of uncertainties, the Bayesian approach to probabilities is required. [27]

Another classification of different uncertainties classes is presented by Lundin[28]. In his work, he presents four different classes to define uncertainty. These include:

i. Resources
ii. Assumptions
iii. Models
iv. Input

Resource uncertainties are the most general class of uncertainties. It includes factors such as the limitation of time and money that is possible to spend on an analysis, the available models, etc. Means of reducing resource uncertainties include a quality control system, ensuring sufficient competence of the risk analyst and standardised risk analysis methods procedures.[28]

Assumption uncertainties are then introduced by the risk analyst. It is always necessary to make simplifications and assumptions to be able to model risk. Assumption uncertainties can be reduced by peer-review of the assumptions. Another possibility is to align and standardise assumptions for a certain kinds of problems whenever possible.[28]

Model uncertainty stems from the fact that models inherently deviate from reality.[28] In risk quantification, such as the quantification of explosion risk, there are many different models available. Model uncertainty can be reduced by validation efforts, model development and tuning etc. A more detailed discussion on the uncertainties associated with CFD explosion modelling is presented in chapter 3.3.6.

[26] Johansson, H. (2000) *"Osäkerhetshantering i riskanalyser avseende brandskydd"*
[27] Paté-Cornell (1996) *"Uncertainties in risk analysis: Six levels of treatment"*
[28] Lundin, J. (1999) *"Model Uncertainty in Fire Safety Engineering"*

Input uncertainties are introduced due to the lack of perfect input. The quality of the analysis results obviously depends on the input parameters, and it is necessary to have as good input as possible. Still it is often the case that some input parameters are hard to obtain; they may be difficult to measure directly or stochastic in nature. Often input uncertainties can be reduced by using more efforts to obtain better input. This can include direct measurements of real world conditions. An illustration is given in figure 3 . [28]

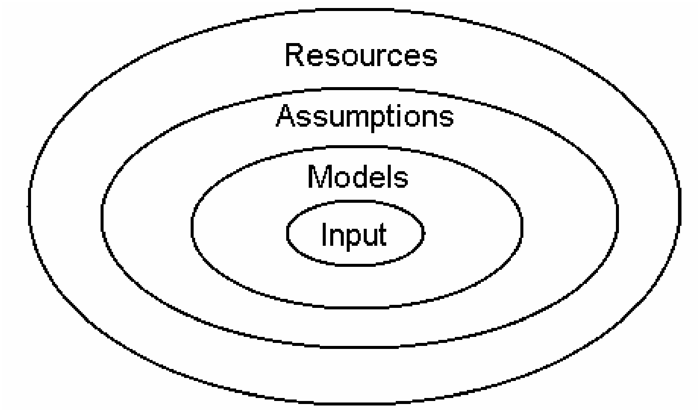


Figure 3: A definition of uncertainty from four different classes. A more detailed description of the different classes is presented in the text .
From Lundin (1999) *"Model uncertainty in Fire Safety Engineering"*

A third concept of uncertainty and risk is presented by Nilsen et. al.[29] In their article they compare the classical approach to uncertainty with a predictive Bayesian approach. In the classical approach, uncertainties are often defined as deviations between the real world and its representation by models. From a predictive Bayesian perspective uncertainties can be expressed as the subjective probabilities to reflect the lack of knowledge. According to Nielsen et. al, all uncertainties are epistemic which means that they are a result of lack of knowledge. Risk is then defined by Nielsen et. al. as a combination of consequences and uncertainties. The consequences are modelled as deterministic causal mechanisms. The uncertainties, representing the risk analyst's degree of beliefs, are then separately expressed in a way the risk analyst deem appropriate. Hence they are not part of the casual modelling. In this framework terms as uncertainty modelling, probability modelling or stochastic modelling have no place. Probability calculus is then used to combine the causal relation models with the uncertainty assessment based on the risk analyst's beliefs to achieve a risk estimate. An illustration of the predictive Bayesian approach to uncertainties compared to the classical approach is given in figure 4 .[29]

Nielsen et. al. argues that attempts to quantify the deviations between the real world and its representation does not add any value to the risk analysis. Instead it requires resources and diverts the attention from the outcome of the activity being studied. The quantification of model/reality discrepancies also counteracts clear communication between the risk analyst and the decision-maker, according to Nielsen et. al. Instead, the degree of compliance between the reality and the models should be discussed critically between the risk analyst, the verification group and the decision-maker. This discussion may include such topics as the risk analysts interpretation and understanding of the problem, the choice of models and methodology, the accuracy of the models included and the assigned subjective probabilities and probability distributions.[29]

1.4.4 Conclusions and recommendations

The first conclusion after this brief survey on the definition of key concepts risk, probability and uncertainty is that there are many different definitions. They illustrate and emphasise different aspects of the complexity of risk. It is important to be clear which definition is used to avoid misunderstandings and communication problems. The recommendation here is to include a section of the report which includes the definition of key concepts that are used.

Before choosing which definitions or set to be used, it is necessary to decide *who* should choose them; the risk analyst or the decision maker? Practically, it is often the risk analyst but it is seen as more important that the definitions suit the decision maker. After all, the risk analysis is of limited value to the decision making process

[29] Nilsen T. et. al. (2001) *"Models and model uncertainty in the context of risk analysis"*

if it does not represent the decision makers perspective of risk. The concluding recommendation is for the risk analyst to suggest suitable definitions to the decision maker, who ultimately accept the definitions.

In and the case study included in this report, the use of NORSOK definitions have been used since they are broadly accepted in the Norwegian offshore risk community. The most important definitions are listed in section 1.5 . The Bayesian approach to probabilities is suggested as it allows the use of expert opinions.

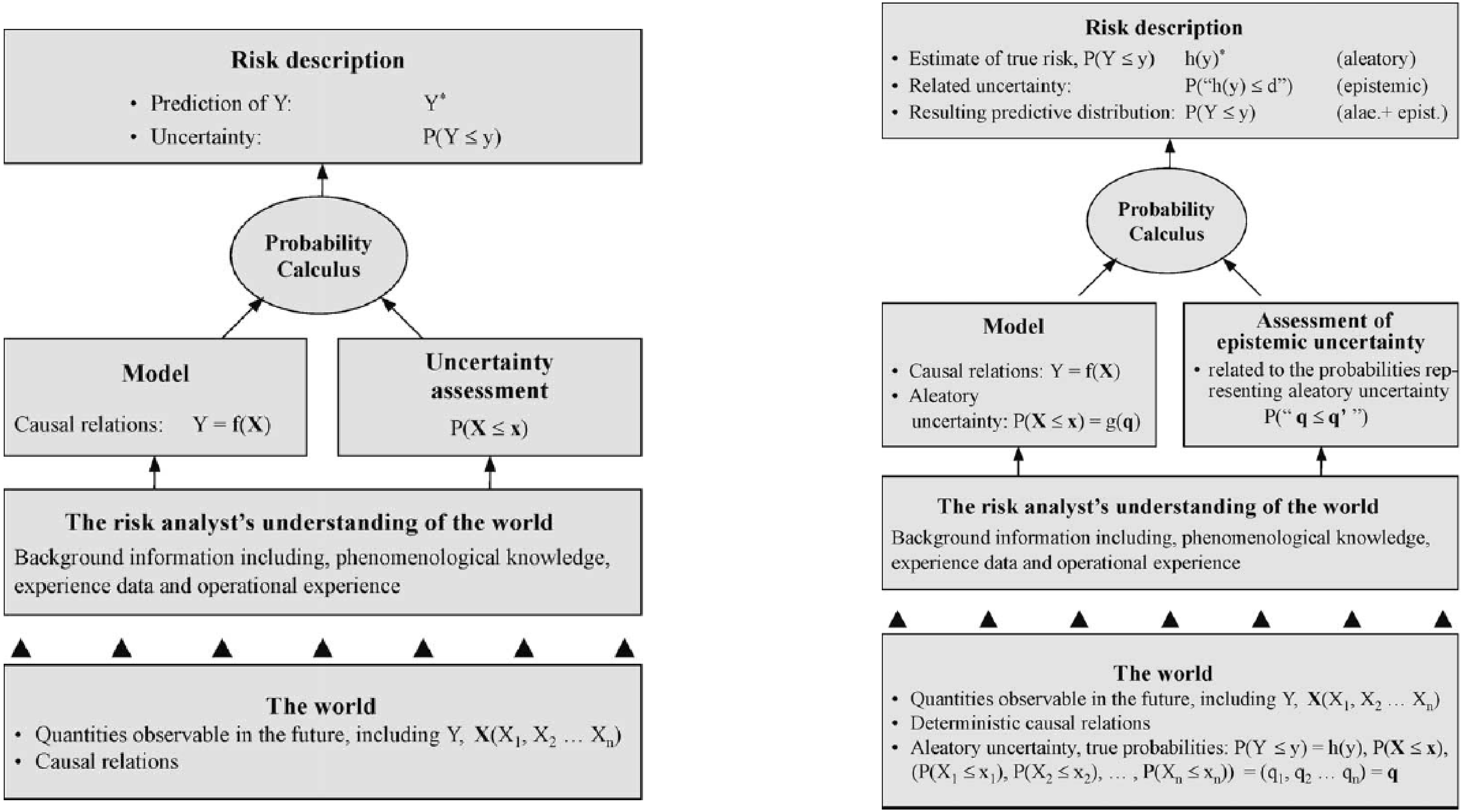


Figure 4: Comparison between the handling of uncertainties in the predictive Bayesian framework (left) and the classical risk framework (right) as presented by Nielsen et. al. The letters *d* and h in the right figure represent dummy variables. P(X) represent the probability of an event or quantity, while f(X) represent a model function to calculate the desired estimate quantity Y.

1.5 Definitions and abbreviations

In this section definition and abbreviations are listed in alphabetical order.

1.5.1 Abbreviations

ALARP – As Long As Reasonably Practical
BAT – Best Available Technology
CASD – Computer-Aided Scenario Design
CBA – Cost/Benefit Analysis
CFD – Computional Fluid Dynamics
DNS – Direct Numerical Simulation
DNV – Det Norske Veritas
FAR – Fatal Accidental Rate
FLACS – Flame ACceleration Simulator
HSL – Health and Safety Laboratory
HSE – Health and Safety Executive
ICASF – Implied Cost of Averting a Statistically Fatality
LES – Large Eddy Simulation
NPV – Net Present Value
PTIL – Petroleumstilsynet, Petroleum Safety Authority Norway
RNNS – Risikonivå på Norsk Sokkel, Risk level on the Norwegian shelf)
UKOOA – United Kingdom Offshore Operators Association
VOSL – Value Of a Statistical Life

1.5.2 Definitions:

Escalation - An accident within a module or area that spreads to or involves a neighbouring area.

Explosion - Violent combustion of flammable gas or mist that generates pressure effects due to confinement of the combustion-induced flow and/or the acceleration of the flame front by obstacles in the flame path.

Good decision – A decision built on both on the preferences by the decision-maker and evidence based on a scientifically sound analysis of the decision problem.

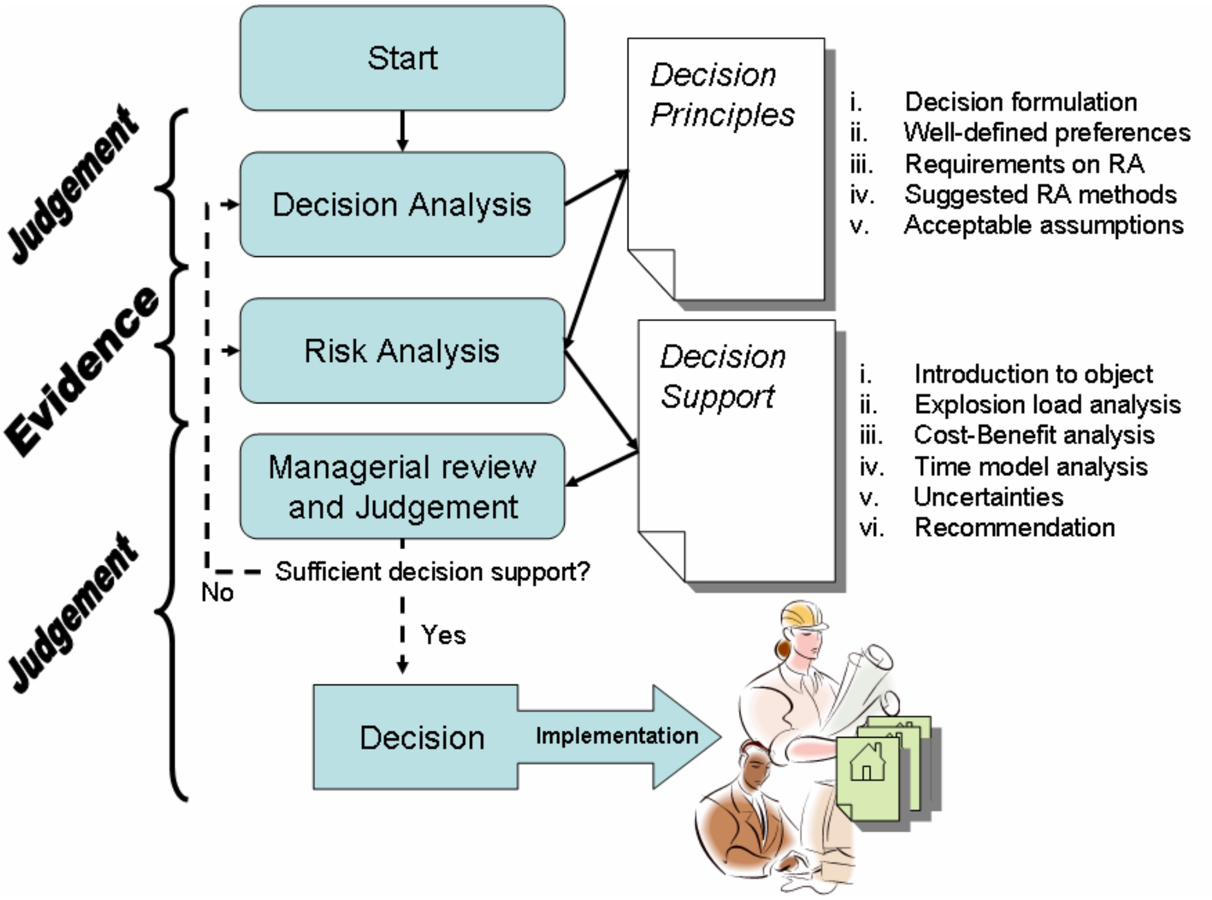
Risk – The combination of probability of the occurrence of harm and the severity of that harm.

Stakeholders - Any individual, group or organization that may affect or be affected by the decision, or perceive itself being affected by the decision.

Uncertainties – The subjective risk analyst estimate of the deviations between the underlying risk and its simplified representation in risk calculation models.[30]

[30] Nilsen T. et. al. (2001) *”Models and model uncertainty in the context of risk analysis”*

PART 1:
Knowledge base and Decision Framework



2 Decision making aspects

Decision making and risk management are indeed intertwined. Not only are decisions an inherent necessity in risk management. It should rather be viewed as the key strategy of risk management to contribute to better decisions, and thereby to increase the overall safety. Hence, a risk manager should not be judged primary by the hindsight biased results, but by the quality of the decisions he or she makes. The quality of the decision is, on the other hand, dependent on and limited by the decision support and information available to the decision maker at the time of the decision. Two questions needs to be answered: what is a good decision, and what are the differences between high-quality, low-quality, moral and immoral decisions?

First of all, risk management decisions involve both elements of facts and judgment. A good decision should reflect both aspects in a satisfying way. It is important to distinguish between facts and judgment values. Facts can and should be gathered with scientific sound methods. The scientific quality of the results can then the can be evaluated in terms validity, reliability and uncertainties. To mark the difference between facts and judgements, a high-quality decision is here defined as a decision built on facts, scientific sound methods and results with high validity, reliability and as low uncertainties as possible. A moral decision is defined as a decision that reflects the judgement values and preferences of the decision maker and the relevant stakeholders interests. Only when a decision is high-quality and moral it can be said to be good. A good decision is defined as a moral high-quality decision. The relations are illustrated in figure :

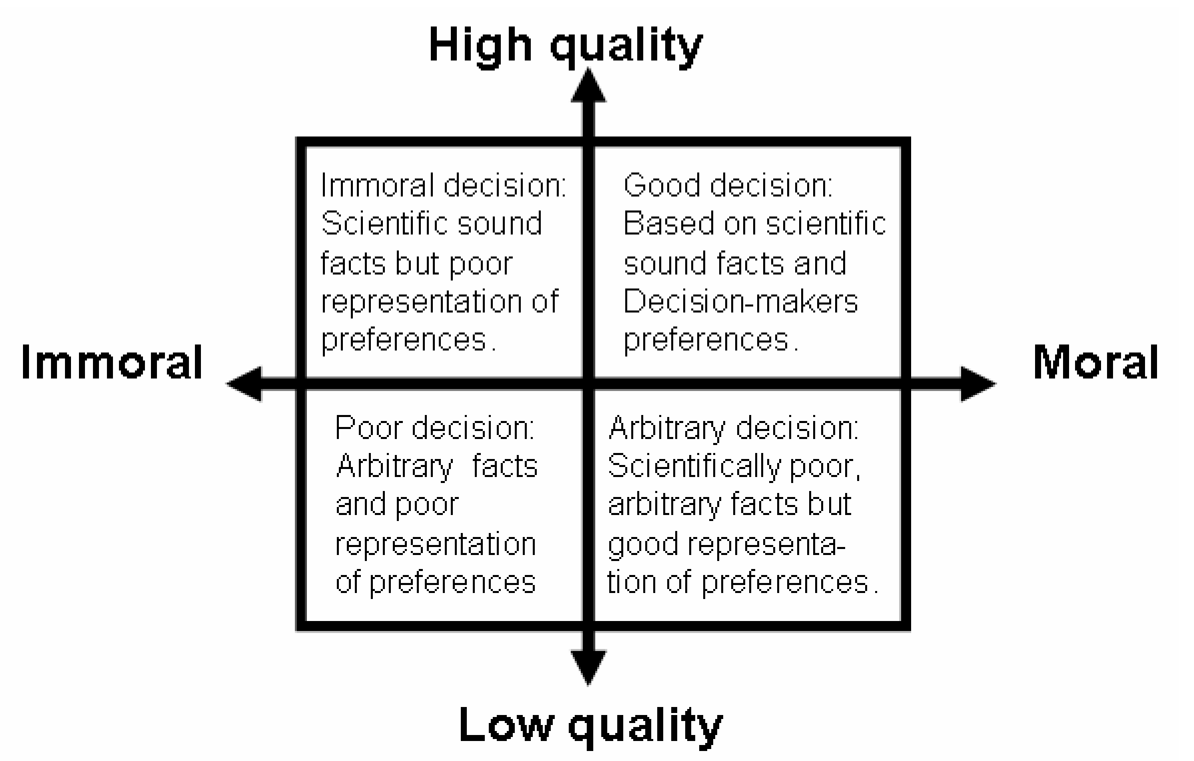


Figure 5: Illustration of different combinations of two decision dimensions which are argued to be important to reach good decisions.

The judgment element is more philosophical and should primary reflect the decision-makers preferences and moral. It is seen as important to examine and clarify these preferences in systematic way. Of special importance is the transition from 'is' to 'ought'.
The transition from 'is' to 'ought' is a classical philosophical problem, first formulated by Hume[31]. It is argued to be impossible to go from a 'is' to a 'ought' without incorporating judgment values. The transition from 'is to ought' marks the combination of judgement and facts, and there is a great need of transparency with this transition. [31]

Often the preferences can be described as optimizing the expected outcome of the decision relating to some dimensions such as risk reduction, safety, money, cost-efficiency etc. Theoretically, it has been showed that the

[31] Hume (1739) *"Treatise of Human Nature"*

decision-makers preferences of utility can be maximized through the expected utility theory by following a number of axioms to the decision making process. The axioms were first described by Neuman and Morgenstern.[32]

The expected utility theory is also close to the ethical theories of utilitarianism, which is theoretically well founded and thus defendable. The main principle of utilitarianism is the moral obligation to act and make decisions in a way that maximizes the utility consequences[33]. At the same time the problems of utilitarianism apply, such as the difficult definition and quantification of utility, injustice in distribution of utility and the difficulties of evaluating the consequences of an act or decision. Utilitarianism is nevertheless seen as a widely accepted ethical theory. A modern presentation and defence of utilitarianism is given by Singer[33].

For many cases in risk management there are also juridical rules concerning the transition from 'is' to 'ought' based on the laws and regulations of our society. The laws and regulations are in this sense an expression of societal judgement values and preferences.

[32] Mattsson B. , (2000) *"Riskhantering vid skydd mot olyckor- problemlösning och beslutsfattande"*
[33] Singer (1996) *"Praktisk etik – Andra upplagan"*

2.1 Decision-making in the Risk Management Process

Since the aim of this report is to establish decision support framework it seems reasonable to start with a coarse decision analysis to identify what information that would be valuable for the decision maker and the stakeholders to make the decision. The output of the decision analysis will then be used as input to the risk assessment, which consists of a risk analysis and a risk evaluation. The goal for the risk analysis is to identify hazards and produce relevant risk estimates for the decision alternatives. The resulting risk estimates are then compared and evaluated, together with other important aspects found in the decision analysis. The results of the Risk Assessment are then summarized, documented and communicated back to the Decision Maker to "close the circle". This is shown in figure 6 , which also illustrates the relations between risk management, risk assessment, risk evaluation, risk analysis and decision making in the risk management process.

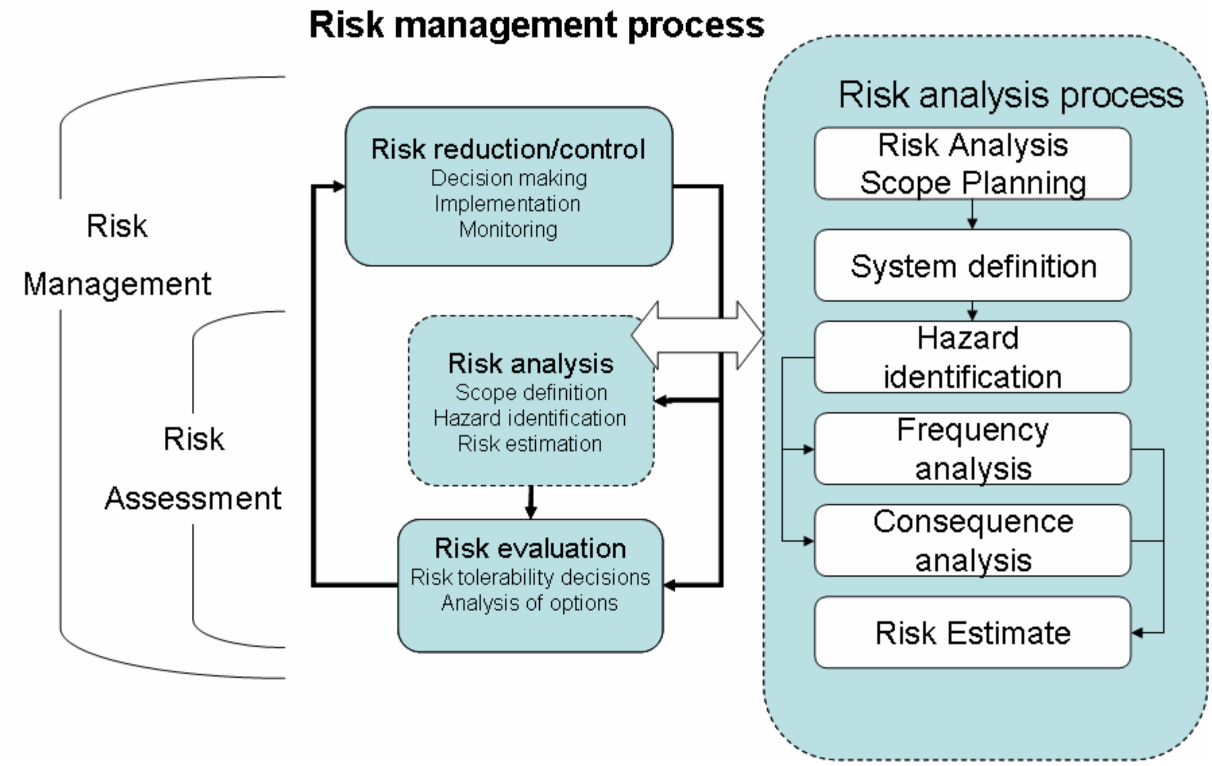


Figure 6: Schematic illustration of the relations between risk management, risk assessment, risk evaluation, risk analysis and decision making in the risk management process. Based on IEC (1995) *"International standard 60300-3-9, Dependability Management – Part 3: Application Guide – Selection 9; Risk analysis of technological systems"*,

It should be noted that the illustration is identical to the risk management process according to IEC[34], except from the order in which the steps are being presented. The order presented here is thought to illustrate that decision making (together with implementation of the decisions) is the highest goal of the risk management process, while risk assessment is primary thought to support good decisions. From this perspective it is argued that the risk management process should start and end in decision making, complemented with a course risk decision analysis which will be described in section 2.2 . A few arguments for this methodology are:

i. The risk assessment should be designed to fit the decision makers preferences and need for information in order to fully support the risk decisions. This may affect the choice of risk analysis methods, depending on the preferences of decision maker. As an example, the decision maker might want the risk analysis results expressed as a specific risk criterion or risk index to be able to compare with other risk analyses. If the risk analysis results are not suitable for decision making, it is questionable what worth they have in a decision making context.
ii. The possible perspectives on risks are unlimited, and it should be up to the decision maker rather than the risk analyzer to define the risk perspective suitable for the risk analysis. While the fatality risk may

[34] IEC (1995) *"International standard 60300-3-9, Dependability Management – Part 3: Application Guide – Selection 9; Risk analysis of technological systems"*

be the most important output for one decision situation, the environmental impact might be more relevant in another situation. What risks should the risk analyst examine? Even if it is possible for the risk analyst to try to take as many perspectives on risk into account when conducting the risk analysis, it is not certain that it is neither effective nor optimal.

iii. The decision should be made primary by the decision maker, not the risk analyst. While the risk analysis should express facts, the risk evaluation and the decision also involve judgments about preferences and priorities. There is thus a need to keep facts separated from judgments as far as is possible, and where judgments are included in the decision support it should be in line with the decision makers preferences.

It may be difficult to draw clear lines between the different roles, and many important minor decisions are made during the production of the risk analysis. For this reason, there needs to be a continuous communication between the risk analyst and the decision maker. It is however argued that it may be helpful to have a course decision analysis as a starting point to clarify the decision maker's preferences and need for information.

A similar perspective on the relation between the risk management process and decision making is presented by Aven et al [35,36]. In their article a decision framework for risk management is presented where the decision process is preceded by the establishment of "decision principle/strategies". The decision principles and strategies in turn are developed with respect to the decision makers and the chosen stakeholders values, visions, goals and strategies. A schematic illustration over the risk management process suggested by Aven et al is given in figure 7 .

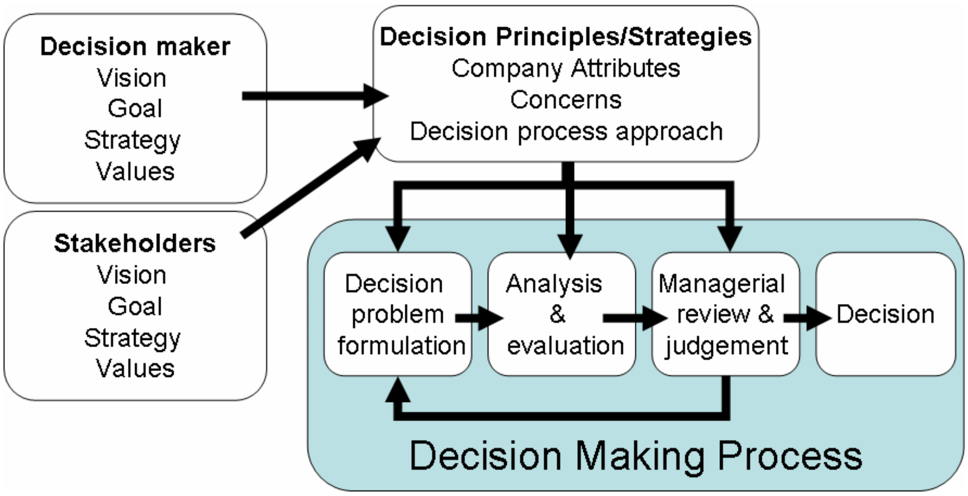


Figure 7: Illustration of the decision making process for risk management. From Aven (2005) *"A decision framework for risk management, with application to the offshore oil and gas industry."*

An important feature of the risk management decision framework suggested by Aven et. al. is the step of 'Managerial review and judgment'. This step has been incorporated in the decision framework to avoid mechanical procedures of transforming risk assessment results into decisions. The analyses need to be reviewed and evaluated together with the results in the light of the premises, assumptions, choice of methods, uncertainties and limitations on which they were built. Further the analyses should be confirmed to be in line with the decision principles and include all the important concerns of the decision maker and stakeholders. If the decision maker finds that the decision support is not sufficient or detailed enough to make the decision, further work is needed on the decision support.[36]

[35] Aven T. et al (2005) *"On the use of risk acceptance criteria in the offshore oil and gas industry"*
[36] Aven T. et al (2005) *"A decision framework for risk management, with the application to the offshore oil and gas industry"*

2.2 Decision Analysis

The quality and efficiency of the risk management process is dependent on the connection between the risk assessment and the decision making process. To address this need a coarse decision analysis is suggested to anchor the needs of the decision maker with the risk analysis scope, create decision principles and strategies and to formulate the problem. An introduction to decision theory is given in "Judgement and Choice: The Psychology of Decision"[37]. The key elements are represented by the five following questions.

i. Who is the decision maker?
ii. Who are the relevant stakeholders?
iii. What alternatives are under consideration?
iv. In which dimensions should the alternatives be evaluated and best presented?
v. How should practicality and simplicity on the one side be balanced be with precision, validity, reliability and theoretical support on the other?

The set of questions have been adjusted to better fit the context of risk analysis and the present subject. Together, the set of questions forms the prerequisites and the outlines for the decision principles and the decision support framework. The questions are discussed in greater length in the following section.

1. Who is the decision-maker, and how are decisions made in the organization?
It is important to identify how the decision support should be structured to best fit the decision maker. The 'decision-maker' is likely not to be a single person but rather consist of a board of safety managers, economists and engineers. The decision support should be written primary with this group in mind. The required level of detail in the report, formal requirements such as references, format, language, confidentiality etc should be decided before the project starts to avoid misunderstandings and increase efficiency. The perception of risk is important to clarify, so that the decision maker and risk analysis project manager share the same language and views of risk. This includes explicit, crystal-clear definitions of key expressions and well communicated risk management decision principles.

There is also a potential problem with expertise and stakeholder bias that the decision maker should be aware of. If the decision maker group consists of only engineers, there is a risk that less weight is put on the economic than in a group of mixed expertise. The same problems apply to other expert groups. Similarly, if the decision maker is represented by a single stakeholder group it is possible that the decision is biased in favour to the interests of this stakeholder group. Stakeholders are discussed in further detail in the next section.

2. Who are the stakeholders, and to what extent should the preferences of the stakeholders be guiding to the decision-making?
A definition of stakeholders is given by Aven et. al[38]. as:

> *"any individual, group or organization that may be affect or be affected by the decision, or perceive itself being affected by the decision"*

It is important to identify the different stakeholders to consider how the decision might affect them, and how they relate to the decision. This can be done by brainstorming techniques. After the identification process the decision-maker will be better prepared to evaluate which stakeholder preferences that should be taken into account.

The stakeholders can be divided into three main groups after a model by Theéden[39]: the decision-maker, risk-takers and cost-takers/beneficiaries. Further, the stakeholders can be either internal or external, depending on whether they are a part of the same organization as the decision-maker or not. Internal stakeholders include employees and platform crew, unions, installation owner and other shareholders, the decision-maker, safety managers, maintenance manager and other organisation managers. External stakeholders may include authorities, interest groups and non- government organisations such as Greenpeace, explosion risk consultants and experts, explosion research groups, competitors and companions, media and the public.

---

[37] Hogarth (1987) *"Judgement of Choise: the Psychology of Decision"*
[38] Aven, T. et. al. (2005) *"A decision framework for risk management, with application to the offshore oil and gas industry"*
[39] Grimvall G. et al (red), (1998) *"Risker i tekniska system", page 215 and forward*

For a decision that reduces explosion risk the primary beneficiaries coincide with risk-takers, namely the platform crew. The preferences of the platform workforce are important to take into account. A decision that neglects the interests and preferences of the risk-takers is not only ethically disputable but also risky, especially in Norway where the unions are well-organized and workforce strikes can be considered a substantial economic risk.

Secondary, the decision might have a beneficial outcome for the cost-takers, namely the stockholders and owners. A cost-benefit analysis can be used to illustrate whether the decision is expected to have positive net economic consequences or not. If the decision is expected to lead to positive consequences for both economic and safety, the preferences of the risk-takers and cost-taker coincide. This is often the case since accidents and process down-time are expensive. Nevertheless there are decisions where the stakeholder preferences conflict, and in these situations there is always a need to balance the interests of the stakeholders. In many cases it is considered useful to have a well-documented risk policy and philosophy as guidance in these matters.

The most important external stakeholders are the Norwegian authorities represented by the regulators, inspectors and authority bodies. It is necessary to take the juridical aspects of the decision into account to assure compliance with the law. For this reason, a decision support should include an overview of laws and regulations that applies to ensure that the decision outcome is legal.

3. What alternatives are under consideration?
For the purpose of the present study essentially there are mainly two alternatives in the present decision situation: It can either be decided that deluge should be activated as a response to gas detection or the opposite, that it should not be activated. For the first alternative, further details should be clarified to optimize the risk reduction effect. Also, potential problem attached to this alternative needs to be addressed and solved.

There might be a large number of other possibilities to reduce the explosion risks that are more cost-effective, suitable, etc. An overview of explosion risk mitigation strategies has been presented by HSE/UKOOA[40], and is shown in figure 8 .

Role	Control/Mitigation Measure
Detection and initiation of control measures	• Gas detection • Acoustic leak detection • Operator/Manual alarm call-point/Phone • Emergency Shutdown (ESD)
Avoidance of the explosion event	• Isolation of electrical equipment • Increase ventilation – start stand-by fans (in explosion zone) • Shutdown ventilation intakes (on detection in adjacent areas)
Reduction of POB exposure	• General alarm • Blast walls, TR, means of escape and evacuation
Reduction of the severity of the explosion hazard	• Initiation of area deluge upon gas detection • Increase ventilation – start stand-by fans
Minimization of the escalation potential	• Isolation of hazardous inventories • Blowdown/depressurisation • Blast walls
Protection of SCEs	• Blast walls/enclosures • Resilient mountings • Inherent robustness

Figure 8: Overview of control and mitigation measures against explosions, from HSE/UKOOA.

[40] HSE/UKOOA (2003) *"UKOOA Fire and Explosion Guidance Part 1: Avoidance and mitigation of explosions"*

To be able to compare deluge with other mitigating measures it is seen as necessary to analyse it in its own right first. If deluge is found to be beneficial, it may then be compared to other methods to reduce the explosion risk.

4. On what dimensions should the alternatives be evaluated, and how can the findings of the risk analysis best be presented to the decision maker?

There are primary two dimensions to be evaluated: the potential explosion risk reduction and the costs of deluge as an explosion mitigation measure. The interpretations of risk and costs are not self-evident, and there is a great need to discuss and present them transparently. There is also a need to characterize the risk and cost dimensions either quantitative in numbers, diagrams or described qualitatively with words.

One way of categorizing different risk dimensions is to focus on the valuable and vulnerable target that needs to be protected. From this perspective risks and hazards are often divided into three main groups: risk for human life and health, risks for environmental damage and risks for economic values or property loss. Environmental and occupational health aspects of explosion risk are seen as subordinate and correlated to the fatality risk and the risk of loss of economic values or property, and will not be evaluated further in the present study. It is argued that the reduction on explosion impact on the environment and human health will be closely correlated to the risk dimensions 'fatalities' and 'damage to economic values and property'.

Risks concerning human life are often measured and expressed as the expected number of fatalities, or some derivate of the expected number of fatalities. Typical are the fatal accidental rate (FAR), potential loss of life (PLL). These and other common risk estimates will be discussed in greater detail in the next chapter, based on the NORSOK Z-013 standard Annex A. [41]

Besides the risk to human life there are other risks associated with explosions expressed in the NORSOK standard Z-013: the risk of escalation and the risk of loss of main safety function.[42] The NORSOK S-001 further adds the risk for total collapse, risk for damage to equipment or to the explosion barriers[43]. Although the primary objective of these risk dimensions is to protect human life and health, they are expressed as property risks. These risks can be expressed as the expected frequency of the specific explosion loads that corresponds to the different dimensions. It is seen as necessary to define installation specific explosion load criteria for these risk dimensions, and even specific for different modules. As an example an appropriate load criteria might be the maximum design pressure load of the weakest firewall in a module, which will differ from module to module.

In addition to the risk dimensions mentioned above, the decision-maker will always need to address how the costs of the decision alternatives should be handled. The costs include the investment costs, increased maintenance costs, running costs etc. Also the opposite to cost should be included such as a cost reduction or increased income due to risk mitigation. A more detailed discussion of the costs of the different decision alternatives will be given in chapter 5.5. Even if the decision alternatives are evaluated primary from the risk dimensions, the costs needs to be examined to see if the alternative is economically possible to implement or not. For this purpose, a suitable economic investment cost dimension needs to be calculated. An introduction to investment decisions and calculations is given by Persson et. al[44]. Costs and incomes related to investments are often described as a Net Present Value (NPV), internal rate of return or annual costs. The net present value, which is sometimes called the life cycle cost, is the most common way to calculate the investment costs and incomes and it is the only investment calculation method considered in the present study. It can be described as the value of present and future costs and incomes, discounted with interest rate. NPV can be mathematically defined as:

$$NPV = -G + a\sum_{k=1}^{n}\frac{1}{(1+i)^k} + \frac{S}{(1+i)^n} \qquad \textbf{[Eq. 4]}$$

Where

G = Initial investment
a = Annual difference between receipts and payments leading to cash surplus (+) or deficit (-)
n = Economic life time

[41] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex A
[42] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*
[43] NORSOK (2000) *"S – 001 Technical Safety"*, rev. 3
[44] Persson I. et al. (2001) *"Investeringsbedömning"*

i = interest rate
k = Year (from 1 and n)
S = Residual value
In many cases, the decision-maker needs to balance the risk reduction and the costs of the risk reduction measure. In these cases, a cost-benefit analysis (CBA) may be a suitable as a decision support. CBA and other methods to compare risks and costs will be discussed in greater detail in chapter 2.3 .

Besides the risk criteria described above, other tools may be helpful to support the decision. These tools include influence diagrams, event trees and sensitivity analysis. While the different risk measures describe the magnitude of the risk in a single number, an influence diagram and an event tree-diagram may help to understand the complexity of explosions.
Sensitivity analysis, on the other hand, helps the decision maker understand the uncertainties in the calculations and methods behind the risk criteria. Together, one or more suitable risk criteria and cost criteria together with sensitivity analysis and event tree- and influence diagrams might offer a good decision support.

5. Whether the practical application of the framework methodology in the context of explosion risk analysis is easy enough.
Decision and risk management can often be time and resource consuming, and therefore impractical to conduct properly. Further, a too theoretical and complicated framework might lead to problems of interpreting and communicating the results. On the other hand a complex risk management decision cannot be simplified too much without adventuring the decision quality. Hence, there is a need to balance between practicality and simplicity on one side, and precision, validity, reliability and theoretical support on the other.

A central strategy to achieve the goals of simplicity and precision at the same time is to use the results of previous analyses as the starting point of the present decision support. This way, less effort is needed to do what others have already done before, and more effort can then be concentrated to further improve the decision support. Concerning risk analysis in the offshore industry, including explosion risks, it is very likely that there already exists a lot of material on the subject. It can be expected that in many cases there already exists hazard identification, explosion consequences calculations, leakage and ignition frequencies, etc. If the previous analyses are used this should be with precaution, so that the decision support is built on old facts rather than old errors. Further, it should be confirmed that no greater changes have been made to the installation that could render the old analyses assumption.

2.3 Decision, risk estimate and acceptance criteria

This section examines the relation between decision-making and different risk measures and acceptance criteria. First some common risk estimates are described and defined based on NORSOK Z-013. [45] Their respective strengths and weaknesses are discussed in relation to the decision problem of this study. Then, four different decision criteria are described and discussed in relation to the risk estimates and their suitability to support the decision maker in the decision situation in question.

2.3.1 Four common risk estimates

According to NORSOK[45], the most common risk estimates used in the Norwegian offshore industry includes:

- Potential Loss of Life, PLL
- Fatal Accidental Rate, FAR and Individual Risk, IR
- Frequency-Numbers diagram, F-N-curves
- Frequencies for escalation, loss of main safety functions or total collapse

In this section, these risk estimates are presented and discussed with respect of their suitability to support the decision of the use of deluge as explosion mitigation measure. It is argued that a variant of F-N curves adjusted to show explosion load instead of fatalities is to be used as the primary risk estimate since it offers more information to the decision maker at a minimum of uncertainties and assumptions.

[45] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex A

Potential Loss of Life (PLL)
The following definition of PLL is given in NORSOK[46]

> *"The PLL value is the statistically expected number of fatalities within a specified population during a specified period of time."*

NORSOK describes two general problems with the use of PLL as a risk estimate. First of all PLL does not take the population size into account. Installations, areas or modules with a lower personal density are biased, which makes it difficult to use for comparison. Secondly the calculation of PLL is bound to include a number of assumptions which makes it more uncertain than for example loss of main safety function or escalation frequency.[46]

For the present decision situation the first objection to PLL seems to be invalid based on the assumption that the decision alternatives will not affect the population in any wider sense. In other words, for the comparison between with/without automatic deluge as explosion mitigation measure the population can be assumed constant. If however the population increases due to increased need of maintenance and inspection, which could be the result of automatically initiated deluge, there might be a problem with comparison between alternatives were PLL tends to favour low personal numbers. PLL is also not suitable to be used to compare between different areas, modules or installations or to create a general decision criterion for the use of deluge as explosion mitigation measure.

The second problem concerning increased uncertainty is more serious for the use of PLL in explosion risk calculation and estimation. Explosions can be described as a chronological chain of events from leakage, formation of an explosive cloud, ignition, explosion propagation and finally to the explosion load. In the calculation of explosion load, each event in the chain adds assumptions and uncertainties. Any attempt to calculate the estimated number of fatalities based on explosion load calculations adds further assumptions and uncertainties. It is a complicated task to try to take into account the fact that explosion may result in escalation, loss of main safety functions or even total collapse, and how these events affect the potential loss of life. From this point of view, it may be better to calculate and present the frequency for these events in their own right rather than weighing them together in a single number.

A third objection against the use of PLL in the present framework is that it includes so much more than the risk contribution from gas explosions. All possible fatality risks should be included in the calculation of PLL, which might overshadow the explosion risk contribution. This can be solved by focusing only on the explosion risk contribution to PLL.

Fatal Accidental Rate (FAR) and Individual Risk (IR)
The following definition of FAR and IR are given in NORSOK[46]:

> *"The FAR value expresses the number of fatalities per 100 million exposed hours for a defined group of personnel."*
>
> *"IR is the probability that a specific individual (for example the most exposed individual in the population) should suffer a fatal accident during the period over which the averaging is carried out (usually a 12 month period)."*

There are a number of different subgroups of FAR, depending on how the group of personnel is defined. FAR can be calculated for a whole installation or platform, for a certain group of personnel, or for a certain area or module. The strength of FAR is that it makes it easy to communicate and compare risks. By using group- and area-FAR the risk estimate can better describe the differences by not averaging over the whole installation.[46] A weakness with FAR is that it is dependent on how the groups or areas are defined which makes it a bit arbitrary. This is particularly true for explosion risks, which may include more than one module or even the whole platform. FAR also suffers the same problems with uncertainty and marginalizing explosion risk contribution as described for PLL above.

The FAR for a group and the average IR are directly proportional to each other and they are therefore presented together in this section. The same problems applies to IR as to FAR for a group. Compared to PLL and FAR for an entire installation, IR has the advantage of being more representative for the individuals exposed to the highest risk levels.

46 NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex A

Frequency-number curves, F-N curves
The following description of F-N curves is given in NORSOK:

> *"The F-N curves are usually a graphic representation of the cumulative frequency distribution for the number of fatalities in the risk calculations that have been performed"*

A strength of using F-N curves is that they can reflect an aversion against major accidents with a large number of casualties. The curve also contains more information than a single number; indeed the F-N curve illustrates the relation between the two dimensions of risk, frequency and consequence. The weaknesses of F-N curves are that they are harder to communicate to non-experts and that they might give an ambiguous decision support. While one alternative is considered 'safer' on one part of the curve, another alternative may be preferred on the other parts. F-N-curves therefore require more from the decision maker than other risk measures such as FAR, PLL and IR which give a 'straight answer'. F-N-curves share the problem of PLL in that they do not take the size of the population into account. [47]

As with PLL, FAR and IR the calculation process of F-N-curves increases the assumptions and uncertainties in the calculation step between explosion load and fatalities.
This can be avoided by replacing 'number of casualties' on the consequence axis with 'explosion load', expressed as the cumulative frequency of exceeding explosion load. To avoid any misunderstandings, such a diagram will be called cumulative explosion load diagram or exceedance curve throughout this report. In a cumulative explosion load diagram it is also possible to draw and compare the different decision alternative risk profiles in the same diagram. This creates an overview that will help the decision-maker to compare the alternatives against each other. An example is illustrated in figure 9 :

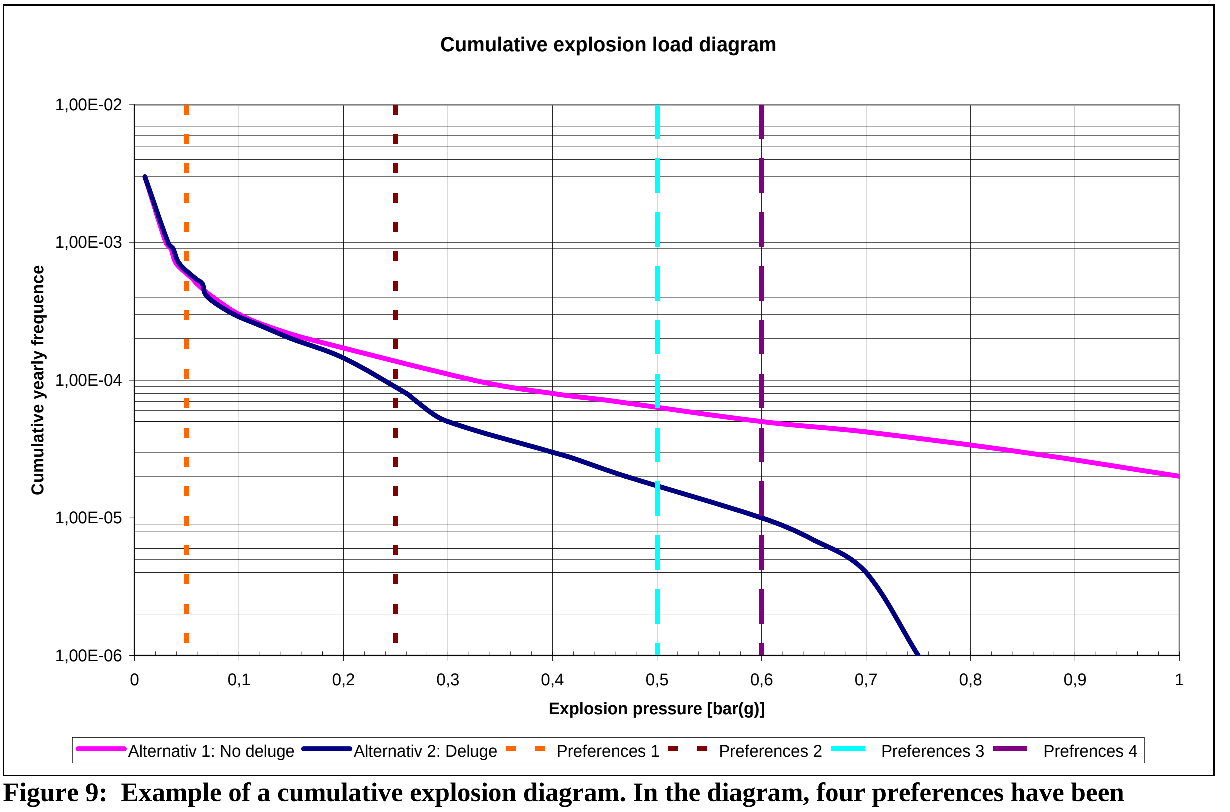


Figure 9: Example of a cumulative explosion diagram. In the diagram, four preferences have been included. With this approach, the decision maker can get a clear illustration of the explosion risk. The preferences could typically include loss of certain important equipment, loss of main safety function, escalation or total destruction of installation.

[47] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex A

These risk estimates share the same strengths and weaknesses. Their main strength is that they are less uncertain than PLL, FAR and IR since they avoid the calculation step of explosion load into fatality consequences. This is at the same time their weakness, since the fatality risk often has the highest priority. Further, it may be difficult to compare and weigh the different frequencies against each other.[48]

The frequencies for loss of a main safety function, escalation or collapse are easy to understand and communicate as long as there are clear definitions what is included in each concept. To be able to find the corresponding frequency there needs to be unambiguous definitions together with detailed information on which explosion load that responds to loss of main safety functions, escalation or collapse. The frequency of loss of main safety functions has especially high relevance to the decision-maker as it is as an explicit legal requirement[49] that this frequency should be below 10^{-4}. The legal requirements are investigated in depth in section 4.1 below but it is important to define what is generally meant with main safety functions, escalation and collapse.

The main safety functions, based on §6 in the Facility regulation, are generally defined as:

i. Preventing escalation of accident situations so that personnel outside the immediate vicinity of the scene of accident are not injured.
ii. Maintaining the main load carrying capacity in load bearing structures until the facility has been evacuated.
iii. Protecting rooms of significance to combating accidental events, so that they are operative until the facility has been evacuated.
iv. Protecting the facility's safe areas so that they remain intact until the facility has been evacuated.
v. Maintaining at least one evacuation route from every area where personnel may be staying until evacuation to the facility's safe areas and rescue of personnel has been completed.

How the main safety functions are protected differs between different modules and installations and there is always a need for installation specific definitions. Typically the main safety functions include the main support structure, the control room, the evacuation routes and the firewalls that separate different platform areas from each other.[50]

The interpretation of the NORSOK standard[50] and facility regulation leads to the following definition of escalation: An accident within a module or area that spreads to a neighbouring module or area. According to this definition, escalation is not identical to a domino effect event. A domino effect event, citing Cozzani[51] , is defined as:

> *"an accident in which the primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than the primary event."* [131]

Domino effect events is however often likely to result in escalation or loss of a main safety function, but it is still important to note the difference in the definitions. Finally, collapse is defined as critical damage to the main load bearing structures. It may typically be expressed as a maximum critical load.

The frequencies of loss of main safety function, escalation and total collapse may very well be included in the cumulative explosion load diagram described above. Indeed, it is argued that this combination should be the primary representation of the explosion risk based on the following arguments:

i. As a decision support it offers the most complete and transparent illustration of the explosion risk function of frequencies, explosion load and consequences compared to single number estimates such as PLL, FAR or IR.
ii. It includes less uncertainties and assumptions than PLL, FAR and IR where the explosion load has been calculated into fatalities.
iii. It includes information necessary to fulfil the legal requirements and is thus highly relevant to the decision maker.

---

[48] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex A
[49] Facilities Regulations, see especially §10 and §6
[50] NORSOK (2001) *"Z-013 Risk and emergency preparedness analysis"*
[51] Cozzani V. et. al. (2006) *"Quantitative assessment of domino scenarios by a GIS-based software tool"*

iv. Even in situations where the decision cannot be made on cumulative explosion load diagram alone, they can be complemented with fatality risk estimates as well. In the calculation process of fatality risk estimates, such as PLL, FAR and IR the cumulative explosion load diagram is seen as a good starting point.

2.3.2 Four different categories of decision criteria

Decision criteria are a systematic ways of combining the judgement part and the facts of the decision. They are the link between judgement and facts, which was described as the 'is-ought' problem above. Decision criteria are often divided into three main categories; technology-, equity- or utility-based criteria[52,53]. Further, the three criteria can be combined to create a forth category, called hybrid criteria. The different criteria are discussed in relation to the most common risk estimates and the decision situation of this study. Finally, a hybrid decision criterion is presented that is in accordance with the Norwegian regulation. A more detailed discussion of the Norwegian legislation is presented in section 2.4.

2.3.2.1 Technology-based decision criterion

A description of technology-based decision criterion is given by HSE:

"A technology-based criterion which essentially reflects the idea that a satisfactory level of risk prevention is attained when 'state of the art' control measures (technological, managerial, organisational) are employed to control risks whatever the circumstances."

The technology-based criterion is also often referred to as the best available technology criterion (BAT). Two objections raised by HSE against BAT are that it is unrealistic and that it ignores the balance between risk and costs.[53] Mattsson develops the last arguments further in that BAT in general leads to an ineffective usage of the economic resources available to reduce risk, as the marginal cost of the risk reduction is not considered. Further, the continuous development of research and science make the BAT criteria even more difficult to use. In the strict interpretation of BAT, Mattsson renders it useless as a risk decision criterion.[52]

From a practical point of view the technology-based criteria may very well be used with any of the risk estimates described above that produces a clear answer on what decision alternative is the 'best available'. BAT may have a bias towards the newer safety technology. It is problematic that newer technology may be subject to more uncertainties than older, well-known technology. If this is suspected, the decision maker is recommended to perform some form of uncertainty or sensitivity analysis. For newer platforms, the decision whether to use deluge to mitigate explosions or not is legally bound to be based on the BAT criterion. For older platforms, other criterions are legally acceptable. The laws and legal requirements will be examined in greater depth in chapter 2.4.

2.3.2.2 Equity-based decision criteria

The equity- or rights-based decision criteria are based on the premise that all individuals should have the right to a certain amount of safety. This often expressed by a specific risk estimate that should be below a certain level.[53] A relevant example is found in the Norwegian offshore safety regulation which states that the expected frequency of loss of main safety function due to explosions should not exceed 10^{-4}.[54] Another common application of equity-based decision criteria is to construct risk acceptances curve in the F-N diagram, for example as have been done by DNV[55].

Mattsson raises basically the same objections against equity-based decision criteria as the technology-based criteria. Since these criteria do not reflect cost-effectiveness, they will lead to a waste of resources in the long run.[52] Two additional arguments against the use of equity-based criteria have been formulated by Aven[56]. The first argument is that an extensive use of equity-based decision criteria may work as a counteractive incitement as the focus will be too concentrated on meeting the criteria instead of proper and effective risk management.

[52] Mattsson B. , (2000) *"Riskhantering vid skydd mot olyckor- problemlösning och beslutsfattande"* page 68-102
[53] HSE (2001) *"Reducing Risks, Protecting People"* page 49 and forward
[54] Facillity Regulations §9
[55] DNV (1997) *"Värdering av risk"*
[56] Aven T. et. al. (2005) *"On the use of accept criteria in the offshore oil and gas industry"*

The second argument is that the accuracy and precision of the risk analysis methods are not sufficient for mechanical use of equity-based criteria.[56]

There are some practical benefits of the equity-based decision criteria. They are generally easy to define, understand and communicate. Further the use of equity-based decision criteria simplifies the risk evaluation as no comparisons are needed to other technology or to the costs. It may be formulated very clearly, such as in the Norwegian legislation, which reduces the potential problem of misinterpretation.

Finally, it has been argued by HSE that the equity-based decision criteria are more humane and morally acceptable than the utility-based criteria since the all individuals are guaranteed a minimum level of safety. Therefore, it ensures that the risks are not to unfairly distributed which could be seen as a form of injustice.[57]

The validity of the last argument is however based on the moral attitude by the decision-maker. A review of the connections between risk management, decision making and moral philosophy is given by Ersdal[58]. The moral philosophy direction of deontology is more compatible with equity-based criteria than utilitarianism. Deontology means duty-based ethics and in this school of thought decisions can be right or wrong, whatever the consequences or benefits. Utilitarianism in turn is more compatible with utility-based decision criteria. In contrast to deontology, utilitarian ethics are strictly based on the consequences, and the net balance between pros and cons.

2.3.2.3 Utility-based decision criteria

The basic idea of utility-based decision criteria is to balance the pro and cons of each decision alternative, and then choose the alternative with the most positive expected net consequences. To be able to do so, suitable measures for the gained utility and the sacrificed resources needs to be specified respectively. The main utility of a risk decision is typically a risk reduction, but it may also include other dimensions such as economic benefits. The sacrificed resources are normally expressed in monetary terms, such as the investment cost of a certain risk mitigation measure. The utility and resource sacrifices are then compared; an example is to present it as the implied cost of averting a statistical fatality (ICASF) for each alternative. This is called cost-effectiveness analysis. Some recommendations on how to evaluate ICASF[59] is presented in figure 10 .

ICASF (in NOK)	Assessment
$0-10^5$	Highly effective; always implement
10^5-10^6	Effective; always implement
10^6-10^7	Effective; implement unless individual risk is negligible
10^7-10^8	Consider; effective if individual risk levels are high
10^8-10^9	Consider; at high individual risk levels or when there are other benefits
$> 10^9$	Not socially effective – look at other options

Figure 10: Assessment of Implied Cost of Averting a Statistical Fatality (ICASF)
From the PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*

A special case of utility-based decision criteria is the cost-benefit analysis (CBA). A CBA guideline is presented in the NORSOK Z-013 standard[60]. In CBA both the utility and resource sacrifices are translated into monetary terms. To translate the risk reduction benefits into monetary terms is not straight forward. For fatality risk, the conversion factor is often expressed as the value of a statistical life (VOSL). Further detail on CBA and how the VOSL may be calculated is described in greater detail by Mattsson[61] and in NORSOK Z-013[62].
.

[57] HSE (2001) *"Reducing Risks, Protecting People"* page 49 and forward
[58] Ersdal (2005) *"Risk management and its ethical basis"* Part of the Ph.D
[59] PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*
[60] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex E
[61] Mattsson B. , (2000) *"Riskhantering vid skydd mot olyckor- problemlösning och beslutsfattande"* page 232ff

Some cited values of VOSL are presented in Figure 11

Cited VOSL	Comments	Reference source
5 MNOK, (1997)	Value used in an official CBA for helicopter search and rescue preparedness in 1997.	NORSOK Z-013, page 84
£ 0,6 million ~6-7 MNOK,	The approximate societal loss of production capacity for an average offshore worker, based on a HSE report on tolerability of risk from nuclear facilities.	NORSOK Z-013, page 84
16,2 MSEK (1997)	Value used in CBA by the Svenska Vägverket. (Swedish Road Adminitstration)	Mattsson (2000), page 235
£ 2 million ~24 MSEK (1991)	Value based on Health and Safety Commision for the use in CBA of dangerous goods transport.	DNV(1997) *"Värdering av risk"*, page 7-15
5-25 MSEK (1997)	Value suggested by Svenska Strålskyddsinstitutet. (Swedish Radiation Protection Authority)	Mattsson (2000), page 235
£0,6-6 million ~7,2-72 MSEK (1992)	Value used by an anonymous oil company, as presented by DNV.	DNV(1997) *"Värdering av risk"*, page 7-15

Figure 11: Some cited examples of VOSL used and suggested by Swedish, Norwegian and British authorites. These may be compared with recommandations in table 3 above. Note that the VOSL is presented in different currencies. The currency and the actual year are presented after each cited VOSL.

After all benefits and costs have been translated into monetary terms, the net present value of the CBA can be calculated. This requires some further input, such as a suitable interest rate and last year of field life time. According to NORSOK, the interest rate should be equal to that normally used for investment calculations. Depending on whether the NPV is positive or negative the CBA decision support is said to favour or reject the decision alternative under trial.[62]

Utility-based decision criteria have been criticized for being unethical, as it ignores other considerations except balancing costs and benefits[63]. This is a however a conceptual misunderstanding. In theory, any consideration may be included in the calculation as long as it can be expressed such that it may be compared to the other costs and benefits. Hence, the utility-based decision criteria do not ignore other considerations, it is rather a question of how they should be expressed, measured and included. On the contrary, to use of utility-based decision criteria are very similar to and easily defendable from a utilitarian moral theory.

2.3.2.4 Hybrid criteria

Besides the use of pure decision criteria, it is possible to combine them into so-called hybrid criteria. The prime strength of a well structured hybrid criterion is that it may capitalize on the advantages of each pure criterion and still avoid their individual disadvantages. Due to this reason of the use of hybrid criteria is recommended by HSE.[63]

An example of such a combination is to combine the technology-based BAT criterion with a utility-based decision criterion. This can be expressed as the best available technology as long as reasonably practical (BATALARP). BATALARP corresponds well with a recent interpretation of the Norwegian offshore safety legislation[64], which makes it especially interesting in the present context. An important feature that differ the BATALARP-principle from pure utility-based decision criteria is that the best available technique should be implemented unless it can be shown to be unreasonable expensive or ineffective. This puts the burden of proof on the decision maker rather than the risk reducing measure. An illustration of a hybrid criteria is given in figure 12.

The hybrid criteria may be further enhanced by incorporating other important equity-based decision criteria, namely the company accept criteria and the legal requirement that the annual frequency for loss of main safety functions shall not exceed 10^{-4}. This leads to the model of a hybrid decision accept criteria as illustrated in Figure 12.

[62] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex E
[63] HSE (2001) *"Reducing Risks, Protecting People"* page 49 and forward
[64] PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*

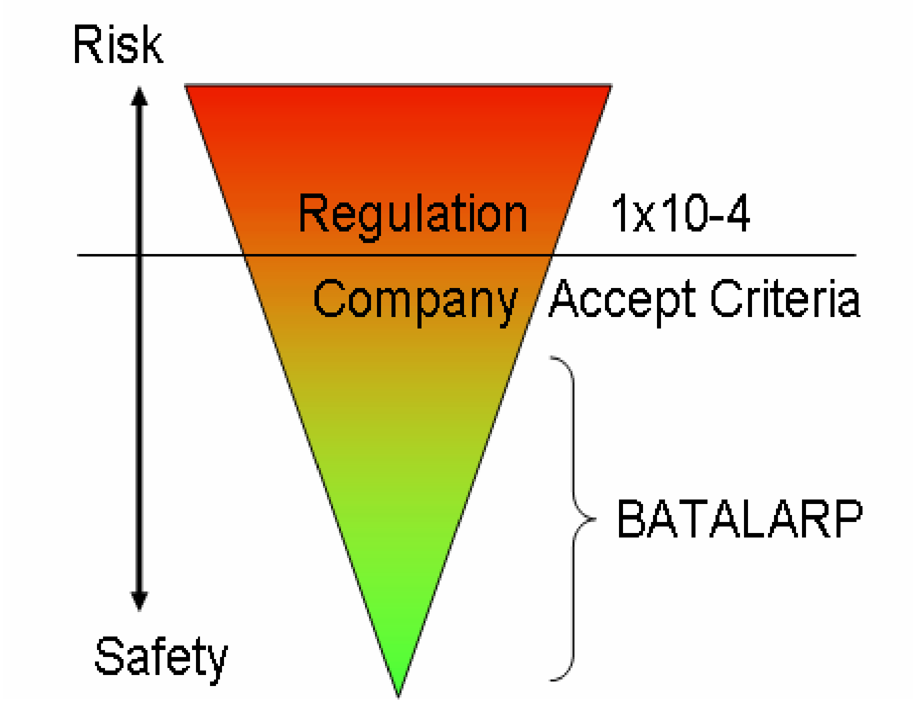


Figure 12: An illustration of a hybrid criterion in accordance with the Norwegian offshore legislation.

2.4 Analysis of laws, regulations and standards

In the previous sections it was stated that the minimum requirement of the decision-making process is to assure compliance with laws and regulations. A decision support should thus include an overview of relevant regulations to demonstrate that the decision is acceptable from a legal aspect. A brief introduction to the Norwegian legislation system is presented in the following section, illustrated by figure 13.

The power of the State is divided between the following three separate branches:

- Legislative; the Parliament (Stortinget).
- Executive; the King and the government.
- Judicial; judges and courts.

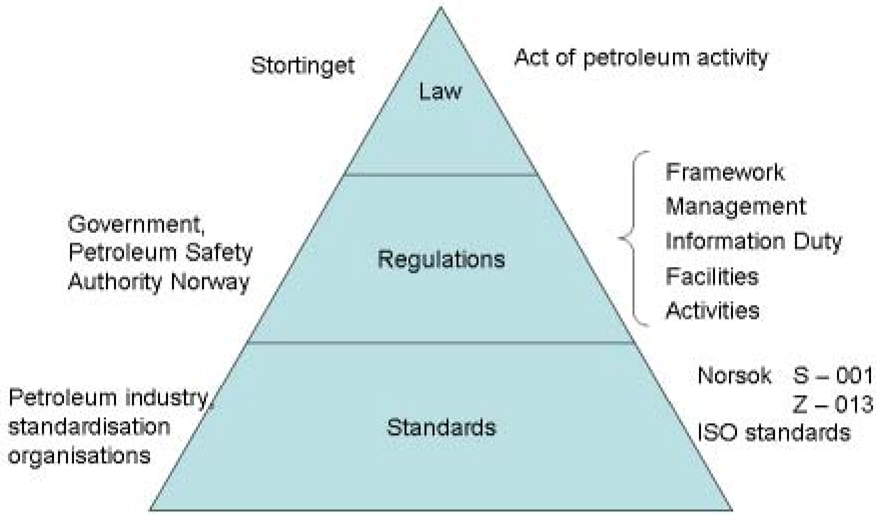


Figure 13: Schematic description of the system of laws, regulations and standards in Norway.

The Norwegian parliament, Stortinget, has the power to pass, amend and repeal laws. Today, the executive power of the King is symbolic and in reality delegated to the government. The most laws include a delegation which gives the government the executive power to pass regulations in accordance to the law. The government further delegates the practical work with the regulations to different authorities, in example Petroleum Safety Authority Norway (PTIL) and Norwegian Petroleum Directorate (OD).[65]

There is a direct connection between the regulations and standards. For the purpose of this study the NORSOK standards are central. These standards are continuous developed and financed by the petroleum industry. Although the standards are not legally binding, they represent recommendations on how the law should be interpreted and fulfilled. There is also close links between international standardisation work, the progress of science and the NORSOK standards. The NORSOK standards are free to download from the internet.[66]

2.4.1 Laws and regulation relevant to this study

This section presents a brief overview of the present Norwegian laws and regulations concerning offshore petroleum activities. The present analysis has been limited to the present laws and regulations, although the existing installations serve under the requirements of the contemporary standards and regulation at the time of construction.[67] It is considered a complicating fact that the regulations and standards are under continuous development, which in turn is coupled to the scientific progresses. This means that the decision-maker needs to be aware of the specific requirement under which the installation serves. The present legislation is nevertheless important even if it can be viewed as normative rather then prescriptive for the existing platforms. All new major modifications to the platform serve under the contemporary regulations. For details, see the quotation of §83 in the Facilities Regulation at page 42.

The analysis is focused on the interpretation of the paragraphs concerning explosion mitigation, deluge and how this should be incorporated in the decision-making framework of this report. The law central for the present

[65] www.stortinget.no
[66] www.standard.no/imaker.exe?id=1061&visdybde=1&aktiv=1061
[67] Kristensen V, Mail correspondence with PTIL 2006-03-30

study is the Act 29 November 1996 No. 72 relating to petroleum activities. Since 2002 the law is attached to the five following regulations, presented in figure 14:

Health, Environment and Safety in the Petroleum Activities. Other names: Framework Regulations, Rammeforeskriften	The Framework Regulations provide a framework for coherent and prudent petroleum activities, and contain provisions governing who is the obligated party, scope, working hours, application of maritime legislation, principles related to health, environment and safety, including requirements as to a favourable health, environment and safety culture, etc. [68]
Management in the Petroleum Activities. Other names: Management Regulations, Styringsforeskriften	The Management Regulations assemble all overarching requirements as to management in the health, environment and safety sphere. They contain requirements as to risk reduction, management elements, resources and processes, analyses and monitoring, follow-up and improvement, etc.[69]
Material and Information in the Petroleum Activities. Other names: Information Duty Regulations, Opplysningspliktforskriften	The Information Duty Regulations set requirements as to material and information to be submitted or made available to the authorities.[70]
Design and Outfitting of Facilities etc. in the Petroleum Activities. Other names: Facilities Regulations, Innretningsforeskriften	The Facilities Regulations deal with the design and outfitting of facilities, safety functions and loads, materials, work areas and accommodation areas, physical barriers and emergency preparedness.[71]
Conduct of Activities in the Petroleum Activities Other names: Activities Regulations, aktivitetsforeskriften	The Activities Regulations contain requirements on the conduct of various activities and in that connection set requirements to the working environment, health-related aspects, the external environment and emergency preparedness. Requirements as to environmental monitoring and requirements associated with the use and discharge of offshore chemicals are listed in appendices, which form part of the regulations.[72]

Figure 14: An overview of the Norwegian regulation concerning health, environment and safety offshore. The laws and regulations are available at the homepage www.ptil.no .

Together, the law and these five regulations form the backbone of the Norwegian offshore HSE legislation. To separate facts from interpretations, the most important paragraphs are quoted in full length and then interpreted. Key sentences have been ***high-lighted*** by the author and will be discussed in greater detail. The relation between the platform age, the application of the present law and previous regulations is described in §83 in the Facilities Regulation. The Framework Regulation §9 and the Facilities Regulations §6, §10, involves the regulation requirements and quantitative accept criteria. Finally, §§35-36 in Facility Regulation are more specific on deluge, fire water systems and explosions.

Quotation of §83 in the Facilities Regulation[73]:
"

Section 83
Entry into force

1) These regulations enter into force 1 January 2002.
2) In the areas of health, working environment and safety, ***regulations that applied up to the time of entry into force of these regulations, may be used for existing facilities.***

[68] www.npd.no/regelverk/r2002/Rammeforskriften_e.htm
[69] www.npd.no/regelverk/r2002/Styringsforskriften_e.htm
[70] www.npd.no/regelverk/r2002/Opplysningspliktforskriften_e.htm
[71] www.npd.no/regelverk/r2002/Innretningsforskriften_e.htm
[72] www.npd.no/regelverk/r2002/Aktivitetsforskriften_e.htm
[73] www.ptil.no/regelverk/r2002/Innretningsforskriften_e.htm

3) In the case of major rebuildings and modifications of existing facilities these regulations shall nevertheless apply to that which is comprised by the rebuilding and modification.

"

This paragraph shows that the existing installations serve under the contemporary regulations of the time they were built, while any major rebuilding or modification serve under the present law.

Quotation of §9 in the Framework Regulation[74]:

"

Section 9
Principles relating to risk reduction

Harm or danger of harm to people, the environment or to financial assets shall be prevented or limited in accordance with the legislation relating to health, the environment and safety, ***including internal requirements and acceptance criteria.***
Over and above this level the risk shall be further reduced to the extent possible. Assessments on the basis of this provision shall be made in all phases of the petroleum activities.

In effectuating risk reduction the party responsible shall choose the technical, operational or organisational solutions which according to an individual as well as an overall evaluation of the potential harm and present and future use offer the ***best results, provided the associated costs are not significantly disproportionate to the risk reduction achieved***.

If there is insufficient knowledge about the effects that use of the technical, operational or organisational solutions may have on health, environment and safety***, solutions that will reduce this uncertainty shall be chosen.***

Factors which may cause harm, or nuisance to people, the environment or to financial assets in the petroleum activities shall be replaced by factors which in an overall evaluation have less potential for harm, or nuisance.

"

The first high-lighted part involves company requirements and acceptance criteria. By tradition, these are usually equity-based, expressed in risk estimates such as PLL, FAR, IR or F-N-curves. Different risk estimates and acceptance criteria will be discussed in greater length later.

The second high-lighted sentence has been broadly interpreted As Low As Reasonably Practical, the so called ALARP-principle[75]. This in turn is closely connected to the utility-based decision criteria such as CBA and CEA, as described in section 2.3.2 above.

The third high-lighted sentence includes a hybrid criterion combining technology- and utility-based decision criteria. In the guidelines to the law the paragraph it is explicitly explained that the BAT-principle applies, provided the costs are not significantly disproportionate to the risk reduction. This is essentially the "BATALARP" principle. A similar interpretation of the Norwegian offshore legislation has recently been presented by PTIL[76], which concludes that it is the obligation of the operator to prove that the best available technology is not sufficiently cost-effective, or else it shall be implemented. Hence that there is a reversed obligation to show that best available technology is too expensive, or expressed in another way, a reversed burden of proof.

The forth high-lighted sentence is a formulation of the precautionary principle, which means that the decision maker should avoid unnecessary uncertain factors when possible.

Quotation of §10 in the Facilities Regulation:

"

[74] www.ptil.no/regelverk/r2002/frame_e.htm
[75] PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*
[76] PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*

Section 10
Loads, load effects and resistance

The loads that may affect facilities or parts of facilities, shall be determined. ***Accidental loads and environmental loads with an annual probability greater than or equal to 1x10-4 shall not cause the loss of a main safety function, cf. Section 6 on main safety functions.***

When loads are determined, the effects of seabed subsidence above or in connection with the reservoir shall be taken into account.

Functional and environmental loads shall be combined in the most unfavourable way.

Facilities or parts of facilities shall be able to withstand the design loads and the probable combinations of these loads at all times.

"

This is clearly an equity-based decision criterion. In the guidelines it is clarified that the criterion should not be applied on the sum of all accidental and environmental loads, but rather on the different accidental load groups. One of these groups is the explosion load. For the purpose of this study the paragraph is interpreted as follows; the explosion probability for a loss of main safety function must not exceed 10^{-4}. In order to specify what the main safety functions are, the §6 of the Facilities regulation is quoted below.

Quotation of §6 in the Facilities Regulation:

"

Section 6
Main safety functions

The main safety functions shall be defined unambiguously in respect of each individual facility in order to ensure the safety for personnel and to limit pollution.

With regard to permanently manned facilities the following main safety functions shall be maintained in the event of an accident situation:

a) preventing escalation of accident situations so that personnel outside the immediate vicinity of the scene of accident, are not injured,

b) maintaining the main load carrying capacity in load bearing structures until the facility has been evacuated,

c) protecting rooms of significance to combating accidental events, so that they are operative until the facility has been evacuated, cf. Section 29 on fire divisions,

d) protecting the facility's safe areas so that they remain intact until the facility has been evacuated,

e) maintaining at least one evacuation route from every area where personnel may be staying until evacuation to the facility's safe areas and rescue of personnel has been completed.

"

It is important to note that the main safety functions are legally required to be unambiguously defined for the specific installation. A further discussion and guidance on explosion loads and the main safety functions is given in NORSOK S-001, section 7.1 and 10.8.

The paragraphs quoted above needs to be interpreted to clarify the regulations requirement and accept criteria, and an attempt is presented as follow:

1. The law requires the company to set up and comply with acceptance criteria that are in accordance with the regulation to demonstrate that the HES risks are low enough. As a bottom line, the annual probability of loss of main safety functions due to explosions should not exceed $1x10^{-4}$. The company acceptance criteria are often equity-based or technology-based by tradition. Direct objections against the use of utility-based acceptance criteria instead have however not been found. It concluded that utility-based criteria are acceptable as long as it can be showed that the safety is as good as or better than the minimum requirements.

2. Even when the criteria above are met, the operator is obliged to work with continuous safety improvement and risk reduction according to the BATALARP-principle. This means that the best available technology is regarded as the starting point, but there is some flexibility towards the

proportions of the risk reduction costs. BATALARP means that the burden of proof lies at the operator to show that the best available technology is too expensive or for any other reason not suitable in the particular case.

3. The decision maker should make decision according to the precautionary principle by avoiding uncertain solutions when possible.

Practically spoken, this interpretation means that the decision criteria should be a hybrid criterion based on the combination of the legally binding 10^{-4} criteria, the company acceptance criteria and a utility-based BATALARP accept criterion. This interpretation will be used throughout the report.

Quotation of §35 in the Facilities Regulation:
"

Section 35
Fire water supply

All facilities with overnight accommodation possibilities shall have sufficient fire water supply to fight fires and if necessary to dampen gas explosions.

Permanently manned facilities shall have fire water supply from fire pumps or other independent supply so that there is sufficient capacity at all times, even if parts of the supply are inoperative. Simpler facilities with overnight accommodation possibility shall have fire water supply from fire pumps or other equivalently reliable supply. Simpler facilities without overnight accommodation possibility shall have the necessary fire water supply to enable protection of the personnel against fires that may occur when the facility is manned.

The fire water system shall be designed so that a pressure stroke does not make the system or parts of the system inoperative.

On facilities where fire water is supplied from fire pumps, the pumps shall start automatically when there is a pressure drop in the fire main and when fire detection has been confirmed. It shall in addition be possible to start fire pumps manually from the central control room and from the prime mover. The prime mover for fire pumps shall be equipped with two independent starting arrangements. Automatic disconnection devices shall be as few as possible.

"Fire water piping shall be designed and located so as to ensure sufficient supply of fire water to every area on the facility.

"[77]

The interpretation of *sufficient* is given as the largest fire area together with the largest adjacent area[78]. It is important to examine if this is also sufficient to mitigate a gas explosion. The examination should also take into account that the deluge requirements differ between fire- fighting and mitigation of explosions. In example, the general area coverage rate to fight a fire is 10 litre/minute/m^2, while the UKOOA recommendation to mitigate explosions is 13-15 litre/minute/m^2 [79]. No explicit interpretation of the *necessity to dampen gas explosions* is given in the guidelines or in the NORSOK standards. The sentence is interpreted as follows: If the deluge system is to be used to dampen explosions it is necessary have a sufficient supply of fire water for this purpose.

Quotation of §36 in the Facilities Regulation
"

Section 36
Fixed fire-fighting systems

Fixed fire-fighting systems shall be installed in hazardous areas and in other areas representing a major fire risk. The systems shall in addition cover equipment containing significant quantities of hydrocarbons. The systems shall be designed so that fire-fighting can take place quickly and efficiently at all times.

[77] www.ptil.no/regelverk/r2002/frame_e.htm
[78] www.ptil.no/regelverk/r2002/Innretningsforskriften_Veiledning_e.htm#p35
[79] HSE (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*, page 46

> The systems shall be automatically activated on signal from the fire detection system. ***In the event of gas detection the systems shall be automatically activated if this can entail lower explosion pressure.***
> In areas where gas is used as extinguishing medium, warning systems shall be installed which give warning when gas is released.
> Manual activation of fire-fighting systems shall activate the general alarm of the facility. " [77]

The first sentence is important because it implies that fixed *fire-fighting systems* shall always be present in *hazardous areas*. Although the broader term fire-fighting system is not directly equivalent to deluge system, in practice deluge is standard. In other words; deluge systems can be expected in all hazardous areas. Hence; if deluge system is found to be suitable for explosion mitigation, it can be used in all hazardous areas with a minimum installation cost since the system in most cases is already installed to fulfil the regulations. See also the last sentence of §35 above.

In the second highlighted sentence *can* needs to be interpreted. Due to the explosion physics the effect of automatic deluge is expected to be situation dependent. This means that automatic deluge entail lower explosion pressure in some cases and higher in others. Small ignited gas leaks and fully confined explosions are generally expected to result in higher explosion pressures with deluge. On the other hand, larger ignited gas leaks are in many cases expected to be efficiently mitigated by deluge. No explicit interpretation of *can* is given, but there is a reference to the NORSOK S-001 standard. The standard will be discussed in greater detail in section 4.1.2 .

The end of the same sentence is important. The consequences are limited to the *explosion pressure*, which in itself is an ambiguous term that needs to be clarified. The broader term explosion load can be described in a number of ways, i.e. as the peak overpressure, impulse, dynamic pressure load, drag loads, pressure differences etc. Here it is only concluded that *explosion pressure* is interpreted as the explosion load represented by the peak stagnation overpressure and impulse.

If consequences are limited to the explosion load, other dimensions such as cost arguments are not valid in the decision context.

2.4.2 NORSOK Standards

Two NORSOK standards have been examined in the present study: S-001 *"Technical Safety"*and Z-013 *"Risk and emergencies preparedness analysis"*. A number of quotations relevant to the present study are presented and interpreted below. NORSOK S-001 *"Technical Safety"* could be seen as the ISO 13702 applied to the Norwegian offshore industry and connected to the Norwegian legislation. The standard is written in accordance with ISO 13702 and the standards are thought to be used together.

NORSOK Z-013 *"Risk and emergencies preparedness analysis"* describes risk analysis methods and a risk management framework. It also includes two informative annexes relevant for the present study: Annex A *"R*isk *acceptance criterias"* and Annex G *"Procedure for probabilistic explosion simulation"*.

Further, the following definition of *can* is given:

> "Verbal form used for statements of possibility and capability, whether material, physical or casual." [45]

This sentence is interpreted in relation to the §36 of the Facilities Regulations and the interpretation of *can* above. If *can* is strictly interpreted as the *possibility* for deluge to reduce any explosion pressure in any possible situation, it could be argued that automatic deluge should always be activated on detected gas release. This is however far from common sense since it does not reflect the risk-paradigm of combining probabilities and consequences, which is central in the Framework Regulations. A more balanced approach would be to weigh the positive and the negative consequences of automatic deluge with their respective probabilities. This 'risk approach' catches the dual nature of the *possibility* ***and*** *capabilit*y and will be used throughout this report.

> ”Mitigating measures to reduce possible explosion overpressures, such as start of deluge on confirmed gasdetection, shall be evaluated and considered for implementation.” [80]

This sentence adds another dimension of the §36 in the Facility Regulations, namely that the company is obliged to evaluate and consider the use of deluge on confirmed gas detection as an explosion mitigation measure. Note that the standard focuses on overpressure rather than the broader term explosion load. Another interesting detail covers the requirements of the fire water system to deliver the water sufficiently fast.

> ”The fire water system shall be operable at all times including periods of maintenance and shall ensure adequate supply of water for fire fighting. The system shall be designed and calibrated such that deluge nozzles will receive water not later than 30 seconds after a confirmed fire signal has been given.” [81]

Time is a critical factor for deluge to mitigate explosion; if ignition occurs before the deluge is present there will be no mitigation. Hence, in the analysis of deluge as an explosion mitigating measure the time from confirmed gas detection alarm to full area coverage is essential and needs to be carefully evaluated.

> ”Calculation of explosion overpressures related to the scenarios shall be performed with an advanced explosion simulator e.g. FLACS.” [82]

It is important to note that in spite of the methodological problems, weaknesses and difficulties to use CFD explosion modelling it is still recommended. The standard also recognises FLACS as an acceptable simulation tool.

A detailed procedure for probabilistic explosion simulation is given in the NORSOK Z - 013 standard *“Risk and emergency preparedness analysis”*, Annex G. In relation to deluge and explosion mitigation, the following quotation is of special interest:

> ”Deluge reduces high overpressure in congested areas, but has no such effect on scenarios with low pressure. As it is necessary to establish deluge before ignition, deluge will only be effective with late ignition (typically 20 s or later).
>
> The ignition probability will normally not increase when using deluge. As of today, FLACS seems to give a good prediction of tests with deluge. Thus it is acceptable to use FLACS for scenarios with deluge.”[83]

Besides confirming what has already been said, the quotation also recognises the use of FLACS to simulate scenarios with deluge. This makes it possible to simulate the explosion load with and without deluge and then use the results in the decision-making process. FLACS is thus concluded to be a suitable tool for the purposes of this report.

It should be noted that according to the standard the ignition probability is normally not increased, assuming all electric equipment is sufficiently protected from water ingress. This assumption simplifies the analysis a lot. At the same time it is crucial to check that the assumption is valid.

2.4.3 ISO 13702

Besides confirming what has already been said above, the standard makes an important point in that retrospective application of the standard only should be undertaken when reasonably practical. Reasonably practical is here interpreted as the BATALARP-principle and this will be used throughout this report.

[80] NORSOK (2000) *”S - 001 Technical Safety”*, rev. 3, page 31
[81] NORSOK (2000) *”S – 001 Technical Safety”*, rev. 3, page 28
[82] NORSOK (2000) *”S – 001 Technical Safety”*, rev. 3, page 32
[83] NORSOK (2001) *”Z – 013 Risk and Emergency preparedness analysis”*, rev 2, page 99 Annex G

2.4.4 HSE/UKOOA Standard

In the British sector of the North Sea, the British Health and Safety Executive (HSE) and the United Kingdom Oil Operators Association (UKOOA) cooperates to improve the offshore safety. In a joint project HSE and UKOOA have recently published a standard on the subject of avoidance and mitigation of explosions[84]. The standard and a number of related documents are free to download from the Internet[85]. An advantage of this standard in comparison to the ISO and NORSOK standards is that it includes results of recent scientific research. The discussion on deluge as an explosion mitigation measure is thus more detailed than the NORSOK and ISO. Some examples of important details are given in the three following quotations:

> "Deluge from standard MV or HV nozzles has been found to be suitable for reducing overpressure in congestion generated explosions. Congestion generated explosions are characterised by a fast moving flame front. This acts on the droplet to break it up and give a greater overall surface area so that it more efficiently achieves the quenching effect on the combustion mechanism." [86]

> "Where the overpressure is generated by confinement, for example in enclosed modules, there is not sufficient kinetic energy in the flame to break up the deluge droplets for them to be effective. In enclosed modules deluge will be ineffective in lowering overpressures and may even result in an increase due to the turbulence caused by the water spray." [86]

> "It is important that the deluge is employed as area coverage rather than equipment specific protection." [86]

The distinction between congestion and confinement generated explosion overpressure and the criteria for droplet break-up have will be discussed in greater detail in the following chapters. It is noted that standard nozzles have proved to be suitable in a number of full-scale experiments. [86]

[84] HSE/UKOOA (2003) *"UKOOA Fire and Explosion Guidance Part 1: Avoidance and mitigation of explosions"*
[85] www.fireandblast.com
[86] HSE/UKOOA (2002) "Updated guidance for fire and explosion hazards CTR 104 – Management of explosion hazard - rev A2" page 51 ff

3 Gas explosion basics and modelling aspects

3.1 Explosion basics

An excellent overview and introduction to gas explosion theory and safety is given by Bjerkvendt et al. A combustion explosion, such as a hydrocarbon gas explosion, can be defined as a

> *"violent combustion of flammable gas or mist that generates pressure effects due to confinement of the combustion-induced flow and/or the acceleration of the flame front by obstacles in the flame path."* [87]

The combustion process is an exothermic reaction of a fuel and an oxidizer, which often constitutes of the oxygen in air. As an example, the combustion of methane in air can be described as

$$CH_4 + 2O_2 + 7.52\ N_2 \text{ -------\}}\ CO_2 + 2\ H_2O + 7.52\ N_2 + \text{energy} \quad \textbf{[Eq. 5]}$$

Note that this is a considerable simplification of far more complicated chemical processes, including intermediate species and reactions. To initiate or sustain a combustion reaction the right proportions of fuel and oxidiser need to be in the same place at the same time with enough energy in order to react. Practically this means that the air and fuel needs to be mixed in order for the reaction to take place. Two different combustion regimes can be identified depending on when the mixing occurs: pre-mixed and diffusion flames. Pre-mixed flames indicates that the fuel and air are mixed before the reaction while diffusion flames are initially separate and burn in the region were they mix.[88]

The energy release term in Eq. 5 above can be described as the difference in enthalpies between the reactants on the left side and the products on the right side of the equation. If the energy release is sufficient, it may continuously heat and ignite more of the unburned fuel air mixture to keep the flame burning. Eq. 5 can however be manipulated to inhibit the reaction by adding other substances or changing the proportions of fuel and air. One example is when water is efficiently distributed by deluge. The water drops will then work as a heat sink and extinguish the flame. Evaporation and heating of water steam cost a lot of energy, and the temperature may be lowered enough to make the reaction impossible.

Another example is to change the proportions so that the mixture cannot sustain a flame, e.g. by diluting the fuel-air mixture with access air through ventilation. This is often expressed in the flammability limits. Outside the flammability limits the mixture cannot ignite because there is to much excess air or to much excess fuel. Below the lower flammability limit, LFL, the fuel concentration is to low to react. Above the upper flammability limit, UFL, there is not enough oxygen. For methane the flammability limits in air are 5% -15% by volume under normal conditions, but it should be noted that the flammability limits vary with temperature, pressure and oxygen concentration.[89]

A simple model of a premixed gas explosion is to describe it as a chronological chain of events: leakage, formation of an explosive cloud, ignition, explosion propagation, and in worst case, escalation. An illustration is given in Figure 15. Each event is dependent on the preceding events, which means that an explosion can be prevented by interrupting any of the events in the explosion chain. It is preferable to break the chain as early as possible; hence, the best thing would be to prevent all leakages. This is however not reasonably practical and to have a defence in depth against explosions all the events in the explosion chain should be counteracted.

---

[87] ISO (1999) *"Petroleum and natural gas industries – Control and mitigation of fires and explosion on offshore production installations – Requirement and guidelines"*, page 3
[88] Drysdale, D (1998) *"An introduction to fire dynamics"* 2nd edition, page 11
[89] Ibidem, page 75-107

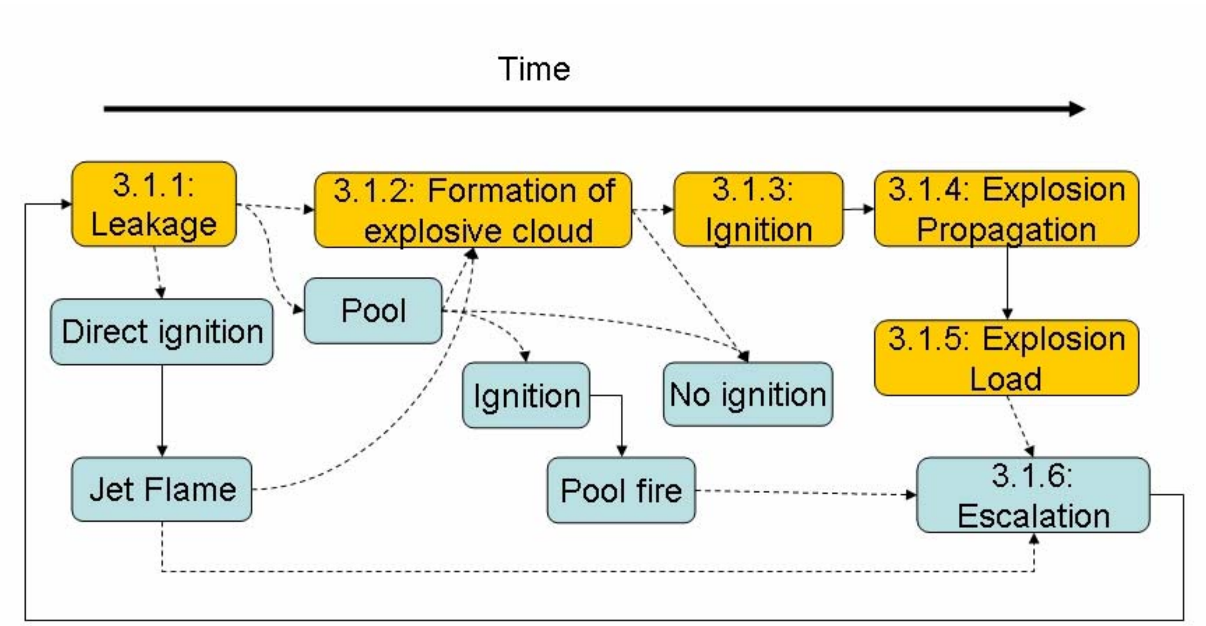


Figure 15: A simple model for premixed gas explosions. The explosion path is emphasised by the yellow colour. Note that the model shows the chronological order of events. Dotted arrows show different alternatives on how the chain of events might develop. The explosion events have been coloured yellow. The numbers represents the chapters of this section as a logical disposition.

Deluge works mainly as a safety barrier mitigating the explosion propagation, explosion load and to prevent escalation. It may however affect all of the events in Figure 15 above. It may affect the leakage frequencies by i.e. increased corrosion and maintenance. It may increase the turbulent mixing processes in the formation of explosive cloud and change the ventilation flows. The probability of ignition may be different due to electrical equipment short circuit and the cooling effect of deluge on hot surfaces. The effect of increased turbulence on ignition sensitivity needs to be addressed and the possibility of static electric sparks examined and possible ruled out. Further, it is possible that deluge may extinguish a jet flame with might then develop into a premixed gas explosion.

3.1.1 Leakage

The so called RNNS-project[90] , run by PTIL, has the aim of monitoring the offshore risk level and trend development on the Norwegian shelf. As an introduction to the problem of hydrocarbon leakages, a bird-eye view over the total number of reported leakages on the Norwegian shelf is presented in Figure 16.

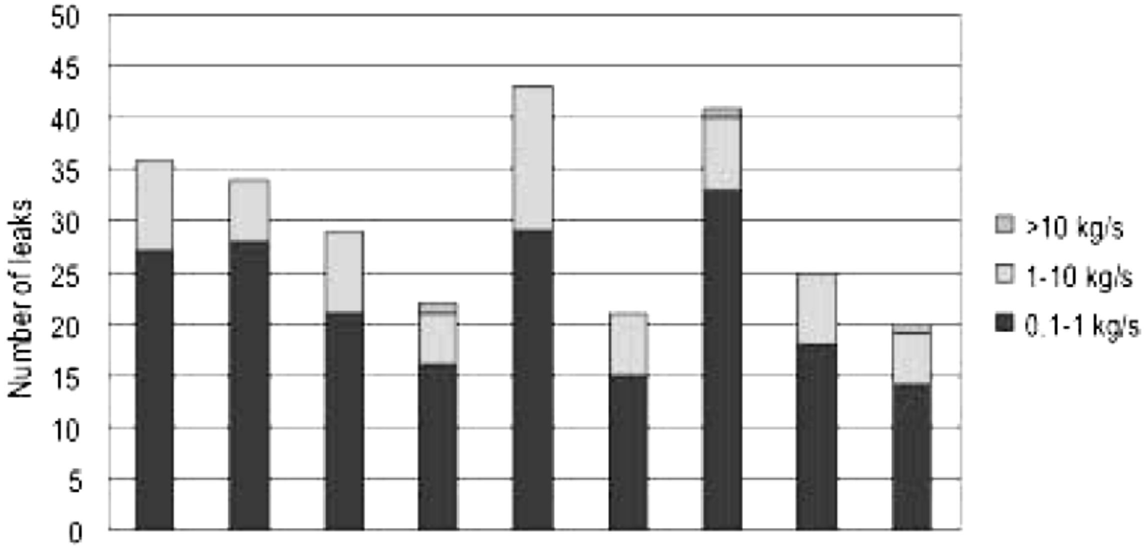


Figure 16: Diagram showing the numbers of leakages during 1996 – 2004 on the Norwegian shelf, distributed over three mass flux classes.

The diagram in figure 16 shows the distribution of leakages on three different classes of mass flux and have been taken from a RNNS-report from 2005. A total of 271 leakages were recorded in the period during 1996-2004.[91]

An informative work covering the underlying physics of leakages and gas spread is given by FOA[92] . Leakages offshore can be divided between liquid, gaseous or two-phase. Due to evaporation there may be a possibility of forming of an explosive gas cloud even if the leakage is mainly liquid. Under specific circumstances an explosive atmosphere of mist is possible.[92] It is however conservative or even very conservative to approximate aerosol mist explosions with gas explosion, according to HSE[93].

From a risk view leakages can be described as a set of possible combinations of probability and consequences. A suitable measure of the leakage consequences is the mass flux [kg/s]. It is a complicating fact that the mass flux is often transient. A way to further characterise the consequences of a leakage is thus to express it as a function of mass flux over time, which also makes it possible to calculate the total leakage mass.[94] Since the mass flux normally decreases over time, it can in many cases be considered conservative to use the initial mass flux as a constant in consequence calculations. Caution should however be taken not to underestimate the duration of a leakage with this assumption. The mass flux is dependent on a number of scenario specific parameters such as pressure differences, temperature, size of leakage, leakage point, density, reservoir volume etc. The possible combinations of these parameters are endless and it is necessary to simplify the complexity into a number of mass flux classes. A leakage risk distribution can then be achieved by attaching each class with a probability, preferably in terms of an estimated annual leakage frequency [year^{-1}]. For the purpose of probabilistic explosion modelling, a recommendation from the NORSOK standard Z -013 is to use nine classes between 0,1 kg/s - >60 kg/s [95].

[90] RNNS is a Norwegian abbreviation for Risikonivå på norsk sokkel (Risk level on the Norwegian shelf)
[91] PTIL (2005) *"Trends in risk level 2004 – Summary report"*.
[92] FOA (1998) *"Toxic and inflammable/explosive chemicals – a Swedish Manual for Risk Assessment"* , rev. 2
[93] Bull (2004) *"A critical review of post Piper Alpha developments in explosion science for the offshore industry"*
[94] DNV , RF (2002) *"Årsaksanalyse av prosesslekkasjer"*
[95] NORSOK (2001) *"Z-013 Risk and Emergency preparedness analysis"*, Annex G

The leakage frequency of each class can be estimated using statistical methods, experience and expert judgements.

Generic frequency analysis is however of limited value, since substantial differences between operators and installations have been showed[96]. This is shown in Figure 17 to the right. The statistical material for the specific installation alone is however often too small to be suitable for a statistical analysis. To increase the quality of the leakage frequency approximation, expert judgement should be used. This can be done by using Bayes theorem.

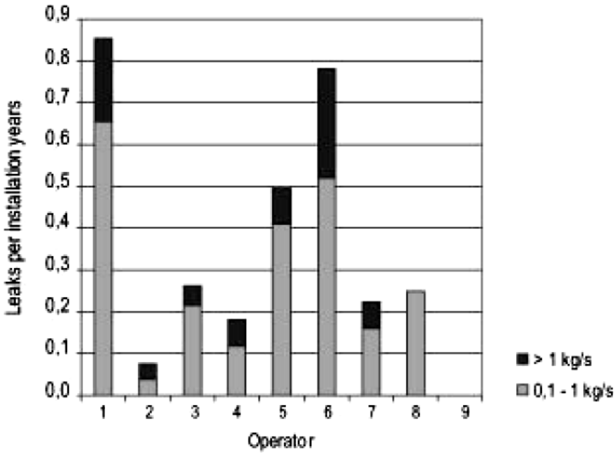


Figure 17: Diagram over the average leak frequency per installation year for nine anonymous operating companies on the Norwegian shelf[96]

A systematic and more accurate method to estimate the leakage frequency for an offshore platform module is to first count the process equipment and pipe length. Then, an appropriate leakage frequency contribution to each class can be attached to each item. Finally the leakage frequencies for all equipment and classes can then be summed up to get the overall leakage frequencies distributed over the different mass flux classes.

It is also recommended to include information on the causes in the analysis when estimating the leakage frequency distribution. An informative work covering the causes of leakages is given by DNV/RF[97]. The benefit of analysing the causes is two-folded. Besides better understanding and thus more accurate leak frequency estimates, the result of a cause analysis can also be used directly to reduce the leakage risk more efficiently. A full leakage cause analysis is however outside the present scope. A detailed description of a cause analysis method is found in the DNV/RF report[97].

It is interesting to note some statistic findings on leakage causes from the RNNS report[98]. An illustration is showed in figure 18 to the right.

Normal operations, which were the cause of leakage in 35% of the cases, are to a high degree related equipment failures and can thus be explained in terms of corrosion, erosion and material fatigue. Pipes, flenses and valves brings the highest contribution of equipment related leakages.

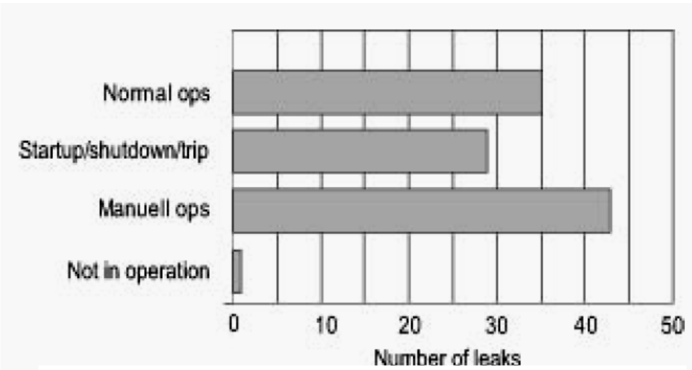


Figure 18: The diagram illustrates how leaks happened during the period 2001-2004. It should be noted that some leakages hade more than one cause. From PTIL (2005) *"Trends in risk level 2004 – summary report"*

The remaining cases are mainly related to manual operations and start/shutdown/trip. [96]These are more related to failures in operations and procedures. The importance and necessity of proper maintenance is also emphasised in the PTIL report.[99] For the present study it is also noted that the long term effect of increased use of deluge may lead to increased corrosion and hence increased leakage frequencies if maintenance is not satisfactory. This means that the suitability of an increased deluge usage is dependent on the quality of inspection and maintenance. It is also concluded that this might add an increased maintenance cost, and that the leakage frequency might increase due to increased process start/shutdown during maintenance. Also the average population might be increased with increased maintenance.

[96] PTIL (2005) *"Trends in risk level 2004 – Summary report"*
[97] DNV , RF (2002) *"Årsaksanalyse av prosesslekkasjer"*
[98] PTIL (2005) *"Utvikling i risikonivå - norsk sokkel Fase 5 hovedrapport 2004*" page 170 ff.
[99] PTIL (2005) *"Utvikling i risikonivå - norsk sokkel Fase 5 hovedrapport 2004"* page 170 ff.

Another type of leakages that need to be considered is well incidents and subsurface leakages.
An excellent overview of barriers and problems with well incidents, together with a recommended risk analysis approach is given by Miura et al.[100]. A diagram showing the totality of possible fluid paths between the well and the environment is showed in Figure 19 to the right.

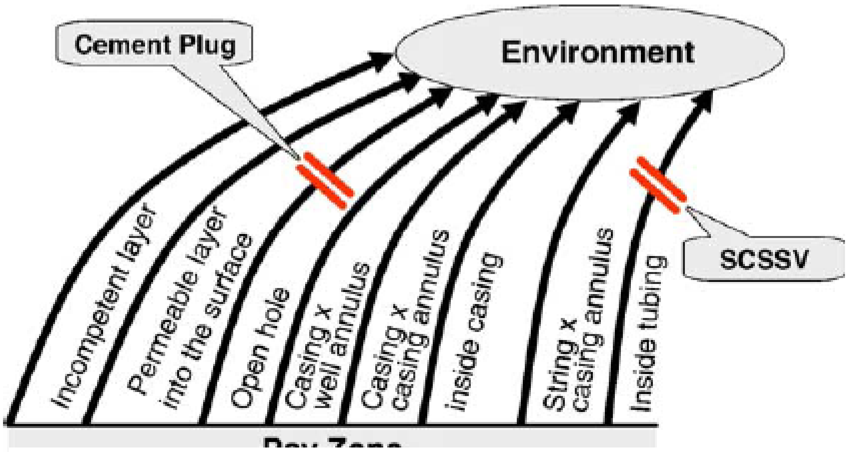


Figure 19: Totality of possible fluid flow paths between well and the environment, with two examples of well safety barriers. From Miura et a.l.[100]

The NORSOK standard D-010 [101] contains more information and references on the well incidents. This is however outside the scope of the present study. The relevant conclusion is that process leaks, well incidents and subsurface leaks all contribute to the overall explosion risk and should thus be taken into account.

3.1.2 Formation of explosive cloud

After the leakage is initiated the gas is dispersed into ambient air. At some point the fuel-air mixture concentration is within the flammability limits, which means that the cloud is explosive. The flammability limits of methane are under normal conditions ~5-15% by volume[102], which means that within these limits the methane-air mixture can ignite and explode. The formation of the explosive cloud is critical for the further stages of an explosion; the ignition probability is dependent on the size and concentration of the explosive cloud that might come in contact with ignition sources. The explosion propagation and hence also the explosion load is dependent on the size, shape and concentration of the cloud. Mixtures close to stoichometric proportions are generally easier to ignite produce higher pressures and have higher flame speeds.

The cloud can be characterized with size, shape and concentration profile. The dispersion of fuel and formation of an explosive cloud depends on the combination of a number of parameters for the specific situation such as the leakage mass flux, physical properties of the fuel, flammability limits etc.

Other important factors are ventilation air exchange, wind speed and direction, and the relation between wind and leakage direction. For example, a situation of a small leakage combined with a strong wind and high ventilation will create a small explosive cloud since the leakage is quickly diluted by air. On the other hand, a large leakage with low ventilation and wind speed might result in a small explosive cloud as well since the concentration of a large part of the cloud is above the flammability limits. Ventilation is often complex and non-intuitive, and even well ventilated modules can have 'pockets' where an explosive cloud might build up. A good introduction to the subject of ventilation, dispersion and CFD is given by HSE[103]. It is free to download from the HSE homepage and contains detailed experimental data.

Ventilation, dispersion and the development of a leakage can be simulated with CFD-models. The principles, advantages and problems with CFD compared to other modelling approaches are discussed in greater detail in section 3.2.3 . It is however noted that a number of scientists have showed substantial advantages of CFD dispersion modelling compared to other common models in complex geometries[104,105]. A detailed methodology for ventilation and dispersion simulations with CFD is given in NORSOK Z-13 G.

[100] Miura, K et al (2006) *"Characterization of operational safety in offshore oil wells"*
[101] NORSOK (2004) *"D-010 Well integrity in drilling and well operations"*
[102] Drysdale (1998) *"An introduction to fire dynamics"* page 77 table 3.1.
[103] HSE (2005) *"Natural ventilation on offshore platforms"*
[104] Sklavounos (2006) "*Simulation of Coyote series trials—Part I: CFD estimation of non-isothermal LNG releases and comparison with box-model predictions"*
[105] Riddle (2003) *"Comparisons between FLUENT and ADMS for atmospheric dispersion modelling"*

The effect of deluge on ventilation and dispersion is complex and no accurate theories or models seem to be available yet. At present HSE is working on a research project to evaluate the effects of deluge on ventilation and dispersion.[106] Brief descriptions of the LICOREFLA project experiments examining the effect of deluge on dispersion is presented in Gexcon and FABIG newsletters[107,108]. The conclusions reported for these experiments is that deluge will increase gas mixing and turbulence, especially for leakages with low momentum. Based on this experimental evidence it is assumed that deluge will increase dispersion, mixing and turbulence. For the majority of leaks, initiated deluge is expected to have a net beneficial effect on the total explosion risk since the initiation of deluge will help dilute the explosive gas cloud with excessive air. It must however be recognized that for larger leakages where a part of the cloud has a concentration above the higher flammability limit, the increase of gas mixing due to the activation of deluge may in fact increase the explosive cloud.
Note that in parallel to the activation of deluge, other safety measures will be initiated such as closing segment isolation valves, sending hydrocarbons to the flare and closing down potential ignition sources.

3.1.3 Ignition

Although as many as 271 leakages with a mass flux above 0.1 kg/s was recorded by the RNNS project on the Norwegian shelf between 1996-2004, none of them led to explosions. This can be explained to a large extent by successful control of ignition sources. This does not mean the ignition probability is infinitesimal low or negligible; there have just not been enough rolls with the dice. [109]

Based on statistics from the British sector it is possible to get an idea of the order of magnitude on ignition probabilities. During the years 1992-2004, 164 out of 2814 reported hydrocarbon leakages ignited, corresponding to an average ~5.8%. It is further interesting to note that out of the 164 ignitions, 120 ignited directly while only 44 led to delayed ignition. Assuming that direct ignition will lead to a jet-flame rather than an explosion, this means that the delayed ignition probability is even lower, ~1,6%. [110]

Experience from the British shelf suggests that the ignition probability depends heavily on zone classification. For leakages in areas classified as zone 1 the average ignition probability was only ~3%, for zone 2 ~6% and for unclassified zones ~16%. This can be explained with higher the ignition source control in zone 1, which is defined as an area where an explosive atmosphere is likely to occur occasionally during normal operation. Zone 2 is defined as an area in which an explosive atmosphere is not likely to occur in normal operation, and if it does occur is likely to do so only infrequently and will exist for a short period only such as equipment failure, breakdown or service and maintenance. This includes all kinds of leakages such as oil, condensate, 2-phase and gas in all areas. For gas releases alone the corresponding numbers were 46 ignited to 1526 gas releases, an average 3% ignition probability.[110]

It should be noticed that there are differences between the Norwegian and British shelf. There might also be substantial differences in statistical gathering and interpretation that implies that the numbers cited above should be used with great caution. A recommended overall delayed ignition probability of 3.2% is given by UKOOA for the use of explosion calculations and event trees.[111]

[106] Connoley, S (2006) Mail correspondence
[107] Gexcon (2003) *"FLACS-Newsletter Fall edition 2003"* , available at www.gexcon.com
[108] FABIG (2003) *"Water deluge and influence of dispersion"*, FABIG Newsletter August 2003, issue No 36 Article R485
[109] PTIL (2005) *"Utvikling i risikonivå - norsk sokkel Fase 5 hovedrapport 2004*"
[110] HSL (2005) *"Offshore ignition probability arguments"*
[111] HSE/UKOOA (2003) *"UKOOA Fire and Explosion Guidance Part 1: Avoidance and mitigation of explosions"*

Minimum Ignition Energy
The ignition sensitivity of a fuel is often characterized as the minimum ignition energy, MIE. The MIE can be defined as the lowest energy capable of igniting the fuel – air mixture. The MIE for quiescent natural gas/air mixture is approximate 0.24-0.28 mJ, depending on the composition of natural gas which normally consists of mainly methane, ethane and propane. Methane is dominant, often with a percentage of ~80% or more. Besides the composition of the fuel, the energy required to ignite a fuel-air mixture is dependent on a number of other parameters. In fact, the effective ignition energies spans over several orders of magnitude depending on the situation. Two relevant factors are discussed below in the light of their relationship with deluge.

Gas cloud concentration, MIE and deluge
Higher ignition energy is required to ignite a fuel-air mixture far from the stoichiometric proportions. Deluge can contribute to dilute the cloud with air, making it harder or even impossible to ignite. On the other hand the effect might be the opposite if the cloud is sufficiently large and has a large volume above the upper flammability limit. Then the introduction of a deluge might increase the size of the explosive cloud and ignitability by mixing the fuel with air.

Initial turbulence and deluge
The fuel air mixture will normally not be totally quiescent. It has been found that explosive atmospheres with a higher initial turbulence are more difficult to ignite then less turbulent, quiescent clouds.[112] From this perspective, is deluge expected to have a beneficial effect on ignition sensibility by increasing initial turbulence and thus the energy threshold for effective ignition.

The relation between ignition sources and deluge
The relations between the most common ignition sources and deluge are discussed in the section below. Special attention have been put to examine the generation of static electric sparks by deluge, since there have been some discussion that deluge in it self could be an ignition source.
The examined ignition sources include[113]:

i. Hot surfaces
ii. Flames, hot gases and particles
iii. Mechanically generated sparks
iv. Static electricity
v. Electric apparatus, sparks and arcs

- **Hot surfaces**

The capability of a hot surface to ignite a fuel-air mixture increases with surface temperature and area. Examples of hot surfaces includes exhaust pipes, radiators, heating coils but also all mechanical and machining processes which might convert mechanical energy to heat. This includes all moving parts in bearings, shafts, pumps and compressors that may gather heat due to friction, especially if the lubrication is inadequate.[113]

Initiated deluge is expected to have a beneficial effect on the ignition probability contribution from hot surfaces due to cooling.

- **Flames, hot gases and particles**

An important contributor to this category of ignition sources is cutting, welding and welding beads during maintenance and reparations. Burners, like the flare on offshore platforms, are included in this category. Fires and fire gases can act as ignition sources for premixed fuel-air clouds to initiate explosions. Flames, even small ones, are very efficient ignition sources. For this reason, smoking is forbidden on most offshore installations.[113]

Initiated deluge is expected to have a beneficial effect on the ignition probability contribution from flames, hot gases and particles.

- **Mechanically generated sparks**

In friction, impact or abrasion processes such as grinding, particles can become separated from the solid material. These particles may have a high temperature from the energy used in the separation process. If the particles consist of material that can undergo an oxidation process, such as iron and steel, this might further

[112] Eckhoff (2003) *"Dust explosions in the process industries"* 3rd edition
[113] NSF (1997) *"Explosive atmospheres Explosion prevention and protection Part 1: Basic concepts and methodology",* NS-EN 1127-1

elevate the temperature and create a mechanical spark. Mechanical sparks also include so called thermite sparks, in which a reaction between rust and aluminium can create a highly energetic sparks. Even other metals, especially advanced metals and alloys with titanium, are susceptible to mechanical sparks.[113]
Deluge is generally not expected to effect the ignition probability of mechanically generated sparks.

- **Static electricity**

During 1969 three serious explosions occurred when supertankers were being washed out with high pressure seawater jets. The investigations of the accidents later showed that ignition had occurred due to static electricity sparks.[114] A question therefore arises if deluge can contribute to static electricity spark ignition of explosive natural gas and air mixtures.

The generation of static electric spark ignition can be explained in four steps as presented in figure 20 . When materials come in contact and are then separated, the balance of electric charges between the materials may change in the separation process. If the equipment is not grounded, the separation process might lead to a build-up of electric charges. When the potential is sufficiently large to overcome the electric breakdown strength of air, which is approximately 3000 kV/m, an electric spark may propagate between the charged object and earth.[114]

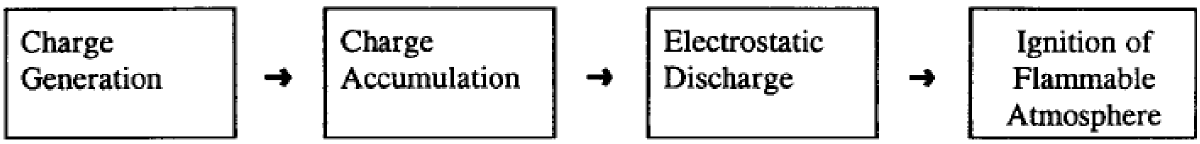


Figure 20: A simple model of static spark ignition. From HSE (1995) *"Electrostatic hazards associated with water deluge and explosion systems offshore"*

If the energy of the spark is above the minimum ignition energy, MIE, of the fuel-air mixture present the mixture ignites.

An analysis conducted by HSE[114] of the electrostatic ignition hazards of initiated deluge on natural gas releases concluded that the charge accumulation is not sufficient to generate incendiary sparks. This conclusion is based on the assumptions that all equipment and personnel is sufficient and effective grounded and that the formation of large slugs of water is negligible.[114]

Another experimental investigation conducted by Tolson came to a similar conclusion[115]. It is interesting to note that the test included a wide variety of deluge and spray nozzles and that a maximal pressure of 7 bar was used in all tests. The HSE result suggested maximal potentials between 9-35 kV and electric fields strengths between 9-18 kV/m. These results are in accordance with the experimental results of Tolson, who found the electric field strengths to be less than 200 kV/m in all tests. These values should be compared to the electric breakdown strength of air ~3000 kV/m, which means there is an order of magnitude between the calculated and measured values and the limit.[114,115]

Based on these reports, it is concluded that the contribution of ignition sources due to electrostatic sparks from the deluge is negligible in the case of natural gas and air mixtures.

- **Electrical apparatus, sparks and arcs**

The use of deluge increases the probability for moist to enter electrical equipment. If moist enters electrical equipment it may damage it and create a spark ignition risk. For this reason, it is recommended to use water-protected electrical equipment.

Based on the assumption that suitable water-protection is in place, the increase in ignition probability due to deluge induced moist in electrical apparatus creating electrical damage and sparks can be neglected.

---

[114] HSE (1995) *"Electrostatic hazards associated with water deluge and explosion systems offshore"*
[115] Tolson (1989) *"Examination of possible hazards arising form the use of water spray barriers to disperse flammable vapours"*

- **Other ignition sources**

Besides the ignition sources mentioned above, there are additional ignition sources that are considered to be less probable and important in relation to deluge. They have not been examined further, but are listed for completeness[116]:

- Lightning
- Electromagnetic waves
- Ionizing radiation
- Ultrasonics
- Adiabatic compression and shockwaves
- Exothermic reactions, including self-ignition

3.1.4 Explosion propagation

If ignition a gas cloud occurs, the reaction front moves through the cloud; this is called explosion propagation. It can be described as the continuous ignition of unburned gas as the flame moves through the cloud. There are two different modes of explosion propagation, namely deflagration and detonation. Deflagration is the most usual form of accidental explosion propagation. Deflagration means that the combustion wave propagates with subsonic velocities relative to the unburned gas. This means that the burning velocity is lower than the speed of sound in the unburned gas. Burning velocity should not be confused with flame speed. Flame speed is defined as the speed of flame propagation in relation to a fixed observer. Burning velocity, on the other hand, is the velocity of the flame front in relation to the unburned gas. The continuous ignition of unburned fuel-air mixture is mainly due to heat transfer from the hot reaction products to the unburned cloud.[117]

In contrast, detonation means that the shockwave of the explosion is coupled to the flame and that the flame moves above the speed of sound. Detonations are very rare, and are most likely to involve a fuel-air mixture with high burning velocity, such as hydrogen. Under specific conditions, such as explosions in pipes, a deflagration may accelerate and undergo a transition into detonation. Detonation and deflagration to detonation transition is however outside the scope of the present study since natural gas is very unlikely to detonate.

The combustion process of the explosion releases chemical energy which increases the temperature. This temperature increase in turn leads to an increase in pressure, decrease in density (expansion) or a combination of both in accordance with the ideal gas law.

$$\frac{p}{\delta} = RT \qquad \textbf{[Eq. 6]}$$

Where
P = Pressure [Pa]
δ = Density [mol/m^3]
R = Ideal gas law constant [$Pa*m^3*mol^{-1}*K^{-1}$]
T = Temperature [K]

This is corresponds to whether the explosion is fully confined, unconfined or only partly confined. In a fully confined situation expansion is not possible, and instead the pressure will rise with the temperature. This is called constant volume combustion and it can be shown that a stoichometric hydrocarbon/air mixture that explodes in a fully confined system generates a static pressure of approximate 8 times the initial pressure. Due to dynamic effects, it may however be even higher peak overpressures. The opposite of constant volume combustion is constant pressure combustion, where the gas volume increases instead of the pressure. An illustration is given in figure 21 .

[116] NSF (1997) *"Explosive atmospheres Explosion prevention and protection Part 1: Basic concepts and methodology",* NS-EN 1127-1
[117] Bjerkevendt et.al. (1997) *"Gas Explosion Handbook"*

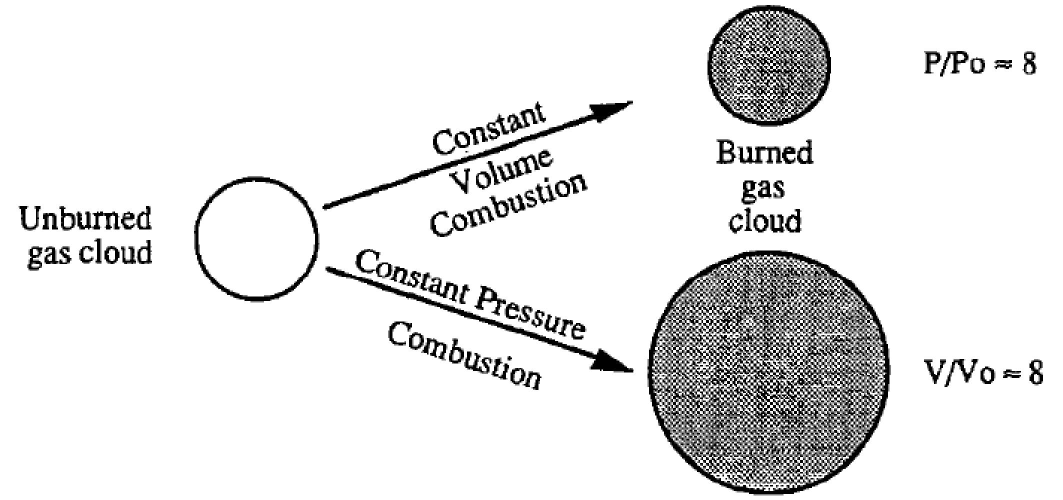


Figure 21: Constant volume and constant pressure combustion respectively. From Bjerkevendt et al (1997) *"Gas explosion handbook"*

For accidental explosions in offshore modules the third possibility of combined pressure and expansion is especially interesting. If the cloud is partly confined the temperature increase leads to gas expansion behind the flame which pushes the unburned gas ahead of the flame. This motion creates a turbulent flow in the unburned gas, which increases the heat transfer and mixing between unburned and burned gas. Further, the turbulence increases the flame surface. The turbulence thus increases the burning rate, which increases the thermal expansion and hence the turbulence ahead of the flame. This creates a positive feedback loop that can accelerate the flame to very high flame speed and burning velocity. This mechanism is often referred to as the Schelkin mechanism after the Russian researcher who first described it.[118] An illustration of this feedback loop is given in figure 22 .

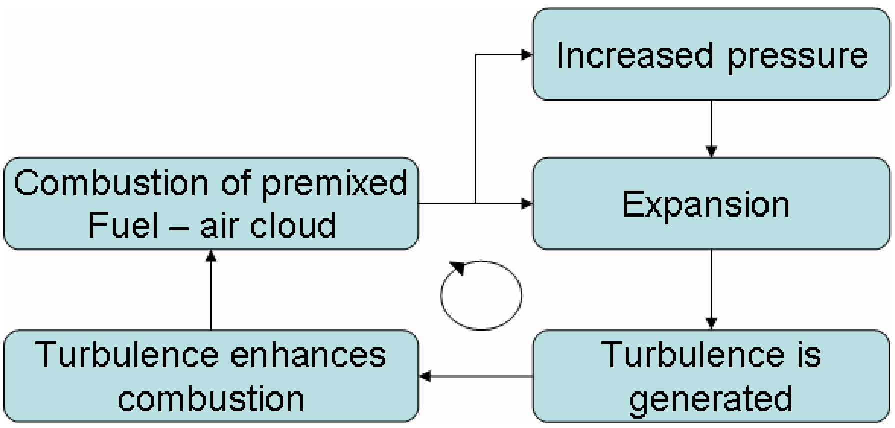


Figure 22: An illustration of the Schelkin mechanism. From "Gas Explosion Handbook"

Because of the Schelkin mechanism, turbulence generation is a very important process for gas explosion propagation. Unfortunately, turbulence and turbulence generation in explosions are difficult to predict and model. Experiments show that turbulence generation is related to congestion, i.e. equipment, piping and grating. It is the interaction between congestion and the flow that generates the turbulence.[118] A description of the attempts to model turbulence with computational fluid dynamic (CFD) techniques will be described in chapter 3.3.

[118] Bjerkevendt et al (1997) *"Gas explosion handbook"*

3.1.5 Explosion load and structure response

In the NORSOK S-001 standard, explosion load is defined as:

> *"The pressure generated by violent combustion of a flammable gas or mist which generates pressure effects due to confinement of the combustion induced flow and/or the acceleration of the flame front by obstacles in the flame front."*

In order to clarify this sentence it is necessary to investigate what is meant with pressure. Pressure is the force per area that is exerted in all directions. It is usually expressed in Pa, which is equal to Nm^{-2}, kPa or bar. The relation between Pa and bar is that 10^5 Pa = 100kPa = 1 bar. In technical drawings, reports and articles pressure is reported either as the absolute pressure or as the pressure above the atmospheric pressure. The last is often called gauge pressure. By connotation, absolute pressure is often denoted bar(a) and gauge pressure with bar(g).

In fluid dynamics terms pressure is often separated between the static, the dynamic or the stagnation pressure. Static pressure is more strictly defined as "the normal component of stress, the force per unit area, exerted across a surface flow moving with the fluid, especially across the surface which lies in the direction of the flow" [119]. It is what is normally understood and perceived as pressure.

The dynamic pressure, or drag, is due to the drag force that a flow induces on an object in that flow. Strictly it is defined as the "the pressure increase that the moving fluid would have if it was brought to rest by isentropic flow against a pressure gradient." The dynamic force can be described and estimated by the following mathematical expression:[119]

$$F_{DRAG} = C_D \times A \times 0.5 \rho u^2 \quad \textbf{[Eq. 7]}$$

where F_{DRAG} = Dynamic drag force
C_D = Drag coefficient
A = Projected area of the object normal to the flow
ρ = Density of the flowing media
u = Flow velocity

The term $0.5\rho u^2$ in the above equation is the mathematical expression of the dynamic pressure. A detailed description of the explosion drag forces and their effect on process equipment is provided by Corr et. al[120]. The article also concludes that drag forces may be present both in the expansion and contraction phases of the explosion, and that the contraction drag forces in some cases are of greater concern than the expansion phase. A number of equations to be used when calculating the drag force load on different objects such as grating and pipes are presented, and a discussion how drag force calculations can be incorporated with the CFD code FLACS.[120]

The stagnation pressure is the sum of the dynamic and static pressure according to the following expression[119]:

$$p_{STAG} = p_{STAT} + p_{DYN} \quad \textbf{[Eq. 8]}$$

While larger objects and structures are mostly subject to the static peak overpressure, smaller inventories such as piping are more sensible to drag forces and the dynamic pressure from the explosion wind. The reason for this is that larger objects may experience the differences or gradients in static pressure, while for smaller equipment these are very small in comparison to the dynamic pressure contribution. For small equipment, the static pressure works equally on all sides and balances itself.[119, 120]

The most important parameters of the explosion load are the maximum stagnation pressure, the pressure rise time dP/dt, load duration, the positive impulse and the negative impulse. The impulse is defined as the time integral of pressure and takes the pressure rise time, duration and maximum overpressure into account.

[119] Bjerkevendt et.al. (1997) *"Gas Explosion Handbook"*
[120] Corr, R. B. et. al. (1998) *"Gas explosion generated drag loads in offshore installations"*

An illustration of a typical pressure-time curve for a gas explosion is shown in Figure 23 . [121]

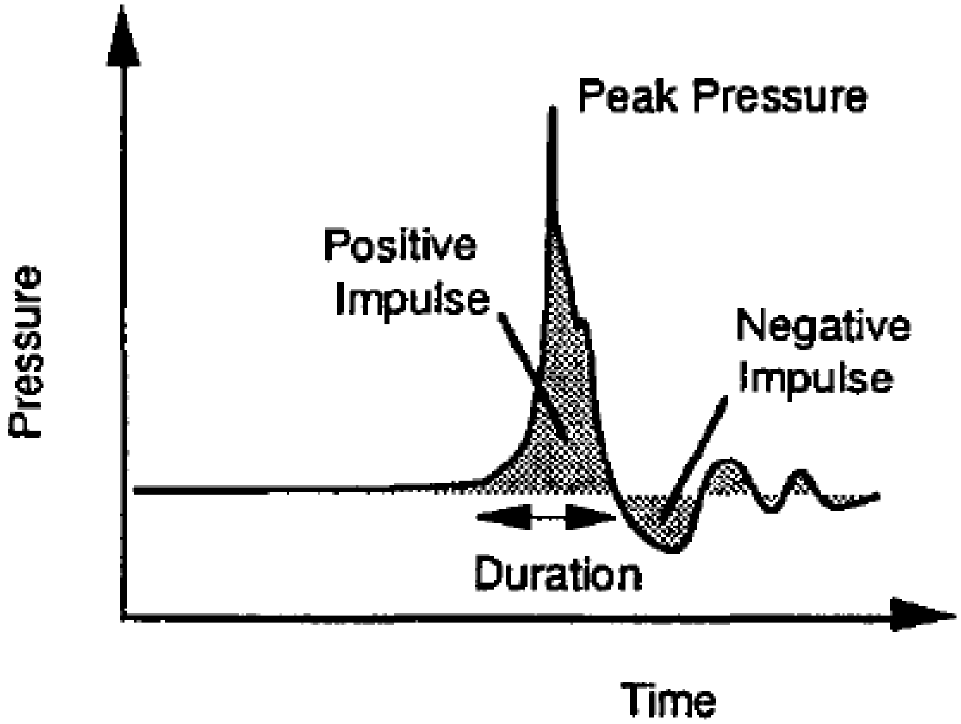


Figure 23: Schematic description of a typical pressure-time curve for a gas explosion. Note that the definitions are explained in the picture. Bjerkvendt et. al. (1997) *"Gas explosion handbook"*

Some of the most important aspects in relation to explosion load include[121]:

i. Ignition location and strength
ii. Congestion and turbulence generation
iii. Confinement
iv. The properties of the exploding gas cloud such as size, gas composition and concentration profile.
v. Initial pressure and turbulence
vi. Structure response

Structure response
The explosion load is closely connected with the structure response. Historically most of the information and research on structure response to explosion load has been focused on military purposes, such as designing blast resistant bunkers. This includes the development of the analytical single-degree-of-freedom (SDOF) models, which have been used for a long time before the more modern and powerful non-linear finite element methods (NLFEM) were developed. Together SDOF and NLFEM are the most commonly used methods to calculate structure response to explosions. Both are acceptable for calculating structure response to explosions according to NORSOK Z-013. A recent review of more advanced single-degree-of-freedom analysis models is given by Morison.[122] Improved simplified response methods to blast loadings, which can be seen as a sophisticated single-degree-of-freedom models, have also recently been presented by HSE[123,124].

A third possibility is to use the modal response spectrum model, which has been described a HSE report[125]. The latter method can be said to lie somewhere between the simple SDOF and NLFEM analyses in complexity. The concept of the modal response spectrum model is to extract Eigenvalues and Eigenvectors which are then used to estimate the structure response at each frequency. Since this function is included in all of major NLFEM software suites, it may be seen as a less resource demanding alternative than a full NLFEM analysis while it still

[121] Bjerkvendt et. al. (1997) *"Gas explosion handbook"*
[122] Morison (2006) *"Dynamic response of walls and slabs by single-degree-of-freedom analysis – a critical review and revision"*
[123] HSE (2006) *"Improved simplified response methods to blast loading"*, RR435
[124] HSE (2006) *"Design, materials and connections for blast-loaded structures"*, RR405
[125] HSE (1999) *"Review of Analysis of Explosion Response"*, OTO 98174

takes the important features of dynamic response into consideration. More details on the modal response spectrum model, and a review of SDOF hand calculation and NLFEM methods is found in the HSE report.[125]

In order to illustrate the relation between explosion load and dynamic structure response a very basic simple-degree-of-freedom model applied to an example It should be underlined that the model in the example is deemed to be to inaccurate to be used for practical purposes and it is only thought to illustrate how the explosion load and structure response relates to each other. The example shows the importance of dynamic structure response, and the difference between static and dynamic structural response. The example, illustrated in figure 24, is originally from Bjerkvendt et. al.[126]

A house subjected to an explosion load can be reduced to a simple spring model, as shown in figure 24. The explosion load is simplified to a triangular pressure-time pulse and represented by the force pulling the spring. The structure response is the displacement of mass. It will therefore depend on the maximal force, the mass and the natural frequency of the system. The natural frequency of a structure and the explosion load duration may interact in a way that increases the maximum displacement of mass, especially if the ratio between the duration of the load and the natural frequency is very large. Therefore, the displacement of mass may be greater for dynamic responses than the static structure response corresponding to a constant load. For this reason, the characteristics of the explosion load such as the duration, pressure-time curve and impulse are important, and it is not considered conservative to only use the static structure response unless the dynamic structure response effects have been shown to be negligible.[126]

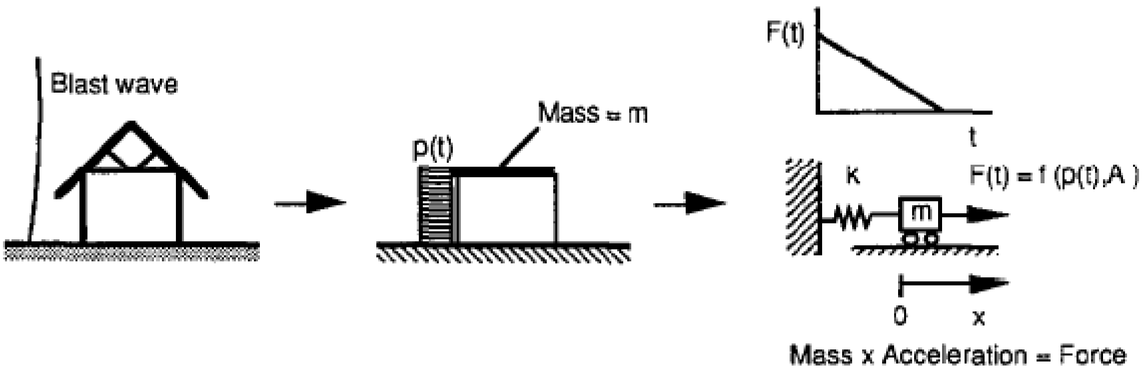


Figure 24: An example of how a house can be reduced to a single-degree-of-freedom system
The example and illustration is from Bjerkvendt et. al. (1997) *"Gas explosion handbook"*

A simplified method of estimating the dynamic structure response based on full-scale experiments has recently been presented by HSE[127]. This method, based on a response spectra diagram, requires an estimate of the natural period of vibration of the target structure and its allowable ductility. A triangular pressure/time load is assumed. The methods allows for a more efficient design as it accounts for ductility. Allowable ductility can be explained as the deformation a structural element can sustain without rupturing or collapsing. A suggested expression for the allowable ductility is a multiple 'μ' of the effective elastic yield displacement. The dynamic load factor (DLF) can then be estimated from the response spectrum diagram as a function of the allowable ductility and the ratio between explosion load duration (td) and natural frequency (T). The dynamic load factor is here defined as the ratio between the required static resistance and effective explosion load. An example of response spectra diagram is presented in figure 25: [127]

[126] Bjerkevendt et al (1997) *"Gas explosion handbook"*
[127] HSE (2006) *"Response spectra for explosion resistant design and assessment"* , RR484

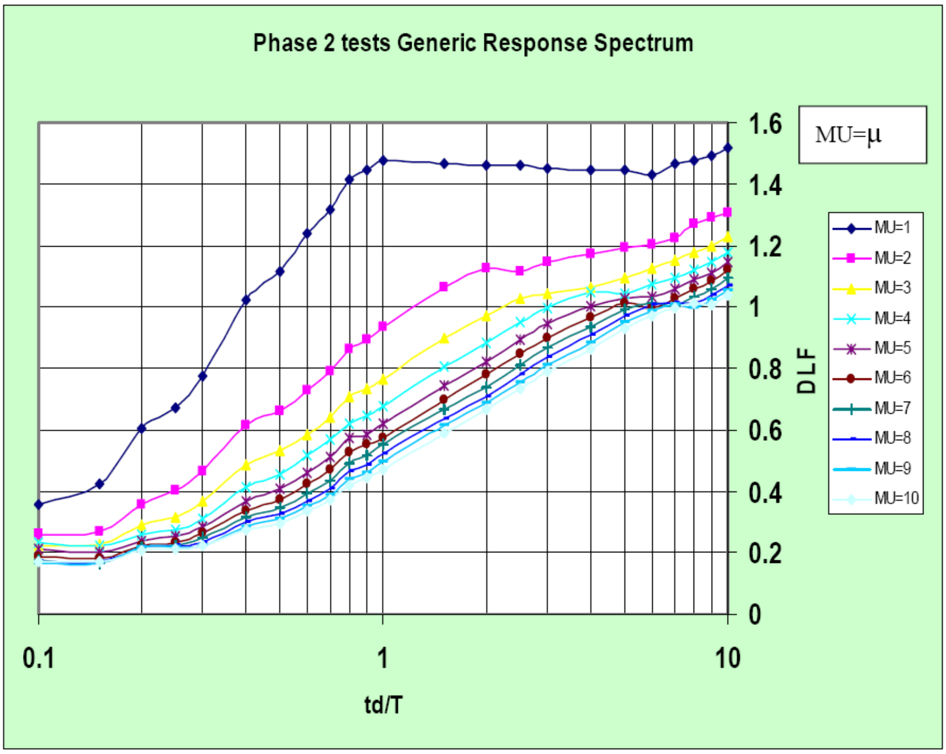


Figure 25: Generic response spectrum diagram, from which the Dynamic Load Factor can be estimated. From HSE (2006) *"Response spectra for explosion resistant design and assessment"*

As a reference, the explosion load duration is normally on the order of 100-200 milliseconds.[128] Full-scale experiment measurements suggest that the natural frequency of a typical offshore module may be on the same order of magnitude. HSE found the natural period of the Spadeadam test rig to be 180-195 milliseconds. [129] It is also interesting to note that the guidelines to the Facilities Regulations states that the main fire divisions in closed areas should be able to withstand at least 70kPa (0,7 bar(g)) for 200 milliseconds.[130] The natural period, allowable ductility and explosion load duration is however scenario and object specific parameters and need to be addressed accordingly.

Yet another complicating pressure load effect is that the blast wave of an explosion may be reflected or diffracted when it runs into an object or building. Reflection phenomena may create locally higher pressures, as much as by a factor of two, while diffraction typically leads to lower pressures. An illustration is given in figure 26 . Reflection and diffraction phenomena also need to be taken into account and dealt with when describing, estimating and calculating the explosion load and structure response.

[128] Bjerkevendt et al (1997) *"Gas explosion handbook"*
[129] HSE (2000) *"Analysis of structural response measurements – Phase 3B Spadeadam"*, OTO 055/2000
[130] §29, Facilities Regulation Guidelines www.ptil.no/regelverk/r2002/frame_ehtm

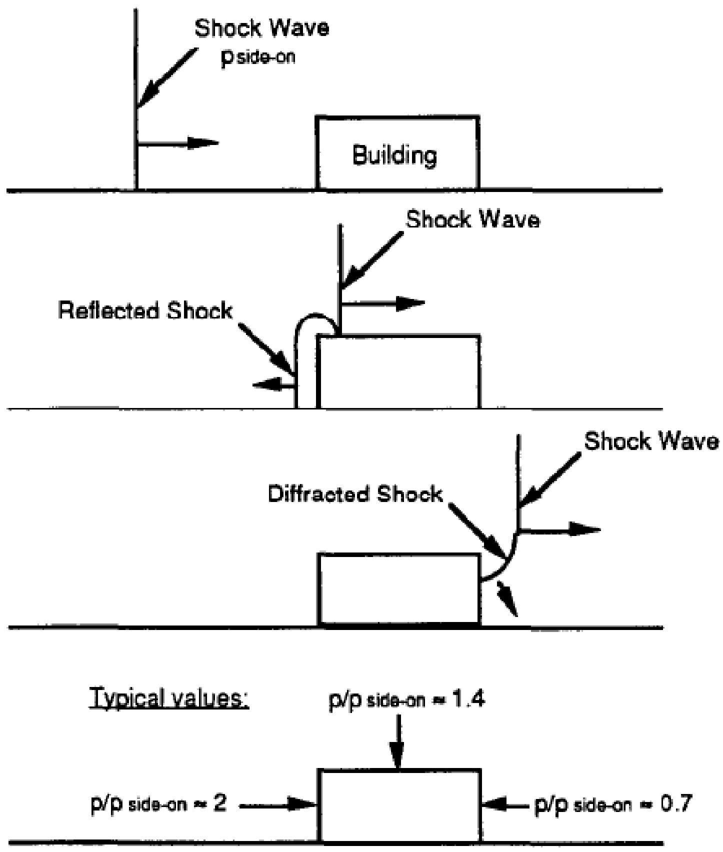


Figure 26: Illustration of reflection and diffraction phenomena when as a blast wave interacts with an object. From Bjerkvendt et. al. (1997) *"Gas explosion handbook"*

3.1.6 Escalation and domino effects

The interpretation of the NORSOK standard[50] and facility regulation leads to the following definition of escalation: An accident within a module or area that spreads to and involves a neighbouring module or area.

Following Cozzani[131], a domino effect event is defined as:

> *"an accident in which the primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than the primary event."* [131]

It is important to note the difference in the definitions and how they relate to each other. Practical examples of escalation include loss or damage to structural passive safety barriers such as fire walls and explosion barriers, which enables the accident to spread **between** modules. Domino effect events typically involve further release of hazardous material or energy such as a rupture of process equipment, escalation fires and explosions **within** a module. The relation between escalation and domino effect events is that they often appear together; a domino effect event is likely to result in an escalation and vice-versa. [132]

Escalation poses one of the most serious threats to safety on an offshore installation. A typical worst-case example of escalation is illustrated by Piper Alpha, were an explosion escalated and initiated a domino effect event which eventually led to the total devastation of the platform. This kind of domino effect escalation is impossible to control after it has begun. Therefore, it is of outmost importance to avoid and limit domino effects and escalation. That explosion load is one of the main initiating event of domino effects is also evident in historical statistics of the MHIDAS database.[132]

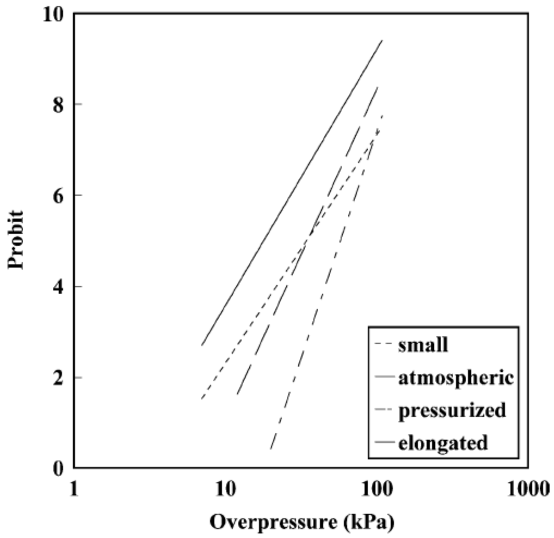
[131] Cozzani V. et. al. (2006) *"Quantitative assessment of domino scenarios by a GIS-based software tool"*
[132] Cozzani et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I. Probit models"*

A probit based methodology for quantitative assessment of domino effects by explosion loads on process equipment has been presented by Cozzani and Salzano in a series of articles[132,133,134]. The first of these include extensive information of data reported in the literature for damage to process equipment caused by peak overpressure. The probit function together with the suggested coefficients for four different kind of equipment is given in equation 9 and figure 23. In figure 23 a table of explosion load data for pressurized vessels is presented.[132]

$$Y = k_1 + k_2 \ln(\Delta P) \qquad \textbf{[Eq. 9]}$$

Where

Y = The probit value. Often a value of 5 is used in risk analyses.
k_1 and k_2 = Empirical constants for different equipment, see figure 27
ΔP = The static overpressure [Pa]



Equipment	k_1	k_2
Atmospheric vessels	−18.96	2.44
Pressurised vessels	−42.44	4.33
Elongated equipment	−28.07	3.16
Small equipment	−17.79	2.18

Figure 27: The right diagram shows the probit functions for different equipment is plotted against overpressure. To the right is a table of empirical constants to use with the probit model for different types of equipment. From Cozzani et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I. Probit models"*

The probit functions suggested by Cozzani et al have been derived from tables of failure data. An example of such a table is given in figure 28 :

[133] Cozzani, V. et al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part II. Case studies"*
[134] Salzano, E. et. al. (2005) *"The analysis of domino accidents triggered by vapour cloud explosions"*

ΔP° (kPa)	Damage
7.00	Failure of connection
20.00	Displacement of steel supports
20.00	Tubes deformation
22.10	Minor damage, pipe supports
30.00	Failure of pressure vessel
37.42	Catastrophic failure, pipe supports
39.00	Structural damage to pressure vessel
39.12	Minor damage, pressure vessel horizontal
42.00	Tubes failure
42.00	Pressure vessel deformation
52.72	Minor damage, tank sphere
53.00	Pressure vessel failure
53.00	Failure of spherical pressure vessel
55.00	20% of structural damage of steel spherical steel petroleum tank
61.22	Catastrophic failure, pressure vessel, horizontal
81.63	Minor damage, pressure vessel vertical
83.00	20% structural damage of vertical cylindrical steel pressure vessel
88.44	Catastrophic failure, pressure vessel vertical
95.30	99% structural damage of vertical, steel pressure vessel
97.00	99% damage of vertical cylindrical steel pressure vessel
108.84	Catastrophic failure, tank sphere
108.90	99% structural damage of spherical, pressure steel vessel
110.00	99% damage (total destruction) of spherical steel petroleum tank

Figure 28: An example of explosion response data for pressurized vessels reported in the literature. From Cozzani et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I Probit models"*

Almost all data on the structure response to an explosion load is reported as the maximal overpressure. There is a lack of reported data expressed in other terms, such as impulse or pressure-time curves. This article also presents a number of probit-functions for different kinds of equipment, and how such function may be derived and used in case studies. It is argued that equipment specific models should be used in the assessment of domino effects rather than some general equipment model. Besides the richness of reported data, the article contains valuable references and a number of probit functions. The methodology is much more simplified than the SDOF and NLFEM mentioned above in the discussion of structure response, but it may nevertheless be a viable alternative in many cases where the more advanced methods are deemed to resource demanding. Due to this limitation, the probit models presented by Cozzani and Salzano estimate only the overpressure quantitatively, while the explosion characteristics are dealt with qualitative by expert judgments. The method was mainly derived to handle far-field blast wave and larger objects. Cozzani et. al. argued that the dynamic drag forces in such cases are negligible.[135]

Another approach to escalation is proposed by Morris et. al. who suggest a computer simulation technique called PLATO. The model consists of a library of objects that may interact with other objects as the scenario develops over time. As an object receives a certain load, it breaks and the effect of this event is incorporated in the succeeding time-steps. As an example, in a scenario one of the fire water pumps is damaged at one stage of the simulation. As this system is vital to the deluge system, the model will simulate the loss of the deluge system and take this into account in the rest of the simulation. In the same way, a tank or a process vessel that collapses or explodes may impose a load on the neighbouring equipment by calculated loads.[136]

[135] Cozzani et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I. Probit models"*
[136] Morris et. al (1994) *"Quantification of escalation effects in offshore quantitative risk assessment"*

PLATO has also been used in a HSE screening study[137] to assess the relative importance of factors affecting the decision to activate deluge on gas detection. In this study, a model of a typical North Sea platform was used to examine the sensitivity of a number of factors. The two factors deemed most important was reduction in explosion overpressure and local fatality rate. For a platform with average susceptibility to explosions, a reduction by approximately 10% -15% of the hydrocarbon risk may be expected according to the report. According to the report, an increased in ignition probability may however outweigh the benefits if sufficient protection is not in place.[137]

Although the approach of PLATO may be tempting, the sub-models have been criticized for its simplification of the underlying physics by Jones et. al.[138]. Only three different combustion types are considered; jet fire, pool fire and fireballs. The loads are calculated with the most simple empirical models and correlations, which on the other hand have been shown to be consistent with some experiments and other empirical correlations. None of the more complex physics of gas leakage and spread, ignition, explosion propagation, nor fire spread or flame impingement is included.[138] For this reason, the use of PLATO is not considered to be suitable for the present study.

3.2 Deluge as gas explosion mitigation measure

Several experiments have shown that water deluge can be effective as an explosion protection measurement. [139] This is due to the good physical characteristics of water for extinguishing flames, which has been discussed by Särdquist[140] and Arvidsson [141]. Both are putting emphasis on the ability of water to cool the flame as the primary extinction mechanism. The large amount of energy needed to vaporize water is the key parameter together with the high heat capacity of water vapour. In other words, the water acts as a heat sink to slow the reaction rates down until the flame is no longer able to propagate. Also the dilution of oxygen is mentioned, but this is also basically a disturbance in the thermo dynamical energy balance leading to lower heat production in relation to heat losses and thus slower reaction rates.

Thomas (2000)[142] also discussed the practical benefits of using water as an explosion protection agent. He concluded that water could be considered a cheap, non-toxic and environmental friendly protection alternative. On an offshore platform, seawater can be turned into an infinite volume of highly effective mitigation and prevention agent. This also adds the opportunity of continuous instead of one-shot protection; instead of reacting on a propagating flame after ignition, the deluge can be activated directly on confirmed gas detection.[142]

The droplet size distribution, coverage and application rate are critical factors for deluge to be effective as explosion mitigation. The reason why the droplet size is so critical can be explained with the extinction mechanism outlined above with the heat loss due to water vaporization. For this to be effective, the droplet must vaporize within the flame. Vaporization is linked to the specific area of the droplet which increases with decreasing droplet diameter. Thus, to have enough droplets of the right size within the flame is essential to get the positive effect of deluge on explosions. The drops need to be approximately on the order of 10μm or smaller to evaporate in the flame. [143]

Andersson et al[144] discusses some of the difficulties to produce and sustain such a mist of small drops. The difficulties include coalescence, which means that the drops will interact so that the larger drops consume the smaller drops as they fall with higher terminal velocities.[144]

The drop sizes theoretically required (10-20μm) are orders of magnitude smaller than the droplet sizes produced by ordinary deluge nozzles (0,1-1 mm). Still, large drops were found to have a good mitigating effect on gas explosions. This can be explained with a theory of droplet break-up. When the hydrodynamic forces acting on a drop are greater than the surface tension force that keeps the drop together, the drop breaks up. This can be mathematically expressed in terms of the dimensionless Weber number [We] which is defined as[143]:

---

[137] HSE (2000) *"Screening Study to Assess the Relative Importance of Factors Affecting the Decision to Activate Deluge on Gas Detection"*
[138] Jones. J. C. et. al. (1997) *"PLATO© software for offshore risk assessment: a critique of the combustion features incorporated"*
[139] Wingerden (2000) *"Mitigation of Gas Explosions Using Water Deluge"*
[140] Särdqvist (2002) *"Vatten och andra släckmedel"*
[141] Arvidsson et al (2001) *"Släcksystem med vatten dimma – en kunskapssammanställning"*
[142] Thomas, G.O. (2002) *"On the conditions required for explosion mitigation by water sprays"*
[143] Wingerden (2000) *"Mitigation of Gas Explosions Using Water Deluge"*
[144] Andersson, P (1997) *"Evaluation and Mitigation of Industrial Fire Hazards"*

$$We = \frac{\rho U_{Relative}^{2} D}{\sigma} \qquad \textbf{[Eq. 10]}$$

where

ρ = density of gas mixture stream [kg/m^3]
$U_{Relative}$ = Relative velocity between gas and droplet [m/s]
D = Droplet diameter [m]
σ = surface tension [N/m]

Smaller drops will accelerate fast and adapt to the gas flow. This reduces the relative velocity for smaller drops, and hence the Weber number. Even for the same relative velocity, larger drops have a higher Weber number. For this reason larger drops will break up much more easily than smaller drops. Experiments show that when water drops reach a critical Weber number of approximately 10-12, they deform and break up.[145] Based on Eq. 10, it is also possible to predict the theoretical effect of adding surface tension reducing chemicals such as different kinds of foam. By lowering the surface tension the Weber number rises and hence drops break up more easily. It also needs to be said that there is an upper limitation in the above equation due to the energy principle. The energy used to break up the drop can never be higher than the kinetic energy in the drop itself.[146]

A high-speed video sequence of a water drop break-up is showed in figure 29. Not all drops fractions after the break-up are sufficiently small to evaporate within the flame. Wingerden el al estimated that only approximately 30% of the original droplet mass will generate sufficiently fine mist during droplet break-up. The fine fraction drops after break-up is dependent on the mass of water that undergoes break-up. It is necessary not only to have the drops with the right size, but also a sufficient amount them as well. Hence, the application rate of water is also an important parameter.[145]

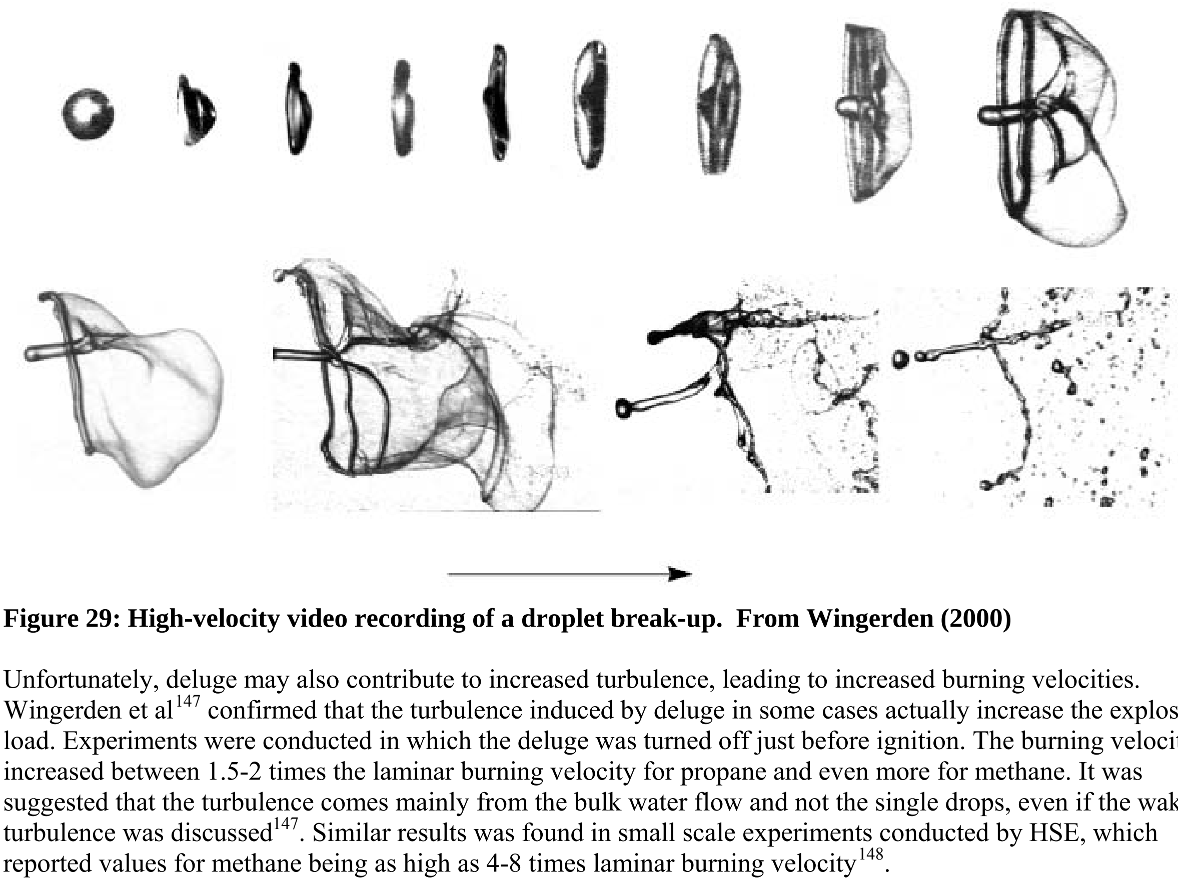


Figure 29: High-velocity video recording of a droplet break-up. From Wingerden (2000)

Unfortunately, deluge may also contribute to increased turbulence, leading to increased burning velocities. Wingerden et al[147] confirmed that the turbulence induced by deluge in some cases actually increase the explosion load. Experiments were conducted in which the deluge was turned off just before ignition. The burning velocities increased between 1.5-2 times the laminar burning velocity for propane and even more for methane. It was suggested that the turbulence comes mainly from the bulk water flow and not the single drops, even if the wake turbulence was discussed[147]. Similar results was found in small scale experiments conducted by HSE, which reported values for methane being as high as 4-8 times laminar burning velocity[148].

[145] Wingerden (2000) *"Mitigation of Gas Explosions Using Water Deluge"*
[146] Holmstedt, G. professor at LTH , personal communication 2007-01-24
[147] Wingerden (2000) *"Mitigation of Gas Explosions Using Water Deluge"*
[148] HSE (1996) *"An Investigation of factors of relevance during explosion suppression by water sprays"*

3.3 Explosion load modelling

This chapter examines the differences, strengths and weaknesses with three main approaches to explosion modelling: Empirical models, Phenomenological models and Computational Fluid Dynamics (CFD). This classification is thought to add clarity in the presentation of explosion models in this report. At the same time it is important to notice that the existing models are always combinations of some of these approaches. Most models have empirical elements imbedded, or have at least been tuned to fit empirical data, and phenomenological sub-models are widely used in more advanced approaches such as CFD. The emphasis has been put on the CFD models, since this is of special interest in the present study. Two excellent overview and discussion of the state-of-the-art in explosion load is provided by HSL[149] and HSE[150], which has been used as the main sources of information for this chapter.

3.3.1 Empirical models

These models consist of empirical correlations based on experimental data. Examples of empirical models are the TNT-equivalence model, Multi-energy model, the Congestion Assessment Model (CAM), and the Baker-Strehlow model. Their prime strength lies in being easy, fast and cheap to use. At the same time, they lack the precision and accuracy of more advanced models and offer much less information. To compensate, the empirical models tend to be over-conservative.[149]

Although still in use by the industry, empirical models seem to have lost ground rapidly to more advanced models. As for the offshore industry in the Norwegian sector, this can be explained by the recommendations from NORSOK[151] to use the more advanced computer models.

3.3.2 Phenomenological Models

These models have been designed to catch the most essential physics of explosions. They are not as geometrically detailed as the CFD-models, but are more theoretical founded than the empirical models. An important difference between phenomenological models and CFD models is how the geometry is represented. Generally, phenomenological models do not model the actual scenario geometry, but simplifies it into an idealised system. The upside of the less geometrical detail in comparison to CFD is that the models are easier and faster to use. It can therefore be used to screen a large number of scenarios and then use CFD to analyze these scenarios in greater detail. The downside is that less accurate data can be retrieved, especially for complex structures. Examples of phenomenological models are the Shell code for overpressure prediction in gas explosions (SCOPE) and the confined linked chamber explosion code (CLICHE). [152]

3.3.3 Computational Fluid Dynamics in explosion modelling

CFD is a general modelling technique that can be applied to a broad spectrum of engineering problems of complex fluid flows. CFD is a group of software codes used to find numerical solutions to the Navier-Stokes equations governing the conservation of mass, momentum, energy and chemical species. In the present context the simulation of gas leakage dispersion, ventilation, explosive cloud formation and explosion propagation is of interest. Within this group there are different solution strategies and modelling techniques. Some of the most common CFD codes for simulating explosions include EXSIM, AutoReaGas, COBRA, FLACS, CFX-4, REACFLOW, and the Imperial Collage Research Code. A detailed review of the different strengths, weaknesses and limitations of each of these codes has been described in a HSE report and are therefore not covered here.[152] Only the basic concept, the general difficulties, strengths, limitations and uncertainties of explosion modelling with CFD are presented here. A more detailed description of the FLACS, which will be used in the case study, is presented in the next chapter.

---

[149] HSL, (2002) *"A Review of the State-of-the-Art in Gas Explosion Modelling"*
[150] HSE (2002) *"A critical review of post Piper Alpha developments in the explosion science for the offshore industry"*
[151] NORSOK (2000) *"S - 001 Technical Safety"*, rev. 3, page 16
[152] HSL, (2002) *"A Review of the State-of-the-Art in Gas Explosion Modelling"*

The basic concept of CFD is to create a 3D geometry representation of the system to be examined. For an offshore platform this geometry typically include all the main structures and as much equipment possible. The geometry is then discretised, which means it is broken down into sub-volumes by a grid. For each and all of these sub-volume cells coupled equations are solved over a number of time steps, using numerical iteration techniques. In each cell, the properties are assumed to have the same values. Hence, at each time step, the in- and outflow from each cell in terms of energy, mass, momentum and chemical species is calculated together with other physical properties of such as pressure, density, and temperature. The physical properties of the flow, such as flow velocity and direction, are calculated at the interface surfaces between neighbouring cells. Other variables of interest such as surface pressure data, overpressure and drag forces are also calculated for each cell or surface. [153]

The grid is of very high importance, as it controls the level of geometry details and the spatial accuracy of the simulation solution. A large number of small cells make the error of averaging across each cell smaller. The ideal would be to let the cell size be so small that the elementary physical processes, such as turbulence, could be simulated directly. This method, called direct numerical simulation, is however not practically possible for most scenarios at present due to the restrictions of computer resources available. [153]

Hence; to be able to solve the Navier-Stokes equations for such a complex system as an offshore module a number of simplifications are introduced. The first simplification is the use of the Reynolds averaged Navier-Stokes (RANS) k-ε turbulence model. While the RANS model is the industrial standard used in almost all codes today, the more advanced technique of large eddy simulation (LES) may be the next step in developing more accurate CFD modelling techniques. Some recent developments of progresses in explosion simulation using LES turbulence modelling is presented by Makarov et al.[154], who showed good results for a very simple geometry. In a distant future the very best approach would be to use direct numerical simulation (DNS), without any averaging or approximation other than the necessary discretization. [153] Both LES and DNS are however to resource demanding for explosion modelling at the present stage for other applications than very simple problems and research.

This can be illustrated by the following example. As the size of the cells decreases, the number of cells increases rapidly and thus also the computer resources required. The resource requirement of each cell in a CFD simulation has been approximated to ~10^3 bites random access memory. For a computer with 1Gigabite memory, this would allow a maximum 10^6 cells, 100 cells in each direction. An attempt to distribute this restricted number of cells on a practical offshore problem will lead to cells with approximately 0.1-1 meter long sides. This is not sufficiently small to represent all important geometrical details and certainly not small enough to represent the physical properties, such as the turbulence eddies.
To solve this problem a second simplification is introduced: the use of a sub-grid turbulence model. An example of such a model is the porosity/distributed resistance model. Many CFD codes are also built on an orthogonal Cartesian coordinates grid, which limits the representation of objects to cubes. More advanced models include non-orthogonal grids which allow a more sophisticated geometry representation. Another interesting technique under development is the use of an adaptive grid, which allows as more detailed representation of the flame.[155]

A third important simplification is connected to the combustion and flame propagation models that are used to represent the chemical reactions and physical properties of the flame propagation, such as flame speed and heat transfer. To cut the simulation running times and make the code more robust very simple phenomenological and empirical models are used. The very complex chemical kinetics of turbulent combustion is often represented as a single-stage reaction between a fuel and oxygen, while flame propagation is described by an empirical correlation for burning velocity.[155]

3.3.4 CFD strengths

Some of the general strengths of explosion modelling with CFD are presented below:

i. The general strength of CFD modelling of explosions is that it includes a much more detailed representation of the complex 3D geometry and flows compared to the phenomenological and empirical models. As was shown in previous chapters turbulence plays a very important role in explosion

[153] HSL, (2002) *"A Review of the State-of-the-Art in Gas Explosion Modelling"*
[154] Makarov et. al. (2004) *"Modelling and Large Eddy Simulation of Deflagration Dynamics in a Closed Vessel"*
[155] HSE (2002) *"A Review of the State-of-the-Art in Explosion Modelling"*, page 34

propagation and as it is governed by the Navier-Stokes equations, the basic concept of CFD to try to solve these equations is a fundamentally more correct approach.

ii. Despite the problems associated with it, CFD has been shown to produce reasonably good predictions of experiments, ranging from small scale to full-size scales. It must however be noted that good in this context means within a factor of two.

iii. There are models to account for the effect of deluge on explosions that have been incorporated in the models. The theoretical foundation, validity and accuracy of these models need to be critically discussed.

iv. It is often possible to simulate ventilation, gas dispersion and explosion propagation with the same CFD code. By using the same geometry model a lot of effort and resources can be saved that instead can be used to improve the analysis in other ways, such as extended sensitivity analyses.

3.3.5 CFD weaknesses

It is important to realize the weaknesses, limitations and problems attached to explosion modelling with CFD.

i. Problems with insufficient computer resources.
The most serious problems associated with CFD are that the Navier-Stokes equations are so difficult to solve, which inevitably leads to considerable simplifications. Ideally the problems should be solved with DNS including full chemistry and advanced physical models. At present simple RANS models are used instead, since both DNS and LES are to resource demanding. Still even with the simpler RANS models, first-order accurate numerical schemes and the most simple combustion model, insufficient computer resources forces the use of large grid sizes and the PDF sub-grid turbulence modelling approach.

ii. Problems with the RANS k-ε turbulence model
One of the most commonly used RANS models, the k-ε turbulence model, is questionable. It should be noted that the k-ε model was originally developed and validated for simple non-reacting, constant density flows rather than complex reacting flows in arbitrary 3D geometries. Even though the k-ε turbulence model has been refined and calibrated, it is still questionable how accurately it models the turbulence in an explosion.

iii. Grid problems:
The grids used to discretise the geometry representation are often coarse and limited by the use of orthogonal Cartesian coordinates. The coarse grids make it necessary to use sub-grid models such as the PDF models. The use of Cartesian coordinates means that the code calculation is limited to represent everything in the shape of rectangles. For example, objects like spheres or cylinders will be represented either as boxes or by the PDF models. This is obviously not very accurate and it is uncertain how this effects the turbulent flow and flame propagation.

iv. Validation problems:
Since the codes have been calibrated and validated for a certain grid cell size, it is often not possible to try to find grid independent solutions. Although all providers of explosion CFD codes claim to have extensive validation for their software, it is questionable how much is actually validation and how much is calibration. Practically this limits the use of the present CFD codes to scenarios that are similar to the experiments used in the calibration/validation process.

v. Problems with combustion and flame propagation models:
The combustion and flame propagation models differ a lot from code to code, but the lion share use very simple empirical models without any detailed chemical kinetics. In fact, the most common approach is to represent the combustion process as a single step reaction with oxygen and fuel. Flame propagation is represented by empirical burning velocity correlations, or by more or less grid dependent eddy break-up expressions.

vi. Numerical problems:
Truncation errors in the numerical iteration process may cause numerical diffusion. This is completely artificial, and often due to the use of first-order Taylor series expansion. A solution to this problem is to

use second-order schemes instead, often referred to as a central differencing scheme. Unfortunately the use of second-order discretization schemes is much more unstable, making it hard and resource expensive to reach converged solutions.

vii. Experimental problems:
Since all explosion modelling techniques descend, directly from or need to be calibrated and validated against experimental data, the difficulties in explosion experimentation limit the modelling accuracy. One important factor is the poor experimental repeatability in many tests. Experimental measurements for identical setup may differ significantly. For some experiments the average pressures varied with a factor of two or more. [156,157] Another potential problem is that most experiments have focused on macroscopic properties such as peak over-pressure, which takes focus off the microscopic modelling such as turbulence generation and combustion physics. It is thus that possible some codes give a good results but for the wrong reasons.[157]

viii. Future accidents are inherently uncertain
A fundamental and important difference between the attempt to predict experimental results and future accidents is that the latter is inherently uncertain. This uncertainty stems from the fact that accident explosions are a combination of a large numbers of parameters such as leakage rate and location, ignition location and strength, type of fuel, gas cloud size and concentration profile, initial temperature, pressure, turbulence etc. that are more or less unknown. The combinations of possible combination are theoretically infinite, and hence needs to be reduced to a representative set of scenarios. When reproducing an experiment with CFD, most or even all of these input parameters are known.

xi. Input and user problems
A chain is never stronger than the weakest part is an old saying. When modelling explosions with CFD, this could be the input from the user. It does not help to have the best code if it solves the wrong problem because the input from the user is incorrect. Further, even if the results are OK a competent interpretation is needed afterward. CFD modelling produces an enormous wealth of data and the user must be able to handle this amount of information. For these reasons, the user needs to be specialised on explosion theory and modelling to conduct CFD explosion simulations in a meaningful way.

3.3.6 Handling the uncertainties of CFD explosion modelling

All the problems and limitations add uncertainties to the results obtained, and it is up to the risk analyst to try to deal with them. Some possible measures to handle or reduce uncertainty and increase the quality of the CFD simulation may include:

i. Ensure sufficient user competence.
ii. Add a greater amount of conservatism in the analysis to ensure that the results are rather on the safe side.
iii. Use transparent, documented, traceable input and results subjected to a critical peer-review of the CFD simulations by an independent expert.
iv. Whenever possible, conduct grid dependency studies.
v. Conduct sensitivity analysis of the most important parameters such as ignition source location, gas cloud location etc.
vi. Use more than one explosion model.
vii. Make a conservative estimate of the uncertainties and present them transparently. An example of this is approach is presented by Høiset et. al. [158] who used statistical analysis to estimate the most important uncertainties in CFD explosion simulations. This was done by first comparing the differences between validation experiments and CFD simulations. The deviations were then used to derive uncertainties factors. It was suggested that the characteristic load should then calculated with the formula:

$$p_C = p_{MAX}\gamma_G\gamma_M\gamma_I \qquad \textbf{[Eq. 11]}$$

in which
p_C = the characteristic load
p_{MAX} = maximal simulated pressure

[156] HSE (1999) *“The Repeatability of Large Scale Explosion Experiments”* page 16.
[157] HSE (2002) *“A Review of the State-of-the-Art in Explosion Modelling”*, page 38 See also appendix E page
[158] Høiset S. (1997) *“Statistical estimation of loads from gas explosions”*

γ_G = Uncertainty factor for gas cloud size and location.
γ_M = Uncertainty factor for explosion modelling idealisation.
γ_I = Uncertainty factor for ignition location.

It is interesting to note that γ_M was approximated by Høiset et. al. to span between 1-2, depending on the level of statistical significance (75-99% quantiles). Similarly γ_I was approximated to span between 1.5-3 depending on the fuel, number of simulations and the level of statistical significance. Other uncertainties, including γ_G, were recommended to be taken care with conservative assumptions.[158] This also indicates that the uncertainties attached to CFD modelling of explosions are indeed very large.

4 Simulation aspects

4.1 *The FLACS simulation code*

The flame acceleration simulation (FLACS) CFD code was originally developed during the eighties as part of the national Norwegian research project called "Sikkerhet på sokkeln". After the project the company Gexcon was created and the FLACS code was made available to the commercial market. The code is subject to continuous development and research by Gexcon who also distributes and promotes the code. For this reason, the reader must aware of the potential bias due to economical interests behind some of the articles covering explosion CFD modelling. Unfortunately, the economical interests may also hinder new knowledge and progresses to be efficiently spread within the scientific society[159].

FLACS uses a modified RANS k-ε model and a PDF sub-grid approach to estimate turbulence generation for smaller objects. The modification to the k-ε model includes a model for near wall flow. The theoretic flaws of the k-ε model have been discussed in section 3.2.4 above. The turbulence estimates are then coupled to a combustion and turbulent burning velocity model. There are two different combustion models in FLACS: the β flame model and the simple interface flame model. The simple interface flame model is still under development and has not been sufficiently validated yet to be used for practical applications. It is thus not examined further although it is supposedly more accurate than the β flame model. The β flame model approach consists of a flame model that moves the reaction zone at a speed which depends on burning velocity. The burning velocity is then modelled by empirical correlations based on laminar burning velocity and turbulence factors. Detailed chemical kinetics is not incorporated in the model, which treats combustion as a single-stage reaction between the reactants fuel and oxygen into combustion products. The β flame model approach has the advantage of being grid independent. The drawback is that it uses empirical burning velocity correlations. [160,161]

Since these correlations are fuel dependent, modelling with FLACS is limited to fuels that have been subject to extensive research and validation experimentation. It shall also be noted that in order to represent the flame an absolute minimum of three cells is required since numerically the reaction zone is three control volumes thick. NORSOK Z-013 recommends that the gas cloud should be represented with at least thirteen cells in each direction.

The geometry may be generated by import of CAD-drawings or by drawing a new model from scratch in the computer aided scenario design (CASD) software. An orthogonal Cartesian grid is used to discretise the geometry. CASD is also used to generate the grid and to write the scenario files including input such as initial conditions, boundary conditions, gas cloud and location, ignition, monitor points, simulation variables and output control. Other optional features in FLACS include simulation models for the effect of deluge and relief. The scenario file may later be copied and edited with a simple text editor to create new scenarios. This makes it easier to create a large number of basically similar simulations with small differences, such as ignition location, to conduct sensitivity analysis.[160,161]

After designing the scenarios in CASD the simulations are run with FLACS. Only first-order accurate numerical schemes are except for the reaction progress variable. Here a second-order accurate van Leer scheme is used to prevent artificial flame thickening caused by numerical diffusion[162]. The results for the defined variables are stored in data files and can be visualised with the flow visualisation software FlowVis. It is also possible to export the data files results to other software programs such as DNV Express or Microsoft Excel. The process from start to goal is illustrated in Figure 30 .

---

[159] HSE (2004) *"A critical review of post Piper-Alpha developments in explosion science for the Offshore Industry"*
[160] Gexcon *"FLACS User's guide V8"*
[161] Gexcon (2005) *"FLACS V8.1 Release notes"*, Rev.2 page 11-17
[162] HSE (2002) *"A Review of the State-of-the-Art in Explosion Modelling"*, page 38 See also appendix E page

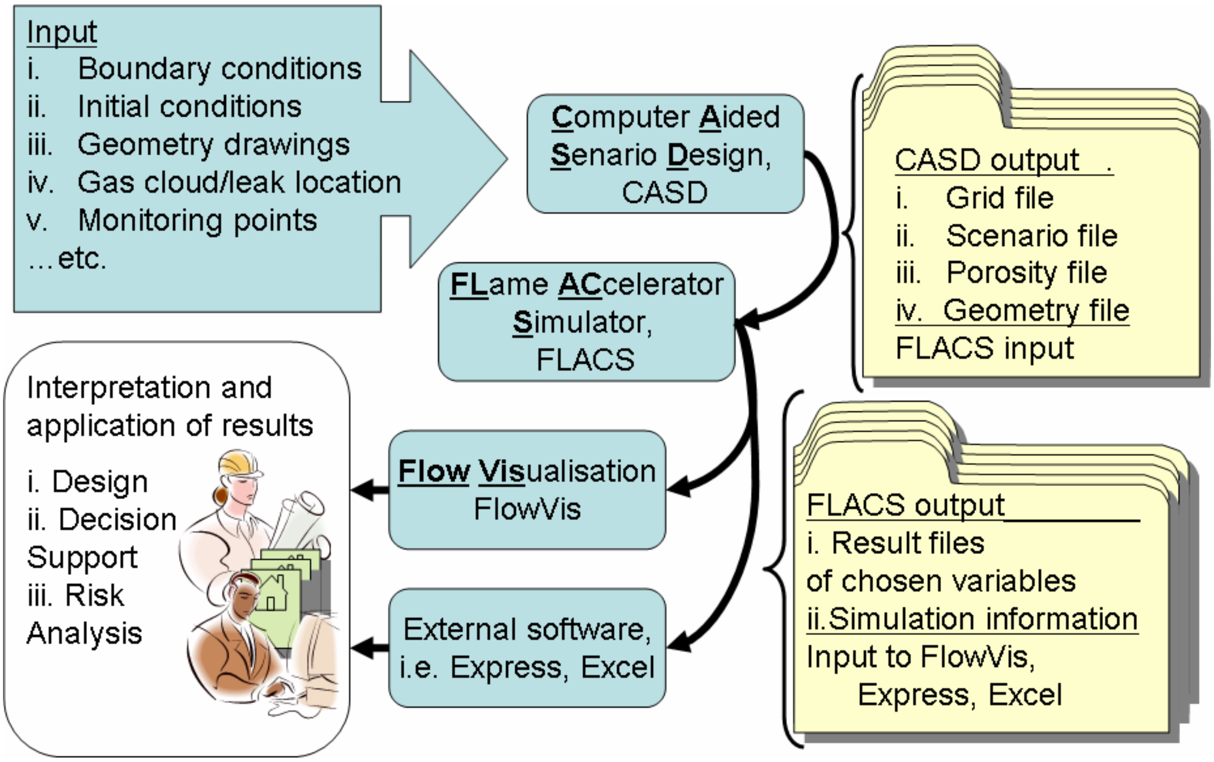


Figure 30: Illustration of explosion modelling process with the CFD code FLACS from the start in input to the goal of interpretation and application of results.

While originally designed to simulate explosion propagation and load, FLACS can also be used to simulate natural ventilation rates, leakage and dispersion with the same geometry used for explosion propagation. Recent updates of the code include modelling of Pasquill classes, user defined gases, fluctuating wind, fan leaks and diffuse gas leaks.[163]

The code is not able to model the transition of deflagration into detonations. According to Gexcon experienced users are able to identify and interpret simulation results where deflagration to detonation transition is probable.[164]

4.2 Deluge modelling in FLACS

4.2.1 Original model

The original deluge and explosion propagation interaction model in FLACS has been described by Dale[165] and Wingerden[166]. Two non-dimensional factors are calculated and implemented in the numerical calculations to account for increased burning rate due to turbulence and decreased burning rate due to deluge mitigation respectively.

$$S_{Water} = (S_{Turbulent} + (F_1 \times S_{Lamiar})) \times F_2 \quad \textbf{[Eq. 12]}$$

where
S_{Water} = Effective burning velocity accounting for the effect of water deluge
$S_{Turbulent}$ = Turbulent burning velocity
$S_{Laminarr}$ = Laminar burning velocity
F_1 = Turbulence factor, ranging from 1-10
F_2 = Quenching factor, ranging from 0-1 (0 means quenching of the flame)

[163] Gexcon (2005) *"FLACS V8.1 Release notes"*, Rev.2 page 11-17
[164] Gexcon (2005) *"FLACS V8.1 Release notes"*, Rev.2 page 11-17
[165] Dale, E. (2004) *"Simulation and modelling of waterspray in the 3D explosion simulation program FLACS"*
[166] Wingerden K. (2000) *"Mitigation of Gas Explosions Using Water Deluge"*

F_1 and F_2 are the calculated as functions of the water volume fraction (WVF) according to the following set of equations:

$$F_1 = 14U_Z \times WVF \qquad \textbf{[Eq. 13]}$$

$$F_2 = \frac{0.03}{D_{Sauter} \times WVF} \qquad \textbf{[Eq. 14]}$$

$$WVF = \frac{n_{Nozzels} \times \frac{Q}{60}}{X_{Spray} \times Y_{Spray} \times U_Z} \qquad \textbf{[Eq. 15]}$$

$$U_Z = 2.5\ D^{0,94} \qquad \textbf{[Eq. 16]}$$

$$D_{Sauter} = P_{Water}^{-0.333} \qquad \textbf{[Eq. 17]}$$

$$Q = k \times \sqrt{P_{Water}} \qquad \textbf{[Eq. 18]}$$

where
U_Z = Average droplet velocity vertically downwards [m/s]
D_{Sauter} = Mean droplet diameter, [mm] expressed as the Sauter diameter = $P_{Water}^{-0.333}$
P_{Water} = Water pressure [bar]
WVF = Water volume fraction, [litre/m^3]
$N_{Nozzels}$ = Number of nozzles in spray region
Q = Water flow from each nozzle [litre/minute]
k = Nozzle specific flow constant
X_{Spray} = Size of spray in X-direction
Y_{Spray} = Size of spray in Y-direction

It is obvious by simple dimension analyses that the factors resulting from the equations given above are not non-dimensional as they are presented by Dale. There seems to be some disguised empirical factors included in the equations to account for this, which could explain the values of 14 and 0.03 in respective equations. How these values have been derived is not clear and not discussed by Dale.[167] It may be that these numbers have been used to tune the model to fit experimental data. The theoretic and physical foundation of the model is thus questionable, and until a better description of the model is available it should be regarded as a purely empirical model.

It is also possible to use the following simplified formulas[168]:

$$F_1 = 0,233 \times WAR \qquad \textbf{[Eq. 19]}$$
$$F_2 = 4.5 / WAR \qquad \textbf{[Eq. 20]}$$

where

WAR = water application rate [liter*minute^{-1} m^{-2}], (typically ranging between 10-20.)

For the deluge to be able to mitigate the water drops in the spray must first break-up. In the original FLACS deluge model this was represented by the following equations describing the break-up criterion:

[167] Dale (2004) *"Simulation and modelling of waterspray in the 3D explosion simulation program FLACS"*
[168] Lecture notes from FLACS user course autumn 2006

Droplet break-up criterion $U_{Critical} \geq U_{\mathrm{Re}lative}$ **[Eq. 21]**

$$U_{Critical} = \sqrt{\frac{0.505}{D_{Sauter}}}$$ **[Eq. 22]**

where
$U_{Critical}$ = Critical velocity for droplet break-up
$U_{Relative}$ = Relative velocity between gas and droplet
D_{Sauter} = Droplet mean Sauter diameter [mm]

The criteria is examined by recalling the definition of the Weber number given in Eq 10 above and conducting a simple dimension analysis:

$$We = \frac{\rho U^2_{\mathrm{Re}lative} D_{Sauter}}{\sigma} \Rightarrow \text{ solve for } U_{Relative} \Rightarrow U_{\mathrm{Re}lative} = \sqrt{\frac{We \times \sigma}{\rho \times D_{Sauter}}} \approx \sqrt{\frac{0.505}{D_{Sauter}}}$$

This criterion seems to be consistent with the present knowledge of droplet break-up, which was presented in section 3.2 above.

Enhanced deluge model
The original deluge model was further enhanced in 2003 to include more theoretically and physically correct sub-models to account for two-phase interactions between the gaseous flow and drops. This was implemented by converting an existing two-phase model for mist explosions into a deluge model. The new model accounts for droplet size distribution, coalescence and evaporation of droplets. The droplets size distribution is represented by a number droplet size classes, and each class has a local representative that varies in time and space. Coalescence means that larger droplets will collide with smaller droplets and consume them.[169]

Dale reported that the evaporation model led to physically impossible results and suggested an improved model. This improved model was based on a reduction in flame temperature as a function of the mass of water divided by the mass of gas. The adjusted flame temperature was then coupled to the burning velocity and further incorporated in the numerical simulation.[169] The enhanced deluge model is still under development, but is included in the most recent version of FLACS. The original model is however still the default.[170]

4.3 FLACS validation and accuracy

Gexcon states that FLACS has been thoroughly validated against small-, medium- and large-scale experiments. Over 2000 experiments have been conducted by CMR and Gexcon in the development and validation of FLACS. Gexcon further states that the accuracy is generally within 30-40% between experiment measurement and simulation result of explosion overpressure.[171]

It is seen as a problem that most of these experiments are not easily available in the open literature, which makes it hard to evaluate their quality and integrity. It also necessary to note that calibration and validation are not the same thing and that there is a possibility for different interpretations of these words. To be clear, validation should mean independent and unique experiments. The results shall be predicted by the CFD model before the experiments are conducted, or at least without any hindsight bias. To try to repeat “validation experiments” similar to the experiments used for calibration is of course of limited value.

[169] Dale (2004) *”Simulation and modelling of waterspray in the 3D explosion simulation program FLACS”*
[170] Mail correspondence with B. Artzen, 2006-08-30
[171] Bjerkevendt et.al. (1997) *“Gas Explosion Handbook”*

In the Modelling and Experimental Research into Gas Explosion project (MERGE), a number of explosion CFD codes including FLACS were subject to predictive benchmark test of large-scale explosions. A comparison between simulated overpressure and experimental measurements from Popat et. al. are given in figure 31.[172]

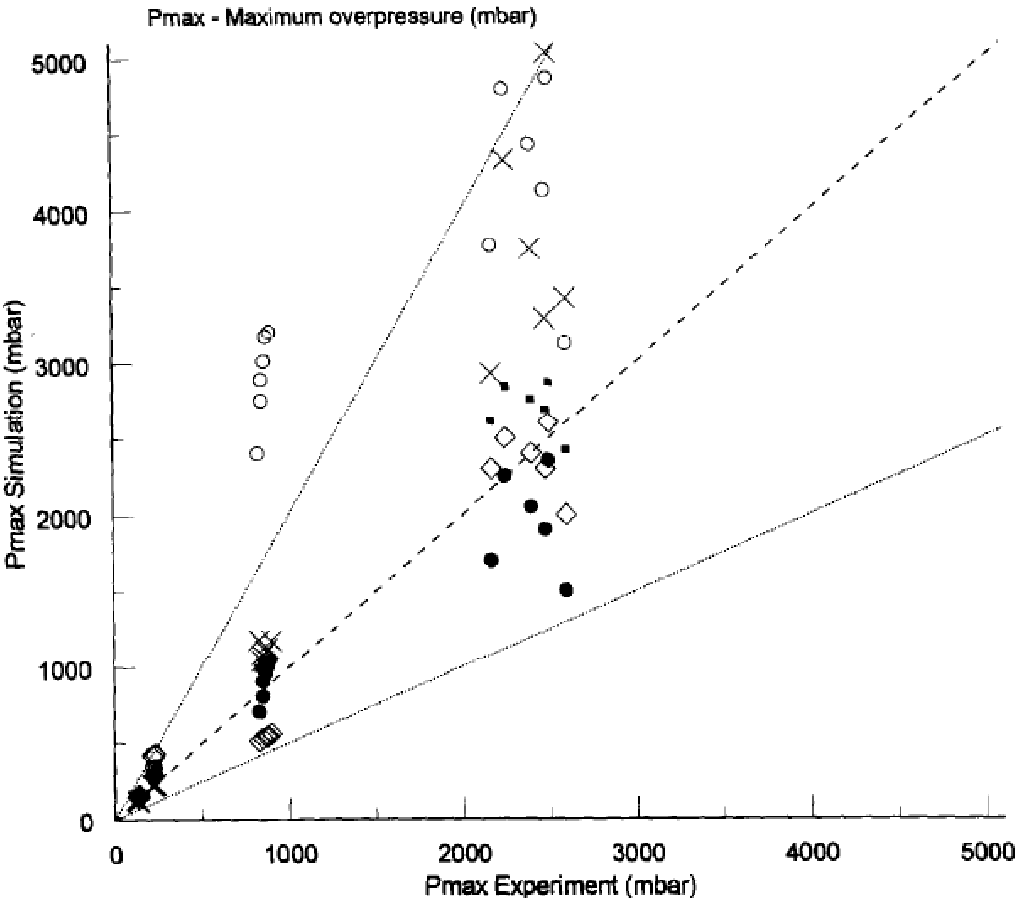


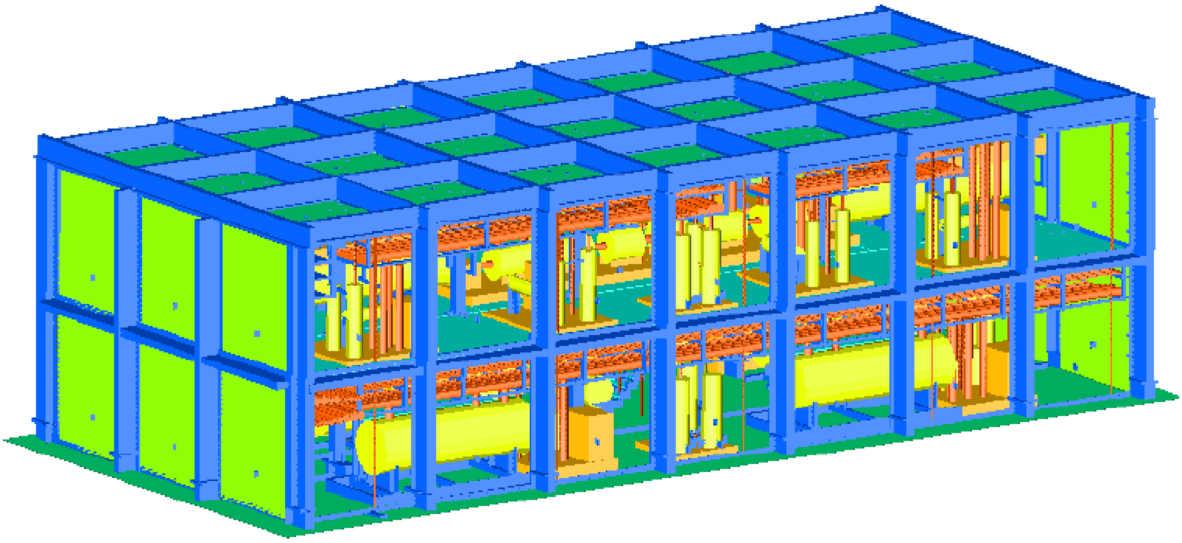
Figure 31: Comparison of accuracy between different CFD codes and experimental results from the MERGE project. FLACS simulations are marked with filled black circles. The outer lines indicate that most of the results are within a factor of two. Note that for experiments above 1000 mbar the accuracy degrades, and that FLACS seems to underestimate the pressures for this range. From Popat et. al (1996) *"Investigations to improve and assess the accuracy of computational fluid dynamics explosion models"*

[172] Popat et. al (1996) *"Investigations to improve and assess the accuracy of computational fluid dynamics explosion models*"

For these tests the accuracy of all the simulations preformed by FLACS is within a factor of 2. It must however be noted that the comparison also shows that FLACS underestimated many of the experiments with pressures above 1bar. This is not conservative, which means there is a need of the user to take the uncertainties into account to ensure sufficient conservatism. Better accuracy was obtained for pressures up to 1bar, which is often of most significance.

The joint industry program "Blast and Fire Engineering project for topside structures" provided further valuable experimental data to be used for validation. In the phase 3a project, funded by HSE and conducted during 1997-1998, a substantial number of experiments examining the effect of deluge on gas explosions were also included.[173]

A comparison between experimental data and FLACS simulation results for these tests has been conducted by Wingerden. A photo of the experiment geometry is presented in figure 32, together with the FLACS geometry.



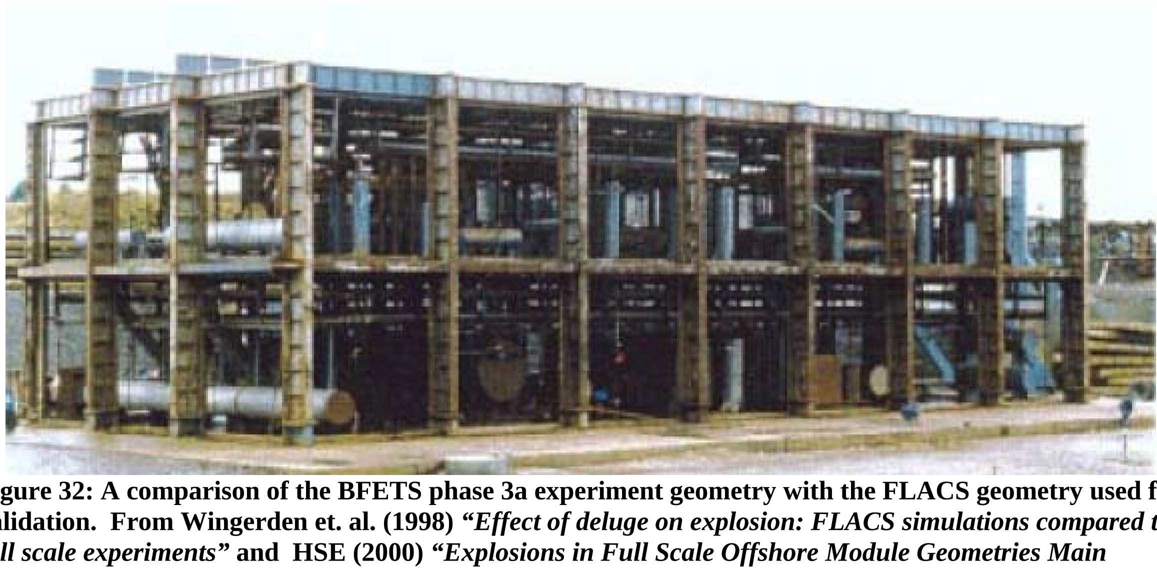


Figure 32: A comparison of the BFETS phase 3a experiment geometry with the FLACS geometry used for validation. From Wingerden et. al. (1998) *"Effect of deluge on explosion: FLACS simulations compared to full scale experiments"* and HSE (2000) *"Explosions in Full Scale Offshore Module Geometries Main Report"* OTO 1999 043

The module in depictured in figure 32 above is 12 meter high, 8 meter broad and 28meter long. Note that the experimental geometry was modified between different experiments to examine different configurations of

[173] HSE (2000) *"Explosions in Full Scale Offshore Module Geometry Main Report"* OTO 1999 043

equipment, walls etc. The photo might also taken from another angle than the FLACS geometry above. This explains the differences between the photo and the FLACS geometry.

Further comparisons between the deluge model in FLACS and experimental data are also presented by Dale[174]. A number of experiments that have been used to calibrate and validate the FLACS code have also been described by Arntzen.[175] Additional references, reports, papers and articles about the validation of FLACS are available at the Gexcon homepage[176].
The results of a validation study are displayed in figure 33 for tests both with and without deluge. [177]

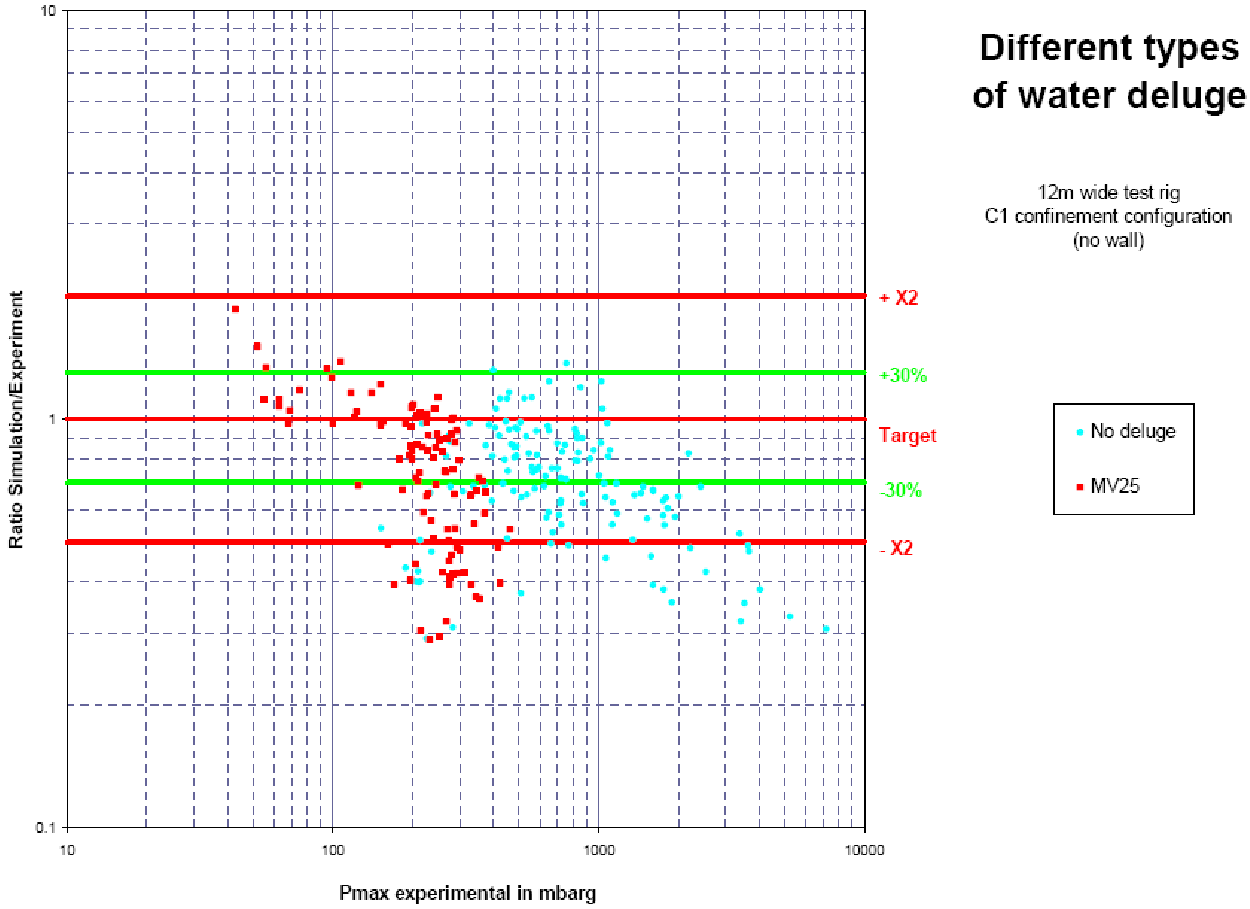


Figure 33: Comparison between experimental data and FLACS simulations for explosions with and without deluge. Although the scales are a bit confusing, the diagram shows that the majority of predictions are approximately within a factor between 0,5-2.
From Wingerden et. al. (1998)

Figure 33 illustrates the ability of FLACS to simulate explosion pressure with and without initiated deluge. The closer the markers are to target line, the closer the simulation is to the experiment. For markers above the target line, FLACS overestimates the pressure while for scenarios below the line the pressure is underestimated compared to experiments. It is interesting to note that there is possibly a trend from the upper left to the lower right in Figure 33. If this is indeed the case, this would mean that FLACS overestimates small pressures while underestimating large pressures. The diagram also shows that FLACS has its highest accuracy between 0,1-1bar(g) where it in general lies within a factor range of 0,5-2.

[174] Dale (2004) *"Simulation and modelling of waterspray in the 3D explosion simulation program FLACS"*
[175] Arntzen, B. J. (1998) *"Modelling of turbulence and combustion for simulation of gas explosions in complex geometries"*, thesis for doctoral degree at the Norwegian University of Science and Technology
[176] www.gexcon.com
[177] Wingerden et. al.(1998) *"Effect of deluge on explosion: FLACS simulations compared to full scale experiments"*

The ability of FLACS to model gas dispersion should also be mentioned briefly. Comparisons between FLACS predictions and dispersion experiments have recently been described by Savvides et. al.[178] and Hanna et. al.[179] For a typical offshore module, the results were typically within ±50% and a below a factor of 1.3. An illustration of some results is given in figure 34 below[180].

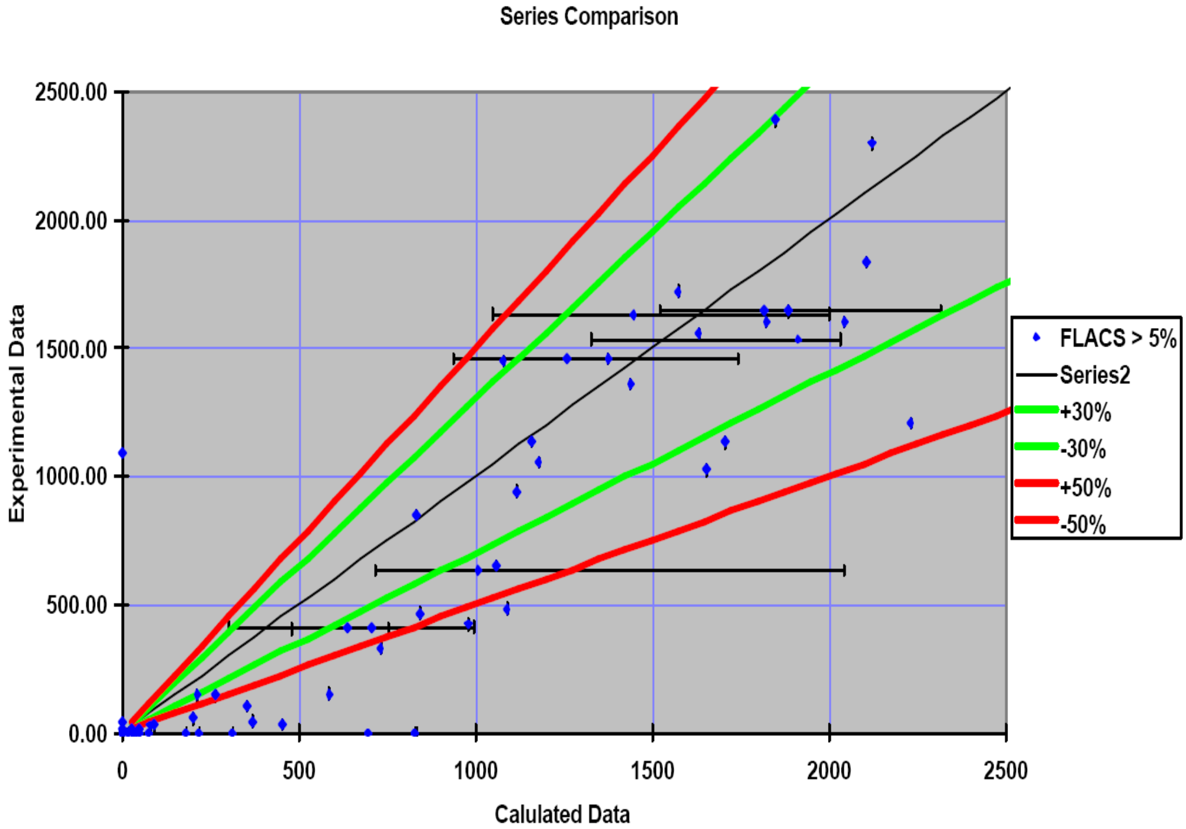


Figure 34: Comparison between gas dispersion predictions using FLACS and full-scale experiments. The diagram shows gas cloud volume with a concentration above 5%, which is typically the lower flammability limit of natural gas. From Savvides C. et. al. (2001) *"DISPERSION OF FUEL IN OFFSHORE MODULES: Comparison of Prediction Using FLACS and Full Scale Experiments"*, available at www.gexcon.com

[178] Savvides C. et. al. (2001) *"DISPERSION OF FUEL IN OFFSHORE MODULES: Comparison of Prediction Using FLACS and Full Scale Experiments"*
[179] Hanna S. et. al. (2004) *"FLACS CFD air quality model preformance evaluation with Kit Fox, MUST, Praire Grass, and EMU observations"*
[180] Savvides C. et. al. (2001) *"DISPERSION OF FUEL IN OFFSHORE MODULES: Comparison of Prediction Using FLACS and Full Scale Experiments"*

4.4 EXPRESS

DNV has developed the program software EXPRESS for calculation of probabilistic explosion load based on CFD simulations in accordance to the NORSOK standard Z-013. With the program the user creates mathematical correlations of the leakage and explosion scenarios based on the CFD simulations. These mathematical representations, called response surfaces, are then used together with Monte Carlo simulation teehnique to connect input probabilities/frequencies with the corresponding consequences. EXPRESS also includes an ignition model, based on a joint industrial project on ignition modelling.[181]
An overview of the EXPRESS methodology is illustrated in figure 35.

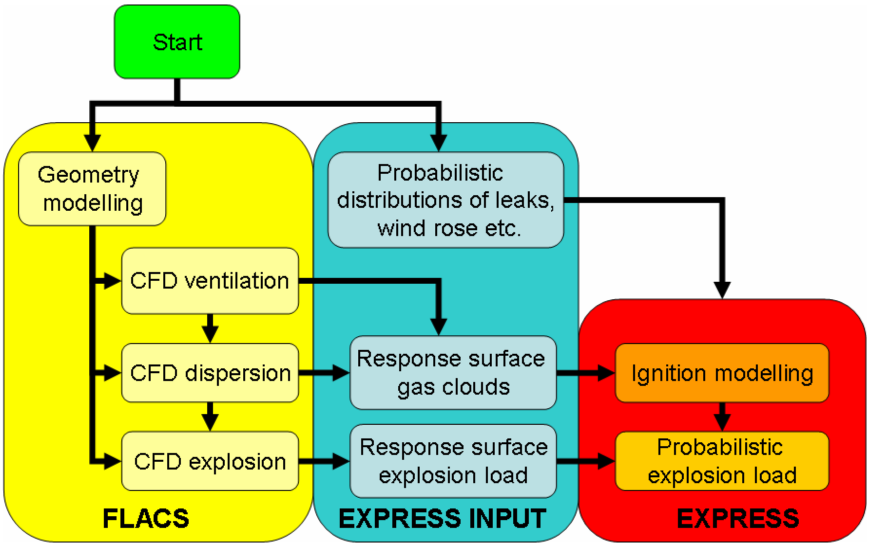


Figure 35: A Schematic description of the connections between FLACS and EXPRESS.

The gas cloud response surface can be described as a function that estimates the stoichiometric equivalent cloud as a function of time, wind speed, wind direction, leakage direction, mass rate given the leak location, gas type and module volume. Mathematically, this can be described as:

$$V_f = f(t, u, \dot{m}, \alpha, \beta | leaklocation, gastype, V) \quad \textbf{[Eq. 23]}$$

where

V_f = the volume of the effective gas cloud (the stoichiometric equivalent cloud) [m^3]
t = time [s]
u = wind speed [m/s]
$\dot{m}$ = mass rate [kg/s]
α = wind direction
β = leakage direction
V = the volume of the module

The dispersion response surface is based on the so-called "frozen cloud" assumption and analysis methodology. The assumption states that the concentration is proportional with leak rate and inversely with wind speed, and can be used to produce estimates on how the dispersion depends on leak rate and wind speed. The results from CFD dispersion simulations are then combined with the frozen cloud assumption to make estimates for scenarios not simulated. The frozen cloud estimates and CFD dispersion results are the used to express the non-dimensional gas cloud size V_F/V as a function of the non-dimensional leak rate.

[181] Huser, A et al (2000) *"EXPRESS- cost effective explosion risk management"*

The non-dimensional leak rate is defined as follows:

$$R = \dot{Q}_g / \dot{Q}_a \quad \textbf{[Eq. 24]}$$

where
$\dot{Q}_g$ = volume flow of gas from the leak [m^3/s]
$\dot{Q}_a$ = volume flow of air through the module [m^3/s]
Vf = volume of effective explosive gas in the cloud (stoichiometric equivalence cloud) [m^3]
V = the volume of the module [m^3]

The value of $\dot{Q}_a$ is known to be directly proportional to the wind speed. This means that only one ventilation simulation per wind direction is needed, since the value for other wind speeds can easily be scaled.

The response surface used to describe the explosion consequence is a function of the explosion pressure related to the stoichiometric equivalence cloud or to the non-dimensional gas cloud size (fraction of stoichiometric gas volume filling in the module). The explosion response surface is normally divided in two different parts. The first part of the response surface is exponential to account for the lower fractions of module filling. In this area, the explosion pressures are expected to increase rapidly with increasing gas cloud volumes. For larger fillings, the gas is pushed out of the module and will burn outside the module. Since there is no congestion or turbulence inducing equipment, it is argued that the pressure will not increase much further even if the gas cloud increases. To represent this, the second part of the response surface is modelled as a linear function.

5 Other aspects

5.1 Practical problems and solutions

A number of practical problems with deluge as an explosion mitigation has been pointed out by HSE/UKOOA[182,183]. The problems are presented together with suggested solutions or measures in figure 36 :

Possible practical problems	Suggested solutions and measures
i. The dependence of any explosion risk reduction effect on the effectiveness of gas detection and the reliability of initiation of deluge systems. Time is seen as a critical factor for deluge as explosion mitigation to be successful.	Both the time between gas leakage and initiated deluge together and the reliability should be estimated and presented in decision support. If necessary, improvements of the active systems may be considered. Due to the outmost importance, a time model is proposed in the next section.
ii. Issue of where gas might be displaced to as a result of activation of deluge (e.g. to more hazardous location)	This issue is still very difficult to simulate. CFD simulations of gas spread together with engineering judgement may be helpful.
iii. Increased probability of ignition due to water ingress in electrical equipment and instrumentation.	Protect instrumentation and electrical equipment at locations where deluge is activated on gas release. Combine deluge with ignition source shutdown.
iv. Creation of initial turbulence leading to increased rate of pressure rise, especial in confined situations.	Conduct CFD simulations with an incorporated deluge model, such as the FLACS code.
v. Conflict between the capability of deluge to provide explosion mitigation in addition to its primary function, i.e. fire protection.	The capability of fire water system to deliver 13-15 litre/m^2/minute and the capacity of delivering foam needs to be investigated.
vi. Frequent spurious deluge may lead to enhanced corrosion of equipment, which in turn may lead to increased leakage and/or ignition probabilities .	Spurious alarms can be minimized by proper engineering of the detection system. Corrosion can be dealt with through good maintenance routines.
vii. Increased downtime costs after an accidental gas leakage.	Increase preparedness to restart the process without compromising with safety.
viii. Increased maintenance and testing involved with deluge systems.	This can be dealt with through a structured maintenance program and routines.
xi. Impact on access and visibility for monitoring and controlling the incident.	The deluge should be possible to shut down if it is suspected to counteract its purpose of reducing the overall explosion risk.
x. Making egress through the module more difficult.	The personal in the module must be able to evacuate even when the deluge is effectively initiated, or evacuate before it is initiated.

Figure 36: Table overview of problems and suggested solutions with deluge as an explosion mitigation measure.

5.2 Q&A on how to use deluge as explosion risk reduction

During the work with the present report some questions emerged on how deluge should best be used as an explosion risk reduction measure. These questions are presented below together with the best available recommendations.

Is it possible to use sea water, or is it preferred to use clean water?
It is possible to use sea water, and it is even recognized that it might improve the effect slightly.[184] However, using sea water may increase the negative effects of corrosion.

[182] HSE/UKOOA (2002) *"CTR 104 –Management of explosion hazards"*
[183] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*
[184] Thomas, G.O. (2002) *"On the conditions required for explosion mitigation by water sprays"*

What amount of flow is needed?
According to HSE, the recommended water application rate is 13-15 liter/m^2/min. It is however expected that lower water application rates, such as 10 liter/m^2/min, generally will have a beneficial effect. The effect of different water application rates can be modelled with FLACS.

Should the whole module be covered or is it sufficient with partial deluge or equipment specific deluge?
The whole model should be covered for an optimal effect.

Should foam be used?
Theoretically, the use of foam lowers the surface tension of the water drops. Lower surface tension in turn leads to a higher Weber number. This means that drops will break-up more easily with foam than without, which is theoretically beneficial for explosion mitigation effect.

However, the effect of using foam has not been tested enough experimentally. Further, the use of foam on gas detection may drain the fire-fighting system from foam. For these reasons, it is recommended that foam is not used for explosion mitigation alone. If foam is used for explosion mitigation despite this recommendation, it needs to be proved that the potential conflict between fire and explosion mitigation systems is taken into account.

What deluge drop size is required to use deluge as explosion mitigation?
Experimental research has shown that generally larger drops have better effect than smaller drops. Drops between 0,020 – 0,2 mm are expected to be the least effective for explosion mitigation. The droplet sizes from standard MV (medium velocity) and HV (high velocity) nozzles can generally be expected to be suitable for explosion mitigation, according to HSE.

Also, it should be noticed that any deluge system will produce a droplet size distribution rather than perfectly and equally sized spray of droplets. It is however not possible yet to account for the full droplet size distribution in FLACS.

Should deluge be manually or automatically activated?
A combination enabling both manual and automatic activation of deluge is recommended in order to minimize the time from the leakage starts until deluge has been efficiently activated.

5.3 Time model

To protect life and property a number of active systems are installed on offshore platforms to detect and respond to any accidental gas release. An accidental leakage will initiate a chain of events to launch a number of different safety systems. This is called the safety shutdown system in NORSOK terminology. First of all, the leakage needs to be detected either manually or by automatic detectors. After gas detection a series of various actions may be initiated. This system includes actions such as shutdown of the process and the ignition sources, sending dangerous substances to the flare, relieving the pressure in process equipment, closing isolation valves and evacuating the platform. More important to the present study, the response to a gas leakage could also be the initiation of deluge. The different response actions are often described in a hierarchy diagram of emergency shut down (ESD).

There are four different ESD levels, ordered in falling levels of seriousness:

i. Abandon platform shutdown (APS)
ii. Emergency shutdown level 1 (ESD1)
iii. Emergency shutdown level 2 (ESD2)
iv. Process shutdown (PSD)

Parallel to the chain of active systems, the accident may develop into different directions, as described in chapter 3.1. A direct ignition of the leakage will lead to a jet flame, while a delayed ignition of a premixed air-gas mixture may explode. For deluge to be effective as an explosion mitigation measure it needs to be initiated before ignition. The initiation of deluge is thus competing in time against the development of the accident event. The time to initiated deluge after accidental gas release is therefore critical to the mitigation effect of deluge on gas explosions. This is illustrated in figure 38 .

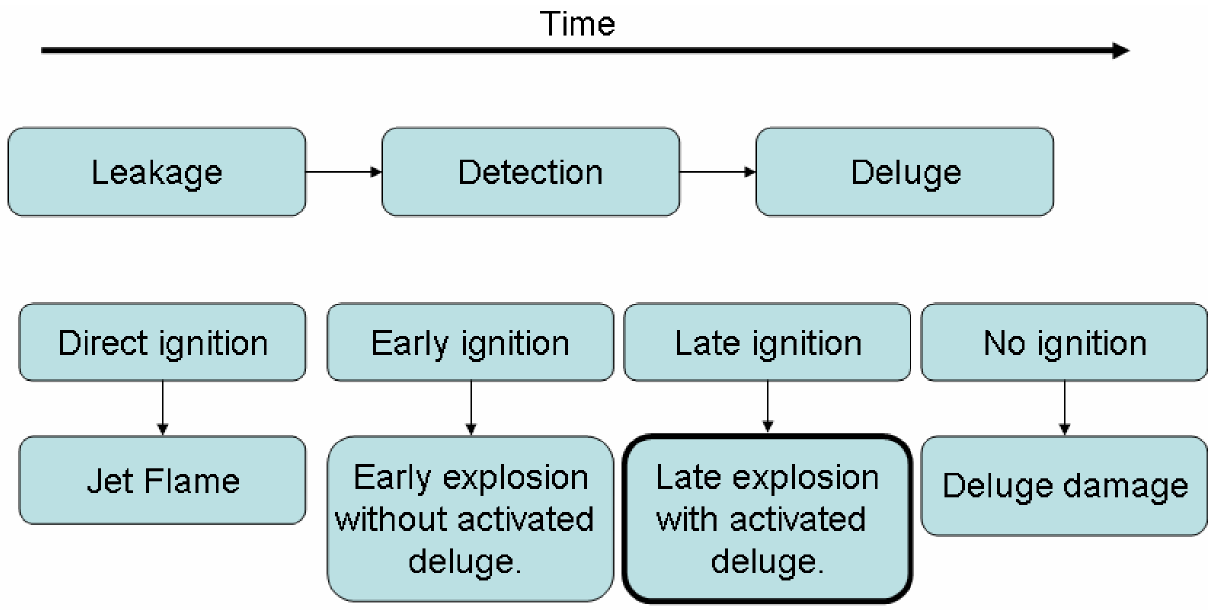


Figure 37: Illustration of the competing of time between the activation of deluge and different possible outcomes of a gas release.

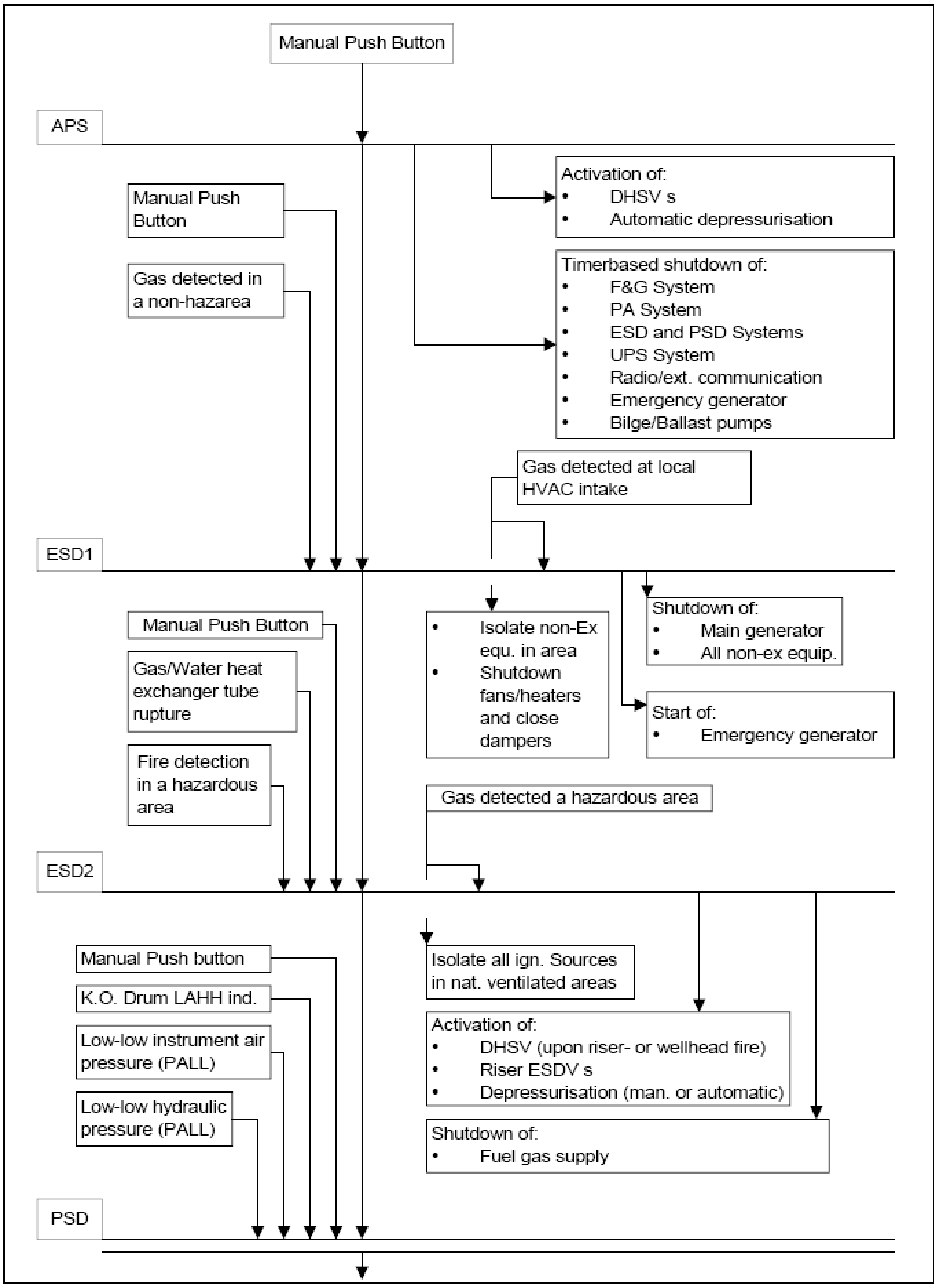


Figure 38: A simplified example of ESD hierarchy, from NORSOK S-001. Activation of the higher levels automatically all the levels below. The means of activation of the different levels are also indicated by the arrows. It must be noted that the ESD hierarchy diagram used in reality are much more detailed and cover a broader set of responses.

Based on the basic concepts of the egress model from Frantzich[185] and the information from HSE[186], a simple model to estimate the time from an initial leakage to activated deluge together with a critical deluge criteria is proposed below:

$$t_{Deluge} = t_{Detection} + t_{Reaction} + t_{Response} \qquad \textbf{[Eq. 25]}$$

where $t_{Deluge} < t_{Ignition}$ expresses a critical criteria for deluge to effective as a mitigation measure. The above parameters can be described as:

t_{Deluge} = Total time from gas leakage to effectively activated deluge. Effectively activated deluge is defined as water out of the nozzles at sufficient flow rate covering the whole module. HSE estimates t_{Deluge} to be on the order of 60-90 seconds[187]. It is recommended to measure t_{Deluge} directly in situ experiments with tracer gas.

$t_{Detection}$ = Time from gas leakage to detection and successful transmission of the first signal. This value depends on both the detection system and the transition system such as wires, voting devices etc. HSE suggests that an acoustic gas detector should be used when possible[187]. The reliability of the detection system to actually detect the leakage needs to be addressed. A recent report based on statistics from the British sector shows that only ~56% of the gas leakages were detected by the equipment fitted for that purpose[188].

$t_{Reaction}$ = Time from receiving the first signal to initiating a response. Two different approaches are acceptable by NORSOK standard: either a voting philosophy or single philosophy should be used[189]. $t_{Reaction}$ includes an operator judgement or automatic voting decision when to initiate the response. In order to minimize $t_{Reaction}$, it is recommended to enable both manual and automatic activation of deluge. For example, deluge buttons could be installed in the modules and in the control room if the automatic initiation should fail. At the same time, automatic activation is expected faster than manual activation. The initiation of deluge needs to be incorporated in the ESD hierarchy.

$t_{Response}$ = Time from initiation of the response until the response is successfully implemented.
This phase includes the initiation of fire water pumps, pressurization of the system, the transport of water to the most distant nozzles. $t_{Response}$ can be shortened by starting fire water pumps automatically at the first indication of a gas leakage. It is an NORSOK requirement that $t_{Response}$ should be below 30 seconds.

$t_{Ignition}$ = Time from gas leakage to effective ignition of gas cloud. This needs to be modelled based on each leakage scenario, since the gas cloud development is coupled to the probability of ignition.

It is expected that t_{Deluge} will vary with leakage size, since $t_{Detection}$ will be coupled to how the fast the cloud develops. Larger leakage sizes will lead to more gas in the module and a faster growth of cloud size. As the cloud grows in size, the probability of detection increases as more detectors are likely to come in contact with gas. Therefore, large leakages are generally expected to be detected faster than small leakages. A similar trend is also expected for $t_{Ignition}$. The more potential ignition sources that come in contact with the explosive gas, the higher the probability of ignition. An important difference between detection and ignition is that detection is possible whenever the lower limit of the detector is reached, while ignition require the gas concentration to be within the flammability limits.

It is also worth noting that a small leakage can result in a larger stoichiometric equivalence cloud than a large leakage, depending on the combination of other variables such as ventilation, gas leakage location, leakage direction in relation to wind direction etc.

[185] Frantzich (1994) *"A modell for performance-based design of escape routes"*
[186] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*
[187] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*
[188] HSL (2005) *"Offshore ignition arguments"*
[189] NORSOK (2000) *"S-001 Technical Safety"*, Annex F

5.4 Influence diagram

Based on the previous sections in general and an influence diagram has been developed to further clarify the influences between the safety response chain, the explosion chain and the event outcome. The dotted arrows describe possible influence while solid arrows describe casual relationships. The influence diagram presented in figure 39 is a modified version of the influence diagram from the paper by Bolsover et. al.[190]

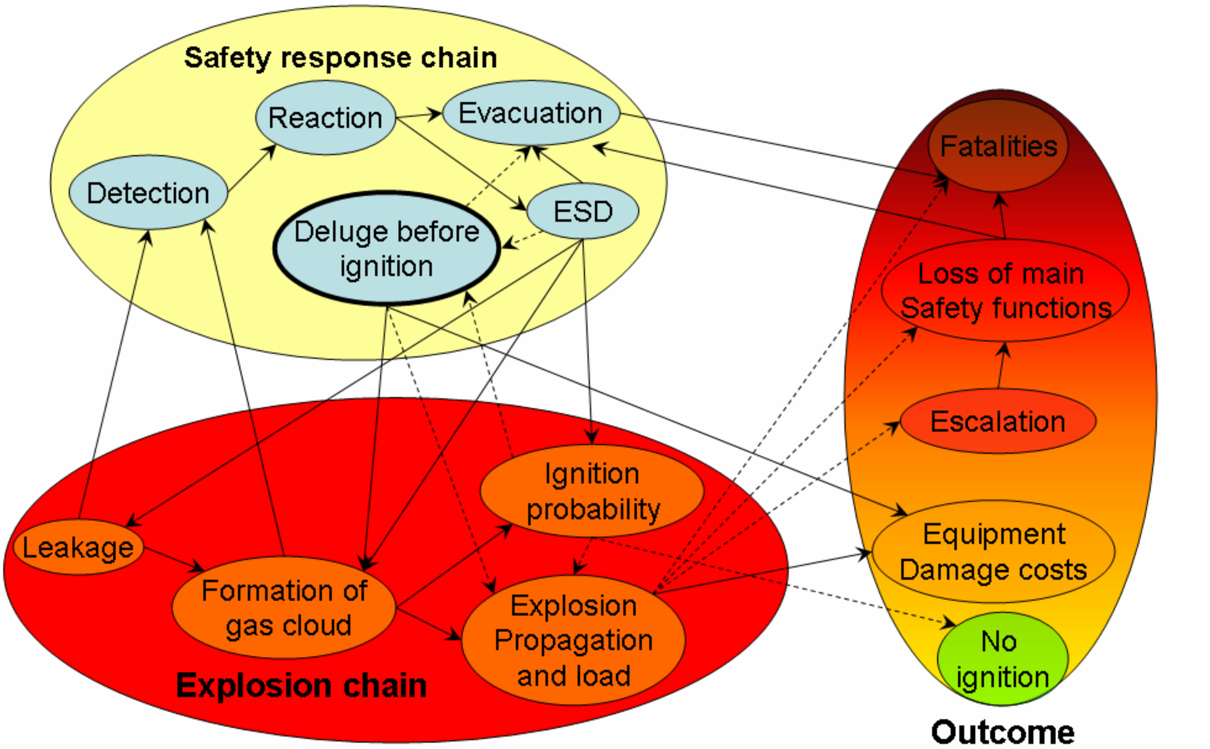


Figure 39: Influence diagram to show the complexity of the decision whether to implement deluge as an explosion mitigation measure or not. Thick arrows indicate a certain influence, while dotted arrows indicate possible influence, depending on the circumstances.

The influence diagram is seen as useful to communicate about the complexity of explosion mitigation.

5.5 Cost-benefit of deluge as explosion mitigation

Based on the net present value method expressed in Eq. 4, cost-benefit of deluge as explosion mitigation may be expressed as follows:

$$NPV = -G - a\sum_{k=1}^{n}\frac{1}{(1+i)^k} \qquad \textbf{[Eq. 4]}$$

$$a = a_{Regular} + (fr_{FalseAlarm} \times (a_{DelugeDamage}) + \sum(fr_{Difference} \times (\pm a_{Risk})) \qquad \textbf{[Eq. 26]}$$

$$fr_{Difference} = fr_{With\_deluge} - fr_{Without\_deluge} \qquad \textbf{[Eq. 27]}$$

where
NPV = Net present value of costs
G = Initial investment cost of installation of deluge
a = Expected annual costs due to deluge
n = Platform life time

[190] Bolsover A. et. al. (1999) *"Decision-making to treat an explosion hazard"*

i = Interest rate
k = Year (from 1 and n)
$a_{Regular}$ = Increased regular maintenance costs

$fr_{FalseAlarm}$ = Expected yearly frequency of false alarms leading to initiated deluge. This can be estimated with the statistical failure rate data from the OREDA database, combined with platform specific observations. A priori, the frequency of spurious hydrocarbon gas detector operation can be approximated with the mean failure rate of 2,44 per 10^6 hours operational time[191]. This is equivalent to a spurious operation failure rate of 0,021 per detector and year.

$a_{DelugeDamage}$ = Increased costs associated with spurious deluge activation.

$Fr_{Difference}$ = Expected yearly difference in explosion frequency corresponding with a particular economic consequence, $a_{Reduced}$.

$a_{Reduced}$ = Particular economic consequence of deluge in case of an explosion corresponding to a certain frequency. This means a decreased costs in cases of decreased explosion risk and vice versa. In cases the deluge has a beneficial effect, $a_{Reduced}$ will have a negative sign to indicate cost reduction.

$a_{Reduced}$ is found by linking a an explosion response to an economic consequence, based on the equipment in the process module being analysed. As an example, imagine a process module where there is a heat exchanger present. Literature studies[192] suggest that a heat exchanger exposed to an explosion load of approximate 60 kPa overpressure will suffer catastrophic failure. The cost of such a catastrophic failure then needs to be estimated.

Finally the expected difference in yearly frequency of explosion of 60 kPa can be estimated from the cumulative explosion load diagram with and without deluge. The cumulative explosion load diagram needs to be translated to a probability density function before the expected values can be calculated. Note that it is the difference in explosion load frequency between with and without deluge that is used in the calculation. As mentioned above, the cumulative explosion load diagram is the suggested output from the explosion risk analysis. The difference in yearly frequency of 60kPa explosions multiplied with the cost associated is then calculated to represent the risk reduction by using deluge.

The suggested model is a simplified approach to CBA. For a complete CBA, the fatality risk reduction and property risk reduction needs to be modelled and included. For the decision support the suggested cost estimate is considered to be sufficient in most cases.

It is expected that the above input will be hard to quantify and involve great uncertainties. The explosion risk diagram includes an amount of uncertainty due to the complexity of modelling explosions, and economical input may be hard to achieve. One way of handling this is by using Monte Carlo analysis techniques, where input parameters can be entered as probability density functions rather than single values. Another benefit of using such an approach is that it will help the risk analyst to examine what input has the greatest impact on the result.

---

[191] OREDA (2002) *"Offshore Reliability Data Handbook"* , 4th edition
[192] Cozzani et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I. Probit models"*

6 Decision support framework

In this chapter the findings, methods, approaches, arguments and assumptions found in the previous chapter are first summarized. They are then used to derive a decision support framework. It was also concluded that due to the rapid development of regulations, standards and science the decision maker should always start the analysis with a review to ensure that the decision is in accordance to the latest available information

6.1 Summary of findings in Part 1

The findings from the first five chapters are presented in the next section.

6.1.1 Findings from decision aspects

i. Before conducting the risk analysis that will be core of the decision support, a brief decision analysis is needed to clarify and anchor the decision-makers preferences. This can be done by answering the following five questions:
   - Who is the decision maker?
   - Who are the relevant stakeholders?
   - What alternatives are under consideration?
   - On what dimensions should the alternatives be evaluated and best presented?
   - How should practicality and simplicity on the one side be balanced be with precision, validity, reliability and theoretical support on the other?

ii. Facts and judgements should be separated as far as possible. It is the risk analysers job to find and present the facts to the decision maker, who then makes the judgements and final decision.

iii. It is recommended to use an cumulative explosion load diagram to represent the particular risk decision alternatives of this study together with the minimum 10^{-4} requirement criteria from the Norwegian legislation. This information is expected to be sufficient to evaluate and rank the best decision alternatives according to the BAT and equity-based part of the suggested hybrid criteria.

iv. The costs of implementing deluge should also always be estimated. If the decision-maker requires, additional decision support may be calculated such as the fatality risk reduction and then even more sophisticated utility-based measures.

6.1.2 Findings from the analysis of laws, regulations and standards

During the analysis of laws, regulations and standards it became obvious that the regulations and standards are under continuous development. Although it might be unrealistic for an older installation to keep up with the development, it is considered to be important that the decision maker is updated with the development of the legislation, standards and the scientific progress. The analysis of laws, regulations and standards presented above has led to a number of conclusions and assumptions that are summarized in the following section.

Law and regulations:

i. The age of the installation determines the judicial requirements. It is thus important to start the analysis with the regulation requirements for the specific installation.

ii. The decision criteria should be a hybrid criterion based on of the legal requirements, minimum company acceptance criteria and a value-based BATALARP accept criterion. The burden of proof lies on the company to show that a mitigating risk measure is unreasonably expensive.

iii. For new installations, the law requires an analysis and evaluation of the effect of deluge on confirmed gas detection. If deluge is expected to have a beneficial effect on the explosion pressure risk, it should be implemented without consideration to other dimensions. The decision criterion is then close to the technological best available technology criterion and no costs considerations should be taken into account.

iv. For older installations, the present standards and regulations shall be considered normative rather than prescriptive and applied according to the ALARP-principle. The ALARP-principle is close to the value-base decision criteria. This is also consistent with ISO 13702.

v. Due to the law requirements concerning fire safety, deluge can be assumed to be installed in all hazardous areas. It should however be recognised that the practical requirements between fighting a fire and mitigating an explosion differs.

vi. The analysis of the specific installation should examine whether the system is suitable for explosion mitigation or not.

NORSOK and ISO standards:

i. The NORSOK standards are closely related to the regulations and are thus an important source when interpreting the regulations.
ii. According to the NORSOK standards, it is obliged to evaluate the effect of deluge as an explosion mitigation measure. The NORSOK have been used to argue for a risk perspective interpretation of §36 in the Facilities regulations. It is the explosion overpressure risk that should be analysed, rather than the worst-case consequence.
iii. The modelling of deluge effect on the explosion overpressure can be preformed using the CFD-tool FLACS. A detailed description of a probabilistic method for explosion risk analysis is given in NORSOK Z-013, Annex G. It is recommended to use this method to ensure that the explosion risk and deluge analysis fullfill the requirement of the regulation to analyse and evaluate the effect of deluge on explosion.
iv. Changes in ignition probability due to deluge can be ignored if it can be assumed that all electrical equipment has been sufficiently protected from water ingress.
v. It is necessary to calculate or measure directly the time between confirmed gas detection and deluge in order to analyse the efficiency of deluge as explosion mitigation.

HSE/UKOOA standards

i. Although not directly related to the Norwegian offshore regulations, these standards should be recognised as valuable sources of information and references.
ii. The HSE/UKOOA standard concludes that standard HV and MV deluge nozzles are suitable to mitigate congestion generated explosion overpressures.
iii. Deluge is not suitable for totally confined areas, since the acceleration of droplets is to low to lead to sufficient droplet break-up and thus no mitigating effect.
iv. Deluge should cover the general area rather than specific equipment.

.

6.1.3 Findings from explosion basics and modelling

One of the main conclusions from the explosion basics is that it is a complex and difficult phenomena. When evaluating the strengths and weaknesses of different explosion modelling approaches, it seems obvious that none of them are flawless. The empirical and phenomenological models lack the possibility to take the geometry and thus the important turbulence generation process into account which leads to less accuracy than CFD modelling. This flaw is compensated with shorter run times and a portion of increased conservativeness.

In spite of all the weaknesses described above, CFD seems to be the most advanced, accurate and theoretically founded approach today. The fact that CFD modelling of explosions are recommended in the NORSOK standards is also a strong argument. The effect of deluge may also be modelled, which allows comparisons of explosion consequences with and without deluge. It is also possible to conduct ventilation and gas spread simulations with the same tool, which simplifies the analysis work. Based on these arguments, it is concluded that a careful and conservative use of CFD modelling is the best available method for purpose of the present study. Focus should be put on the general trends, which CFD reproduces fairly well rather than to focus only on the strict numbers. Suggestions on how to handle the uncertainties in explosion risk analysis was also discussed.

6.1.4 Findings from simulation aspects

The main conclusion of from chapter 4 is FLACS and EXPRESS can be combined to quantify the explosion risk with and without deluge. As mentioned in chapter 3, CFD is a powerful tool to analyse explosions but there are often large uncertainties in the results. This is also the case for FLACS. It was also found that the deluge model of FLACS was however found to be based on simple empirical correlation rather.

6.2 Derivation of framework

Based on Part 1 a decision support framework of methods, input and models has been derived. A general illustration of the framework is presented in figure 40 in the next section.

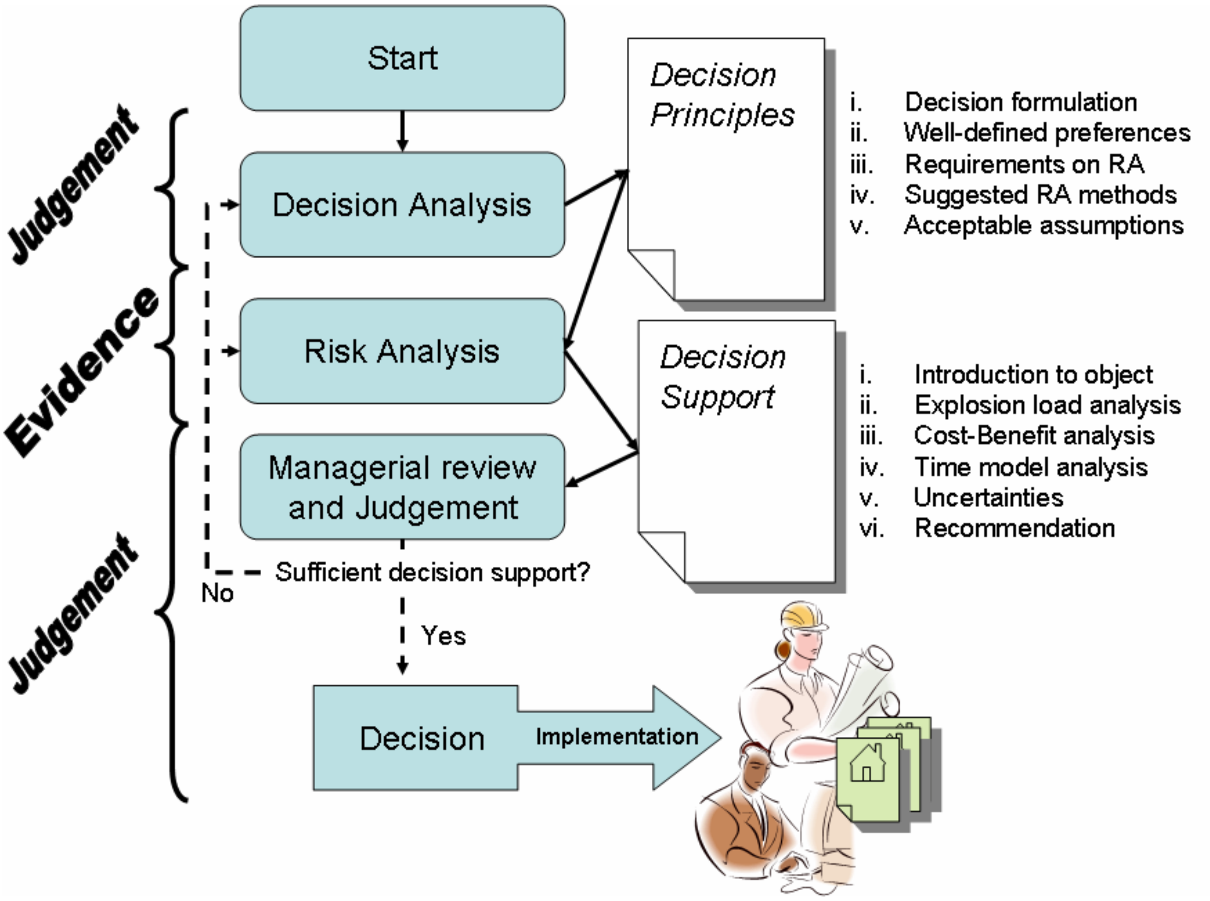


Figure 40: A schematic description of the suggested decision framework. Note that the outputs from the Decision Analysis and Risk Analysis are represented as the Decision Principles and Decision Support documents. Based on the decision and risk management process described by Aven et. al.

6.2.1 Decision analysis

Before conducting the risk analysis that will be the decision support, a brief decision analysis is preferred to clarify and to examine and define the decision-makers preferences. This can be done by answering the following five questions:

i. Who is the decision maker?
ii. Who are the relevant stakeholders?
iii. What alternatives are under consideration?
iv. In which dimensions should the alternatives be evaluated and best presented?
v. How should practicality and simplicity on the one side be balanced be with precision, validity, reliability and theoretical support on the other?

By answering these questions the decision principles are formed, which are then used as input to the risk analysis. There are two main gains with this approach. First of all, it enables the preferences of the decision maker to be the foundation of the risk analysis. Secondly, the judgement and facts are kept apart in a systematic way. It is important that the decision principles are well documented.

6.2.2 Well-defined preferences

A basic assumption is that the decision need to comply with the legal preferences of the Norwegian authorities expressed in the laws and regulations. Based on interpretations of the offshore safety regulations, a hybrid risk criterion has been derived. Once the legal obligations have been fulfilled, company specific criteria may be incorporated. An illustration of the suggested hybrid risk criterion is given in figure 41 in the next section:

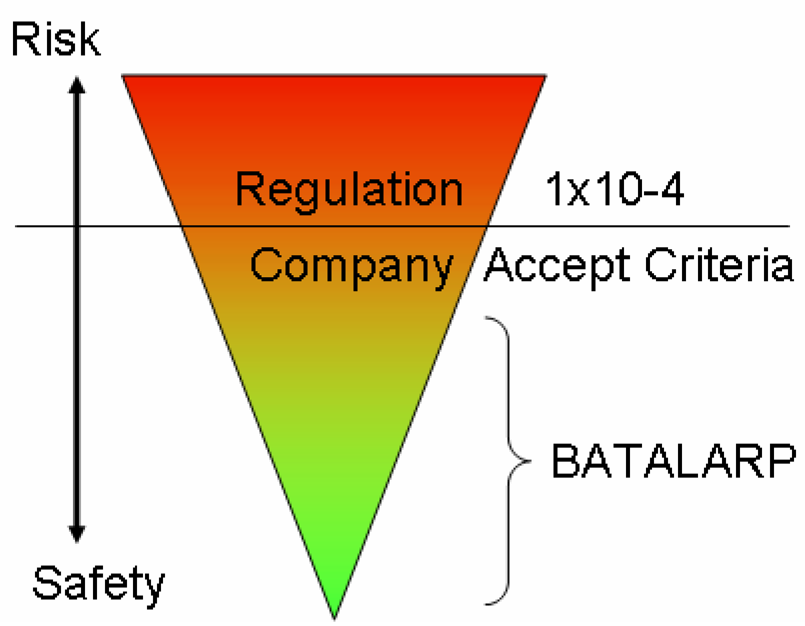


Figure 41: Suggested hybrid criterion in the decision support framework.

The legal requirement, stating that the risk of loss of a main safety should be below 10^{-4}, also needs to be unambiguously defined for each specific installation module.

It is suggested that the hybrid criteria is evaluated with a cumulative explosive risk load diagram, containing the two decision alternatives together with the relevant explosion response data for direct comparison. A cost estimate should also be calculated to give the decision maker a first indication.

6.2.3 Problem formulation

There are basically two decision alternatives to take into account, namely:

Alternative 1: Deluge should **not** be activated on gas detection to mitigate the explosion load.

Alternative 2: Deluge should be activated on gas detection to mitigate the explosion load.

For the second alternative, there are further considerations and practical problems that need to be addressed. There is a need to optimize, describe and adjust the second alternative to the platform module in question. Strictly speaking it is only the most optimal configuration of alternative 2 that needs to be compared to with alternative 1, assuming that the most optimal configuration possible will always be chosen. It is however interesting from a scientific point of view to examine the impact of different configuration on the overall explosion risk.

6.2.4 Requirements on risk analysis

The risk analysis is required to produce a cumulative explosion load diagram, including the specific legal requirements and decision maker preferences together with the two decision alternatives. In addition a coarse estimate of the costs attached to the decision alternative should be calculated. A simple but supposedly sufficient model has been proposed. It is required that the input is as transparent and traceable as possible. Uncertainties should be addressed, and a number of methods and approaches have been presented in the previous chapters.

6.2.5 Suitable risk analysis methods

Based on the comparisons between different approaches to explosion modelling, it is argued that CFD models are the most accurate and suitable for calculating gas dispersion and explosion load available today. Both the decision maker and the risk analyser need to be aware of the uncertainties of limitations of CFD explosion modelling. In order to combine the calculated consequences with their respective probabilities, a Monte Carlo-simulation program called EXPRESS will be used. The methodology is similar to the probabilistic explosion risk analysis presented by NORSOK Z-013.

A time-model has been proposed to estimate the total time from leakage initiation to effectively activated deluge. It is recommended that the input to this model is measured in situ.

6.2.6 Acceptable assumptions

Any attempt to model a complex reality requires simplifying assumptions. There is a need to strike a balance between practicality and simplicity on one side and scientific accuracy, reliability and validity on the other. Three assumptions, aimed at balancing these both sides, are suggested:

i. It may be assumed that the overall ignition probability will not increase due to the use of deluge as an explosion mitigation measure. For this assumption to be valid, all electrical equipment is required to be sufficiently protected against water ingress as a result of water deluge.
ii. It may be assumed that the use of deluge as an explosion mitigation measure will not lead to an increased probability of leakages. For this assumption to be valid, a sufficient maintenance program is required to prevent corrosion.
iii. The NORSOK methodology for probabilistic explosion risk modelling together with FLACS and EXPRESS tools are assumed to be an acceptable approach despite their flaws and limitations.

The underlying assumptions in FLACS, EXPRESS and the NORSOK probabilistic explosion risk analysis methodology are not presented here, since they are discussed elsewhere. During the work with the explosion risk analysis process, further assumptions may be necessary that are not possible to foresee. For example, lack of appropriate input may require the use of engineering judgements, estimates, etc. These assumptions and judgements need to be checked against the decision makers preferences, either continuous during the work or in the managerial review and judgement phase.

6.2.7 Explosion risk analysis

After the decision principles have been established, the explosion risk analysis is initiated. This is the core of the decision support. In contrast to the decision principles which consist of judgements and arguments, the explosion risk analysis should be based on facts. Some of the most important outputs of the explosion risk analysis include:

i. Input
ii. Risk calculations
iii. Results
iv. Uncertainties
v. Recommendation

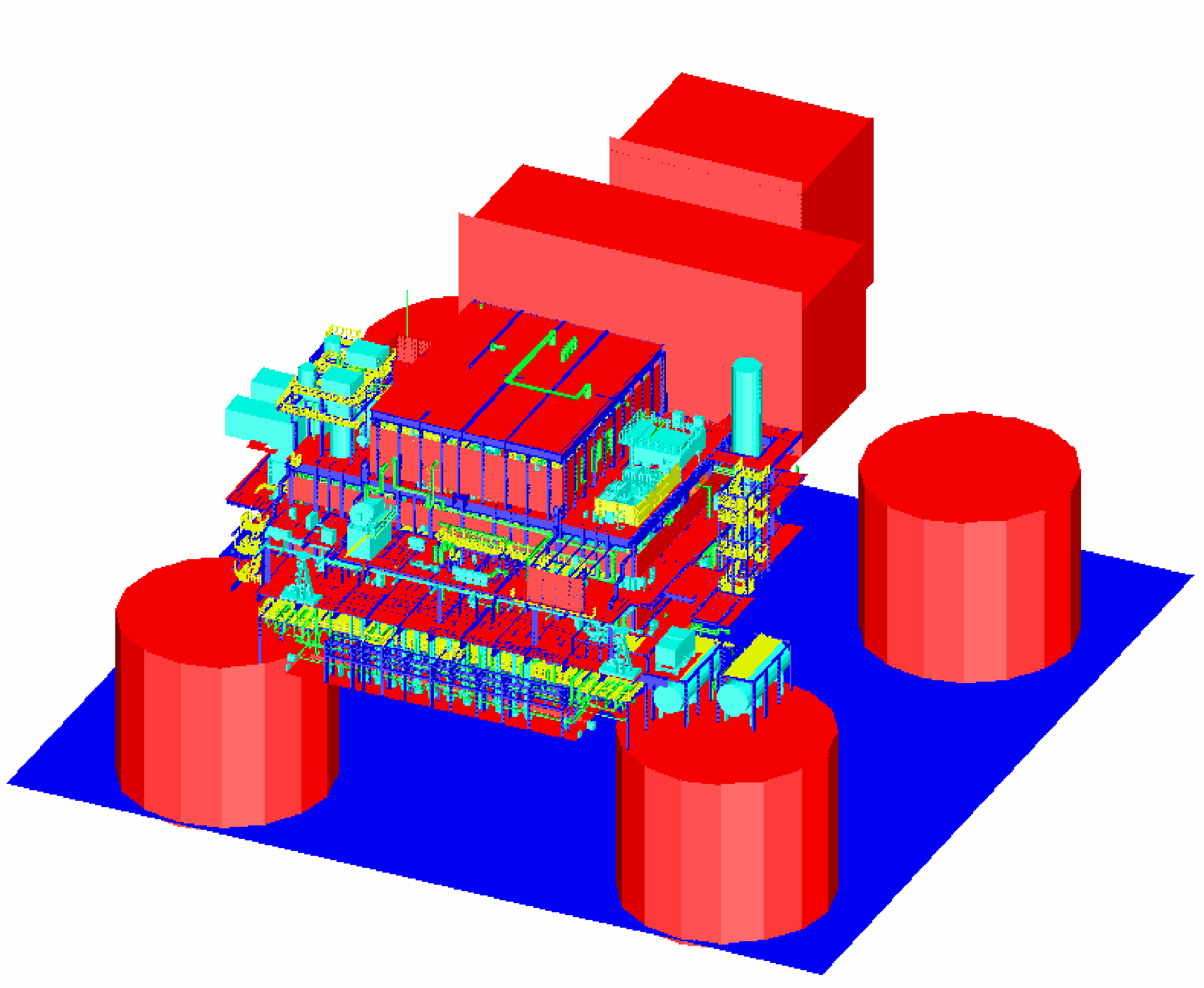
The following structure of the explosion risk analysis is proposed as a template:

- 1.1. Introduction to object
- 1.2. Explosion load analysis
  - 1.2.1. Ventilation
  - 1.2.2. Dispersion
  - 1.2.3. Explosion
  - 1.2.4. Probabilistic analysis
- 1.3. Cost-Benefit analysis
- 1.4. Time model analysis
- 1.5. Uncertainties
- 1.6. Recommendation
- Appendix A: Transparent and traceable input list
- Appendix B: List of simulated scenarios

6.2.8 Managerial review and judgement

The managerial review and judgement phase is needed to review the explosion risk analysis results in the light of all the assumptions, limitations, input, engineering judgements etc. The results and analysis will always be case specific. Thus a case specific judgement is needed to decide whether the decision support is sufficient to make the final decision, or if further analysis is needed.

PART 2: CASE STUDY of Troll B



7 Case study of Troll B

The case study followed the suggested framework as outlined in previous chapters. During the case study, results were continuously interpreted. Unfortunately it was not possible to conduct a full probabilistic explosion analysis in accordance with NORSOK Z-013 as planned due to limitations in resources and time. This can be explained by:

Delay and difficulties in getting important input.
Delay in getting the CFD geometry model.
Difficulties with CFD simulations of dispersion and large explosions.
Difficulties with exporting and analysing the CFD dispersion results.

Despite these difficulties and delays, the case study results are still seen as useful for evaluating the proposed framework. The results and conclusions of the case study also included a recommendation for the object of the study, even if it was not possible to reach the suggested decision support. Instead, a simplified decision support is presented.

7.1 Introduction to the object

The Troll B platform was built in 1995. The platform is a supported by four floating concrete pontoons and a module support frame, which are then anchored to the sea bottom. To the platform 18 underwater production units are tied in. A mixture of oil and gas is pumped up from the underwater production units to the platform and it is then separated and processed on the platform. The processed oil is exported to shore and the gas is transported to the Troll A platform by 15” pipes. The expected capacity of the platform is 35 000 m^3 oil and 8 000 000 m^3 natural gas per day. The five platform modules are illustrated in figure 42 :

i. Living quarters
ii. Process support module
iii. Process module
iv. Unclassified Module Support Frame
v. Classified Module Support Frame

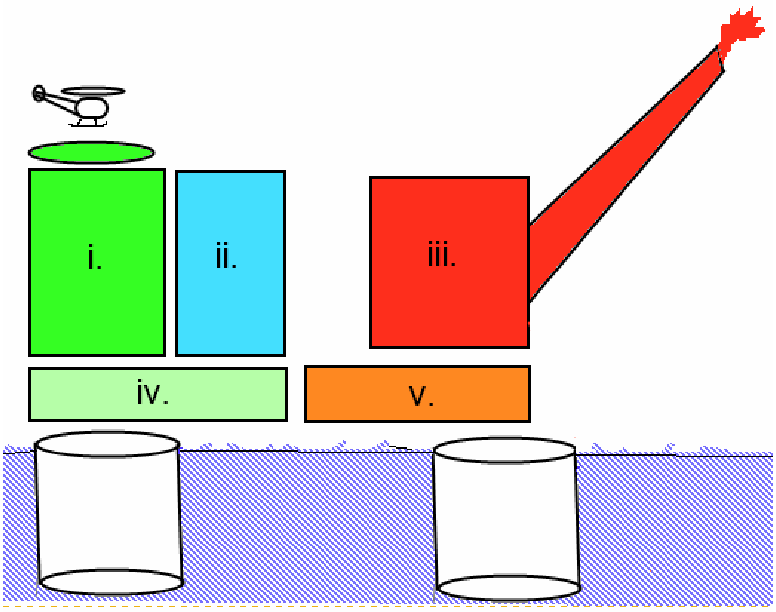


Figure 42: Schematic illustration of the Troll B platform. The platform is constructed to separate the living quarters, helipad and process support module as far as possible from the more dangerous process module, the flare system, the risers and export pipelines.

The process module consists of three decks: the main deck, upper deck and weather deck. Explosion barriers separate the process module from other parts of the installation. These barriers consist mainly of the west wall, the main deck and the upper deck of the process module. The west wall of the process module (iii) separates the process module from the process support module (ii) together with the east wall of the process support module. For an explosion to break both these walls and thus the separation barrier an estimated static pressure of 0,6 bar(g) is required, based on calculations from the latest available risk analysis[193]. The west wall of the process module and east wall of the process support module are designed to withstand up to 0,25 bar(g) and 0,10 bar(g) respectively. The main deck separates the process module (iii) from the Classified Module Support frame (v.). Structure calculations from the latest risk analysis also shows that the main deck can survive pressures up to 0.5 bar(g)[193]. Pressure relief panels are installed on the north, east and south sides to mitigate the consequences in case an explosion occurs.

A more detailed illustration of the process module is given in Figure 43.

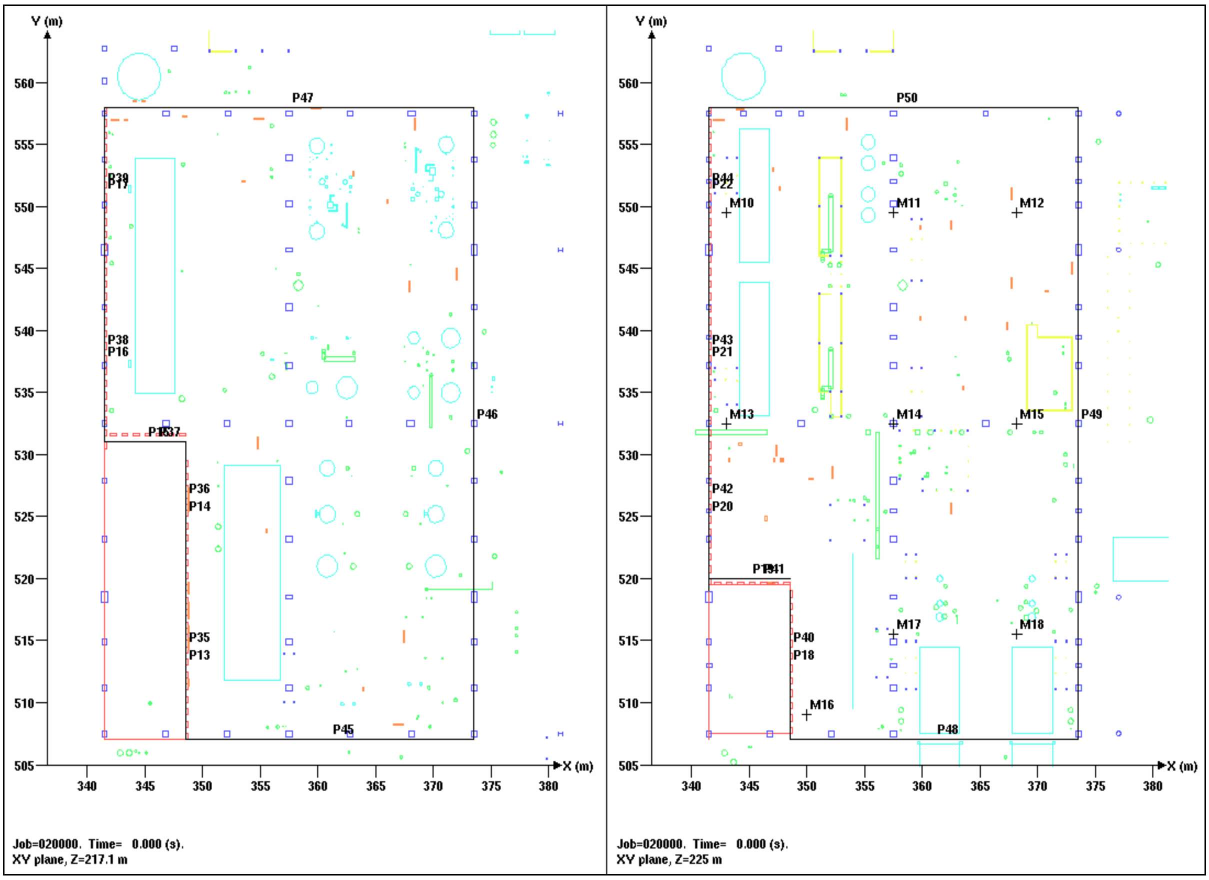


Figure 43: An illustration of the process module as seen from above. The left picture illustrates the main deck, while the right picture illustrates the upper deck. The letters and numbers illustrate the different pressure panels and measuring points used in the analysis: P for pressure panel and M for measure point. A similar set of monitor points was for both deck. Panels also covered the main and weather deck. P45 – P50 represent pressure relief panels, while all other panels represent measure panels where the results of the explosion simulations where recorded.

To the lower left in the illustration of the main deck and upper deck, the measure pressure panels display the limits of the fire and explosion barrier separating a local equipment room at the main deck and a HVAC room on the upper deck from the rest of the module. The large rectangles close to the left wall on the main and upper floor illustrates the separators. The larger circles to the right on the main deck illustrate the scrubbers. Other equipment in the module includes the compressors, water recovery, heat exchangers, pipes, and structure elements.

7.2 Decision Analysis

In accordance with the suggested framework, the risk analysis was preceded by a course qualitative decision analysis to examine and anchor the decision maker's preferences in the explosion risk analysis. The qualitative decision analysis consisted of a set of questions, which were discussed, answered and documented. The results of the course decision analysis were then summarized as the following decision principles.

[193] Scandpower (2003) *"Troll B – Risikoanalyse"*

Who is the decision maker?
The decision maker in the case study is ultimately the field chief. Practically, the decision is made in cooperation between the field group board and the company risk experts. The preferences of this decision maker group have been examined and anchored in the analysis through meetings with Geir Stener-Jakobsen, a company risk expert representative.[194]

Who are the relevant stakeholders?
In the decision analysis, the following stakeholders were identified by an idea generation session at a meeting with between the risk analyst and a representative of the decision maker.

Internal: Platform crew, labour union, risk analyst group, field chief, stockholders.
External: PTIL, customers, external risk consultants.

The only relevant stakeholders of the present study are the decision maker group and the authorities. It is a fundamental foundation of the analysis that the results should support the decision maker to make a legally acceptable decision. For this reason, it is required that the decision support should include an examination of the relationship between the explosion risk analysis results and the legal aspects of the specific case study object.

The object was built in 1995. This means that the platform is **not** legally bound to the present Facilities Regulation requirements. The maximal acceptable frequency of 10^{-4} for loss of main safety function is thus **not** a legally binding criteria in the present case study. It is however an important company risk criteria[195]. For this reason it is a preference by the decision maker that the analysis examines the frequency for loss of main safety functions.

The preferences of other stakeholders than the decision maker group and the authorities will not been taken into account in the present analysis.

What alternatives are under consideration?
The two following main alternatives are under consideration:

A: Deluge should not be used as an explosion mitigation measure.
B: Deluge should be used as an explosion mitigation measure.

The second alternative however includes many further practical considerations on *how* deluge should be used. This includes the time to effectively activated deluge, deluge coverage, rate and droplet size distribution. To cover these aspects, a sensitivity analysis will conducted to evaluate how to optimize the use of deluge as explosion mitigation. Sensitivity studies shall examine the effect of droplet size and water application rate [litre/m^2/minute].

Another issue of specific importance to the decision maker is to analyse the total time to efficiently activated deluge related to the effect of deluge on the explosion risk. This is also related to the effect of automatically activation compared to manually activation of deluge on the total explosion risk.

In which dimensions should the alternatives be evaluated and best presented?
The idea presented in part one of using a hybrid criteria together with an explosion load diagram was suggested and accepted by the representative of the decision maker as a suitable way of presenting the explosion risk and decision criteria together in a diagram. The hybrid criteria was then used to incorporate the preferences of the decision maker in the analysis. The following specific explosion risk criterion was found to be of certain interest for the decision maker:

> *"Umiddelbart tap av eksplosjonsbarriere som beskytter mennesker eller kritiske systemer skall ikke intreffe oftare enn 1 pr. 10 000 år som følge av eksplosjon i naboområde."* [196]

The explosion barriers are further defined as the separation between different modules or areas on the platform. For explosion events in the process module, the explosion barriers includes the west wall, the upper deck and the main deck of the process module together with the east wall of the process support module. The west wall and

[194] Meeting with Geir Stener-Jakobsen, 2006-09-05
[195] Scandpower (2003) *"Troll B – Risikoanalyse"*
[196] Scandpower (2003) *"Troll B – Risikoanalyse"*

upper deck are designed to withstand a static overpressure of 0.25 bar(g). However, for an explosion to be strong enough to break the separation between the process and process support modules a pressure >0,6 bar(g) is needed at the west wall. The main deck explosion barrier, separating the process module from the classified support frame, has been shown to withstand up to 0.50 bar(g).[195]

There are no well-defined BATALARP-criteria for explosions in use in the company. The decision maker representative however expressed a strong preference **not** to make use of methodologies such as Value Of Statistic Life (VOSL) or Implied Cost of Averting a Statistical Fatality (ICASF) in the analysis, based on ethical arguments and beliefs. Instead, the balance between risk and costs has been analysed using the net present value methodology with-out fatalities as described in Part 1. The involvement of the decision maker in defining the preferences and decision criteria was not been as high as would be optimal, but is was seen as sufficient to ensure that the analysis reflects the interests and preferences of the decision maker.

For the calculation of the net present value of activated deluge, the thresholds presented in figure 44 have been used.

Threshold	**Description of consequences**	**Quantitative estimate of consequences**
-	Costs of spurious activation of deluge	20 MNOK [#]
75 mbar	Damage to unprotected equipment, which might lead to loss of confinement of hazardous substances and domino effect scenario. [§]	Downtime: 14 days: 1400 MNOK [¤] Destruction costs: 300 MNOK[+] Casualties: 100% fatality in process module.
>250 mbar	Loss of fire and explosion barrier: west wall failure. Total loss of equipment in module.	Downtime: 30 days: 3000 MNOK Destruction cost: ~3000 MNOK[+] Casualties: 100% fatality in process module and weather deck
>500 mbar	Loss of explosion barriers: main deck failure. Escalation threshold to the classified MSF area below the process module. Eventual total collapse and loss of the installation.	Downtime: 200 days[¤]:20 000 MNOK Destruction costs: 10 000 MNOK* Casualties: 100% in process module and MSF.
> 600 mbar	Escalation threshold. Loss of explosion barrier towards the process support module, with additional fatalities. Eventual total collapse and loss of the installation.	Downtime: 200 days[¤]:20 000 MNOK Destruction cost: 10 000 MNOK* Casualties: 100% fatality in process module and MSF, 50 % fatality in the process support module.

Figure 44: Table showing estimated consequences for different explosion overpressure thresholds.
 # Based on a presentation from the decision group meeting "*Portføljemøte Troll B*" (06.11.2006)
[¤] Based on estimates from Ersdal (2005) "*Assessment of existing offshore structures life extension*"
+ Based on a cost estimate for a similar module[197].
§ Based on the probit functions described in section 3.1.5 above.
*** Based on Piper Alpha data from HSE homepage[198] and DNV course compendium[199].**

All personnel in the module at the time of the explosion are assumed to be killed immediately. Since the decision of initiating deluge does not influence the occurrence of an explosion but only the consequences of one, the fatalities within the process module is seen as similar between the to decision alternatives in the present analysis. Initiated deluge may however have an influence on fatalities in other modules such as the weather deck, the process support module and the classified main support frame area areas below the process module. It may also have an effect on the risk for losing the entire installation. These effects on the total fatality risk are also thought to be represented by the thresholds defined above.

How should practicality and simplicity on the one side be balanced be with precision, validity, reliability and theoretical support on the other?
The framework suggested in Part 1 is meant to lead to a balanced first decision support. It is however impossible to evaluate if the support is sufficient before the analysis has been conducted and the results interpreted. It is

[197] Steinsvik/Wilhelmsen (2005) *"Weight and cost estimates Camilla Belinda (CB) to Troll B"* , Hydro internal note TFD0500007
[198] www.hse.gov.uk
[199] DNV (2006) *"Introduksjon til risikostyring og ledelse"*, coarse compendium for Uib/DNV course 2006

possible that the first decision support is insufficient and that more detailed information is required before a decision can be made.
This is handled in the framework by the iterative process with the managerial evaluation and judgement as a vital procedure.

An important identified strategy for increased practicality and precision is to make use of old analyses where this is acceptable. Input used in the present analysis was also presented and documented as transparently and traceable as possible to reduce the work load for future analyses of deluge and explosion risk. Care must however always be taken when applying input and results from old analyses to avoid that errors are transplanted into the new analysis. Therefore, the results and input from older analyses must always be just as critically examined as with all other input.

7.3 Explosion risk analysis

The FLACS simulations have been conducted in accordance with the latest available Gexcon recommendation and guidelines. 8 ventilation, 14 dispersion and more than 100 explosion simulations have been conducted.

The choices of grids are of outmost importance and are therefore presented in greater detail. In general a standard grid of cubical 1m^3 cells where used in ventilation and dispersion simulations for a volume of slightly bigger that the process module. The grids where then stretched to obtain sufficient distance to boundaries, which means that larger non-cubical cells where used in the less important parts of the calculation domain to save computational effort. For explosions, a finer 0,5 m grid was used in most simulations.

7.3.1 Ventilation simulations

Eight different ventilation simulations were conducted with a constant wind speed of 8 m/s for eight different wind directions. The results were used to identify potential worst-case dispersion calculations and dangerous build-up of explosive clouds.

7.3.2 Ventilation results

Simulation results suggest that the ventilation is highly dependent on wind direction. Highest ventilation rate is found for winds from the east and lowest for winds from the west. This can be explained by the position and design of the process module. When the wind blows from the west the living quarters and process support module shelters the process module resulting in low level of ventilation. At the other hand, winds from the east blow straight into the module giving a high ventilation rate. At the north, east and south walls of the module there are gaps between the deck and the explosion relief panels that allows for ventilation. The west wall on the other hand works as a separating fire and explosion barrier and therefore contains no gaps allowing for ventilation. The ventilation results are illustrated in figure 45 in the next section together with an overview of the platform modules.

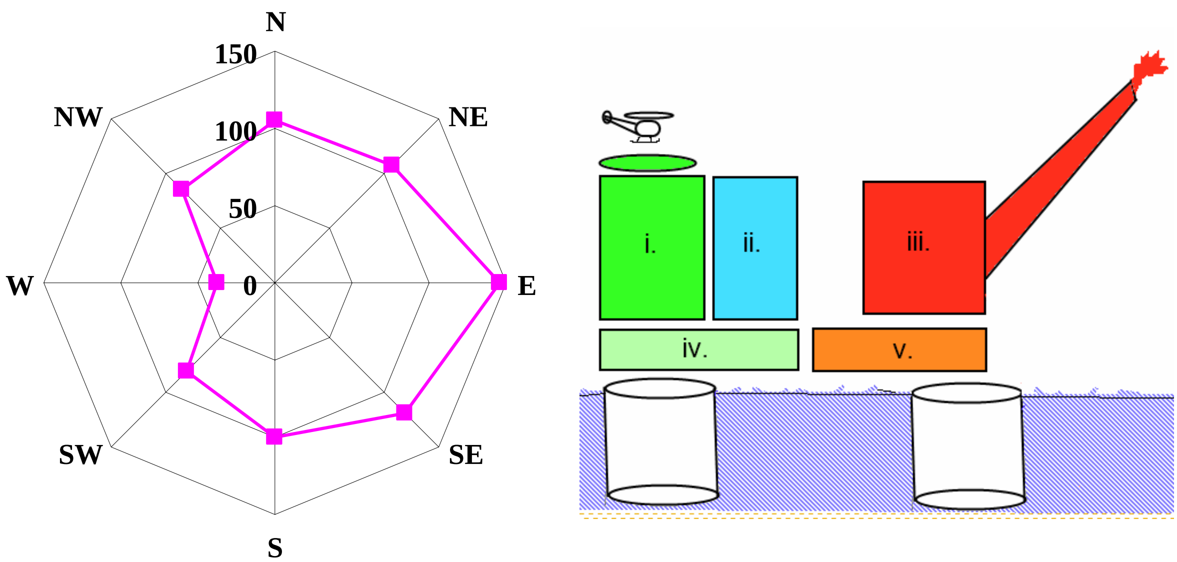


Figure 45: Illustration of the ventilation results (left) together with an overview of the platform (right). Note that the relation between the ventilation results and the position of the process module (iii).

The reason why the platform is constructed this way is to protect the living quarters (i.). This is done by placing the most dangerous parts of the platform such as the process module (iii.), the flare and classified main support frame (v.) opposite to the living quarters. The platform is so that for the most frequent wind direction a leakages will not spread towards the living quarters but instead blow off the platform. The prevailing wind direction in this case is wind from the west.

7.3.3 Dispersion simulations

The dispersion simulations include leakages with mass flux in the range of 5-100 kg/s and wind speeds between 3-12 m/s. The simulated scenarios were designed to give representative but large stoichiometric equivalence clouds in accordance with the EXPRESS methodology and DNV guidelines for probabilistic explosion risk analysis. Typically this includes scenarios were the leakage and wind direction are opposite to each other. This configuration is expected to result in large flammable and well-mixed gas clouds. The simulations scenarios were chosen to cover a range of the non-dimensional leak rate from 0,05-0,15 based on DNV guidelines for probabilistic explosion risk analysis. This way, the ventilation results were used to choose the dispersion scenarios expected to give large stoichiometric equivalence clouds based on the EXPRESS methodology developed by DNV.

For the dispersion simulations, the grid around the leakage was refined according to the FLACS manual and the latest available guidelines to ensure a good representation of the jet. The dispersion scenarios were supposed to be simulated until steady state occurred, but due to computer resources limitations a maximum limit of 150 seconds was set. The dispersion simulations were found to be very time and computer resource demanding.

7.3.4 Dispersion results

A typical example of cloud development for a simulation scenario with a large leakage is illustrated by figure 46 and 47. The three different curves in figure 46 describe the transient cloud development plotted against time: the total amount of gas in the module, the amount of gas within the flammability limits and the stoichiometric cloud equivalent. Note that there are two peaks at the flammable and stoichiometric equivalent cloud curves respectively. The first peak occurs just before steady state is reached while the second peak comes shortly after the drastic fall in total fuel. This can be explained by the fact that for the simulation in question, a large volume of the cloud is above the flammability limits. Hence, the stoichiometric equivalent cloud grows in size until it reaches a maximum; then it decreases slightly because the high concentration in the cloud at steady state is slightly less explosive than during the cloud build-up phase. When the leakage stops, the total amount of fuel drops rapidly as gas is ventilated out of the module. At the same time a second peak is seen in the stoichiometric equivalence cloud size. The second peak is because when the leakage stops air is mixed into the large volumes with high gas concentration leading to a large amount of flammable gas.

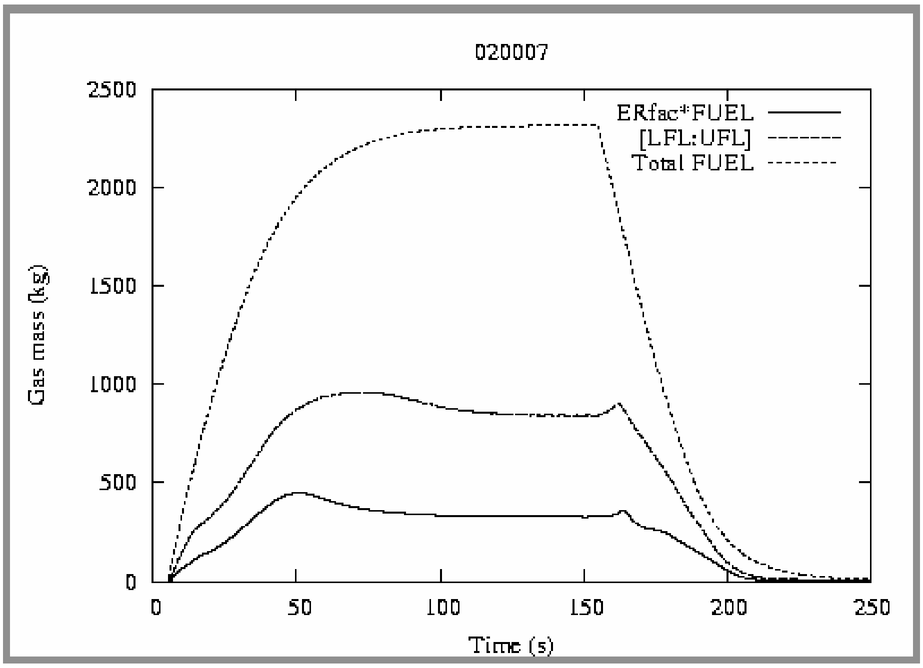


Figure 46: Example of dispersion simulation 020107 with a large mass flux (100 kg/s) combined with a wind speed of 8.5 m/s with opposite direction to the leak .

The results from the dispersion simulations are summarized in figure 47 . Care should however be taken not to draw to far-going conclusions on such a small number of scenarios. The dispersion simulations results indicate that the stoichiometric equivalence gas cloud size at steady state ranges from ~40-400 kg. This is equivalent to ~5-50% of gas filling of the module, or stoichiometric equivalence clouds of 1000-14000 m^3. The time to reach a steady state gas cloud varied from less than 20 seconds to more than 150 seconds depending mainly on the leakage mass flux and ventilation. The simulation scenarios with large leakages rates were generally seen to develop faster than smaller leakages.

Simulation ID Main deck: MD Upper deck UD	Mass flux [kg/s]	Non-dimensional mass flux	Max stoich. gas cloud equivalent	Time to steady state	Stoich. gas equivalent at 50 seconds
020101 (MD)	8	0,097	~350 kg	>150 s	~200 kg
020102 (MD)	20	0,090	~210 kg	>150 s	~200 kg
020103 (MD)	20	0,1	~300 kg	80 s	~210 kg
020104 (MD)	67	0,087	~95 kg	25 s	~90 kg
020105 (MD)	67	0,092	~100 kg	20 s	~100 kg
020106* (MD)	98	0,11	~50 kg	< 20 s	~40 kg
020107 (MD)	98	0,15	~400 kg	50 s	~400 kg
020202 (UD)	7,5	0,04	~225 kg	>150 s	~95 kg
020203 (UD)	7,5	0,03	~130 kg	>150 s	~50 kg
020204 (UD)	15	0,05	~95 kg	43 s	~ 90 kg
020205 (UD)	15	0,075	~40 kg	60 s	~40 kg
020206 (UD)	5	0,015	~100 kg	>150 s	~55 kg
020207 (UD)	5	0,015	~130 kg	130 s	~50 kg

Figure 47: Summary of dispersion simulation results for main and upper deck (MD and UD).

The results show that it is not necessarily the largest leakages that result in the largest stoichiometric equivalent cloud but rather a combination of many parameters such as mass flux, wind speed, wind direction in relation to leakage direction etc. . Note that smaller leakages very well might lead to larger stoichiometric equivalence cloud sizes than larger leakages. This can be explained by that for the larger leakages, a large proportion of the gas cloud was above the upper flammability limit. Figure 48 illustrates an example of how the scenarios can be visualised using FlowVis.

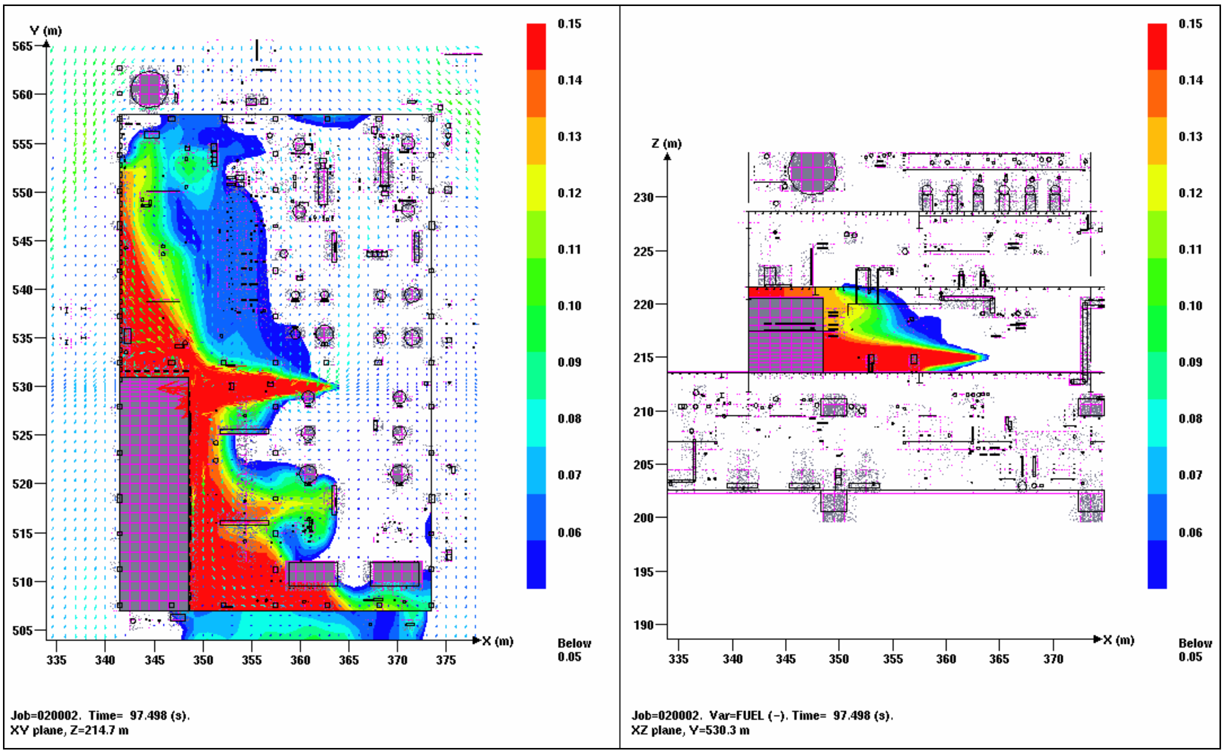


Figure 48: An illustration of gas dispersion simulation 020102. To the left a XY cut-plane of the concentration profile is shown, looking at the module from above. To the right, the same simulation is presented by a XZ cut-plane showing the concentration profile from the side, looking in the Y-direction. The arrows in the left picture illustrates the wind vectors.

A closer examination of the results however revealed that the three largest stoichiometric equivalent clouds coincided with simulations where the wind and the leakage direction were opposite each other. Further, they also had the three of the four largest of the largest non-dimensional leakage rates. Note that simulation 020106, in which the leakage was directed against the wind and the walls of the module, was one of the simulations with the largest non-dimensional leakage rate. It was seen in simulation 020106 that a large, well mixed cloud was formed outside the module. There was however no consistent trend between increasing non-dimensional leakage rate and maximal stoichiometric equivalence cloud. The results of such a small sample of simulations should be interpreted with care and with-out making to far-going conclusions without a proper analysis.

Because of unfortunate circumstances and lack of resources it was not possible to export the results to analyse them properly. The unfortunate circumstances in this case was that the most recent format of FLACS result files did not match the script files needed to export the data and conduct the frozen cloud analysis and construct the response surfaces. Because of this problem, calculating the probabilistic explosion risk was not possible within the limitations of time and resources available. Instead it was decided to use the time and resources left to concentrate on the explosion simulations.

Some further comments and self-critic on the dispersion results presented above is seen as necessary to avoid misinterpretation or to far-going interpretations of the results.

i. The scenarios were simulated with a constant leakage mass flux although it is well understood that the mass flux will decrease with time. The main reason why leakage mass flux is expected to decrease with time is the falling pressure which in turn can be explained with stopped production, segment isolation and controlled flaring.

ii. It was not possible to run all simulations until steady state occurred. This can partly be explained by inexperience and inefficient use of computer power by the user and partly by lack of resources available to the project.

iii. It is understood that ignition may occur before a leakages reaches the stoichiometric equivalence cloud peak or steady state. Hence, the dispersion analysis needs to be combined with transient ignition modelling before it can be used to assess the size of a gas cloud at ignition. It is the gas cloud size at ignition that matters rather than equivalence cloud peak or steady state gas cloud size.

iv. The simulations have not analysed the effect of deluge on dispersion and gas cloud formation. It is not straightforward to simulate the effect of initiated deluge on dispersion with FLACS. The effects are generally expected to be beneficial.

Probabilistic dispersion results study found in the previous risk analysis were used to some extent to discuss the probabilities of different dispersion scenarios qualitatively. As mentioned in part 1, appropriate use of old analyses is needed to optimize the use of resources.

7.3.5 Explosion simulations

Explosion simulations ranged between ~3-100% filling of the module volume with stoichiometric gas mixture (corresponding to ~700 – 24800 m^3). The explosion simulations covered a wide range of variation of ignition location and cloud location, typically simulating the same cloud with three different ignition locations. Identical simulation scenarios were conducted with and without initiated deluge to make direct comparisons possible. Emphasis was put to examine gas leakages below 30% volume of gas filling (8000m^3) while a few simulations where conducted with higher degree of filling. The effect of different ignition source locations was examined by simulating identical clouds with three different ignition locations: one at each end and on in the centre of the cloud. For detailed description of the scenarios, see Appendix A. An example of an explosion control file with deluge is presented in Appendix B for higher traceability and quality assurance.

74 scenarios were simulated with the finer grid: 37 simulations with-out deluge and 37 simulations with deluge. For simulation scenarios with deluge, a water application rate of 10 liter/m^2/minute was used in simulations together with a droplet diameter of 1 mm. Detailed input was unfortunately hard to obtain on the Sauter mean droplet diameter. Based on CFD modelling of deluge effect in the BFETS experiments, 1mm was assumed to be representative size[200]. The effect of deluge was incorporated in FLACS with the simplified formulas as described in chapter 4.2. Only the water application rate and the droplet diameter where required.

[200] CMR/Gexcon (2006) *"FLACS Training"*, course material for FLACS user course

13 sensitivity simulations were conducted with drop sizes of 0.5 mm and 0.1 mm respectively. Additional 14 sensitivity simulations were also conducted with the water application rate 15 liter/m^2/minute since this is minimum recommended water application rate for explosion mitigation according to HSE[201].

Well after the majority of simulations had been conducted, input was made available on the operational pressure in the fire water system. With this information, the empirical formula presented in chapter 4.2 could be used to control the assumption of 1mm droplets. The empirical formula indicates that the Sauter mean diameter of the droplet is likely to be between 0.5-1mm, based on the information that the operation pressure ranges from 0,5 to 7 bar. The three different types of nozzles in use are described in figure 49.

Nozzle type	K-factor	Operating pressures	Droplet size data sheet[202]	Empirical correlation
High-velocity nozzles:	26 / 160	Range: 2.8 – 5 (Design: 3,5 bar)	1,5 - 2 mm	0,59 - 0,71 mm (0.66 mm)
Medium velocity nozzles:	38 / 76	1,4 – 3,5 bar (Design: 2 bar)	85% <0,4mm	0,66 – 0,89 mm (0.79 mm)
Open sprinkler nozzles:	57 / 80	0,5 – 7 bar (Design: 2 bar)	Not available	1,26 – 0,52 mm (0,79 mm)

Figure 49: Table over different nozzles used at Troll B, with available data. The empirical correlation to the right is from the FLACS user manual: $D = P^{-0.333}$. Note that the correlation is not very successful in estimating the droplet size of the HV- and MV-nozzles compared to the suppliers data sheet. It is thus questionable if it can be used to estimate the droplet size for the open sprinkler nozzles.

The most frequently used is the open sprinkler nozzle while medium velocity nozzles are used for equipment specific protection. High velocity nozzles are used where to avoid wind distortion of the deluge spray by using large droplets at locations susceptible for wind. The analysis lacks accurate input on the droplet size distribution for the general area deluge. The empirical correlation was also compared to the available data and found to be rather arbitrary, which can be seen in figure 49 above.

The choice of 10 liter/m^2/minute water application rate was based on the NORSOK S-001 standard guidelines for deluge systems in process areas. Sensitivity studies were conducted for a smaller number of simulations to examine how the results varied with drop size and water application rate. Since larger drops were expected to have better mitigating effect, simulations with 0.5 mm and 0.1 mm were conducted. An increased water application rate of 15 liter/m^2/minute was also tested since this is the recommended water application rate according to HSE.

7.3.6 Explosion simulation results

For explosion calculations, 28 simulations where first conducted using a 1m^3 grid. Grid dependency was then tested by re-simulating the identical scenarios with a finer grid where the size of the standard cell sides was reduced by half from 1 meter to 0.5 meter. For each simulation, the highest recorded panel pressure was plotted against the degree of filling of the module. The results are presented in diagram 50 :

[201] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*
[202] HYDRO (1994) *"Equipment Data Sheets and curves"* Doc. No. 17-1A-NH-F55-05301-0006

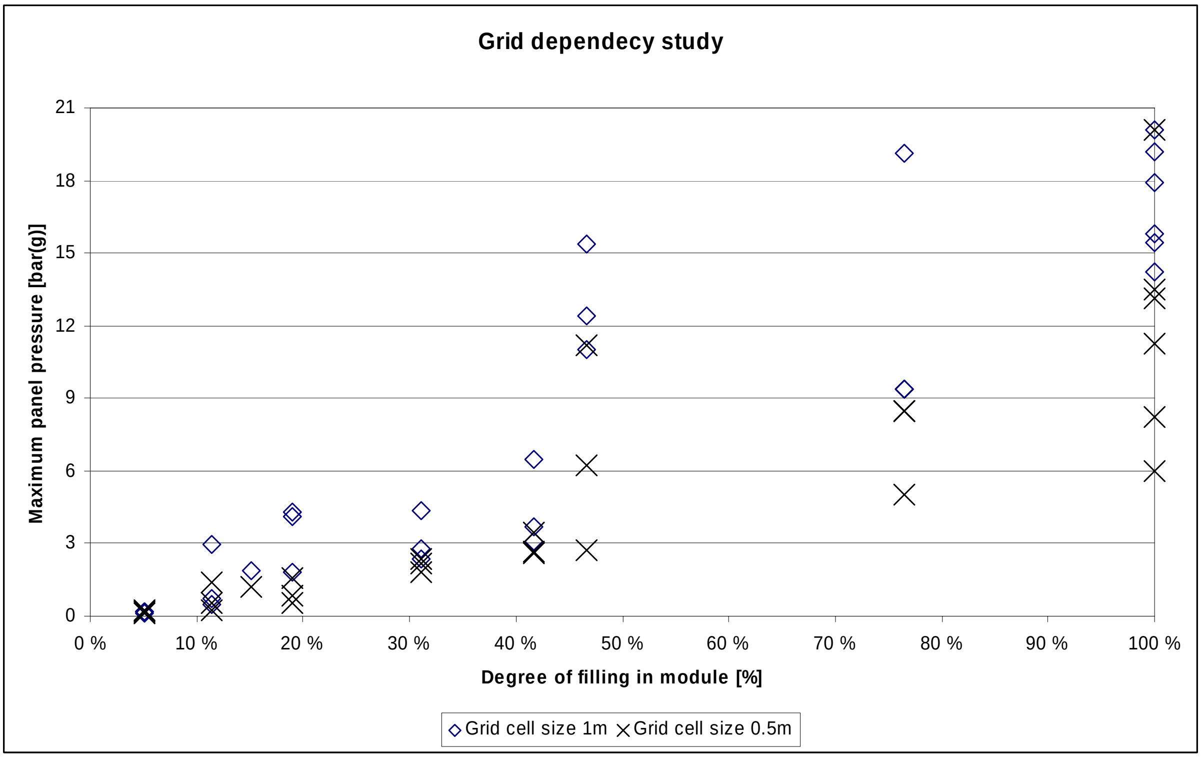


Figure 50: Grid dependency study of 37 scenarios with two different grids. The difference was found to be rather large: for identical scenarios the results differed with a factor of 2 between the different grids. Also note the drastic change and extreme high values achieved for simulations >40% degree of module filling.

Substantial difference (for some simulations a factor of 2) was found between the different grids. In most cases, the finer grid resulted in lower explosion simulation results. The conclusion of the grid dependency study was that the solutions are **not** grid independent. Since the finer grid solutions were considered to be more accurate and correct than the coarse grid, the rest of the simulations were conducted using the finer grid 0.5 m. Also, a finer grid was needed to conduct simulations of the smaller gas clouds in order to follow the grid guidelines, which requires a minimum of 13 cells across the gas cloud.

At the same time it was also decided to concentrate the remaining resources and efforts on the smaller gas clouds, since these were deemed as being of greater interest in the analysis. There were three main reasons for this strategy:

i. The main reason for this is that smaller explosive gas cloud scenarios are expected to have a higher probability than scenarios of stoichiometric equivalent clouds. As an example, the results from the previous probabilistic gas dispersion and explosion analysis suggested that the expected frequency of an ignited stoichiometric equivalent gas cloud 8000m^3 or larger is very small, on the order of 10^{-8}.[203] Given that the total module size is 24800m^3, 8000 m^3 corresponds to about 30% filling of the module. As a reference, the expected yearly frequency for an ignited gas cloud is about 10^{-3}.[203]

ii. Another good reason was that the results from the simulations showed that the calculated pressures for the larger simulations were so high in comparison what the structure can tolerate that they provided little valuable information for decision making. (approximately one order of magnitude, >2 barg vs. ~0,25 barg)

iii. The third reason was that the large clouds proved more difficult to simulate within the limitations in time, computer resources and strict FLACS grid guidelines. Since time and computer resources were limited, it was seen as more efficient and interesting to concentrate on smaller cloud explosions. The large cloud simulations also resulted in some problems with extreme values, which are explained in detail in the next section.

[203] Scandpower (2003) *"Troll B RBA Eksplosjoner"* , Teknisk notat nr. 5 i riskanalysen

Problems with extreme values
In figure 50 above it can be seen that the results for the larger clouds (~40-100% stoichiometric gas filling of the module) the simulation results showed extremely high values, sometimes as high as 10-20 bar(g) overpressure. This is approximately one order of magnitude higher than what is generally expected from experimental experience of full scale tests for natural gas deflagrations, and approximately two orders of magnitude more than the structure can survive, ~0,25 bar(g). These values are thus considered to be unreliable and should be disregarded from in decision. Some possible explanations of the extreme values are:

- Insufficient simulation volume, leaving insufficient distance to the simulation volume boundaries. For the larger simulations it was observed that the flame reached the boundaries. This is seen as the most likely explanation for the extreme values.
- Non-cubical grid outside module volume due to grid stretching. For large simulations, unburned gas will be pushed out of the module and burn outside in non-cubical grid regions. It is uncertain how this impacts on the FLACS results.
- Deflagration to detonation transition. It is however seen as extremely unlikely or even unphysical for natural gas to detonate under the circumstances of the analysed scenarios.
- Reflection phenomena of blast wave. According to the FLACS manual, the program accounts for blast wave reflection phenomena[204]. Pressure reflection could lead to a difference in pressure as high as a factor of two between head-on and side on pressures. This factor can however not explain the extreme values obtained, even though it may contribute to higher values.
- General difficulties and problems explosion CFD modelling, which has been discussed in chapter 3.3.4 above.

It was typically only one or two of the monitor points or measure panels in each simulation that obtained extreme values, while the recordings were in the range between 2-6 bar(g). Ideally, these simulations should have been simulated again with a more appropriate choice of grid but due to limited resources and the explanation given above, efforts and resources were concentrated on smaller gas cloud explosions instead.

[204] Gexcon (1997) *"FLACS-97 User's Guide"*

Effect of deluge

The results for simulations show that in general a good effect of deluge can be expected for water application rate of 10 liter/m^2/minute and the assumed droplet size of 1mm. For the 37 simulations with, deluge had a clear positive effect in all cases except two. The results for all simulations with-out and with 10L/m^2/minute, 1mm droplet deluge are plotted in diagram 51 .

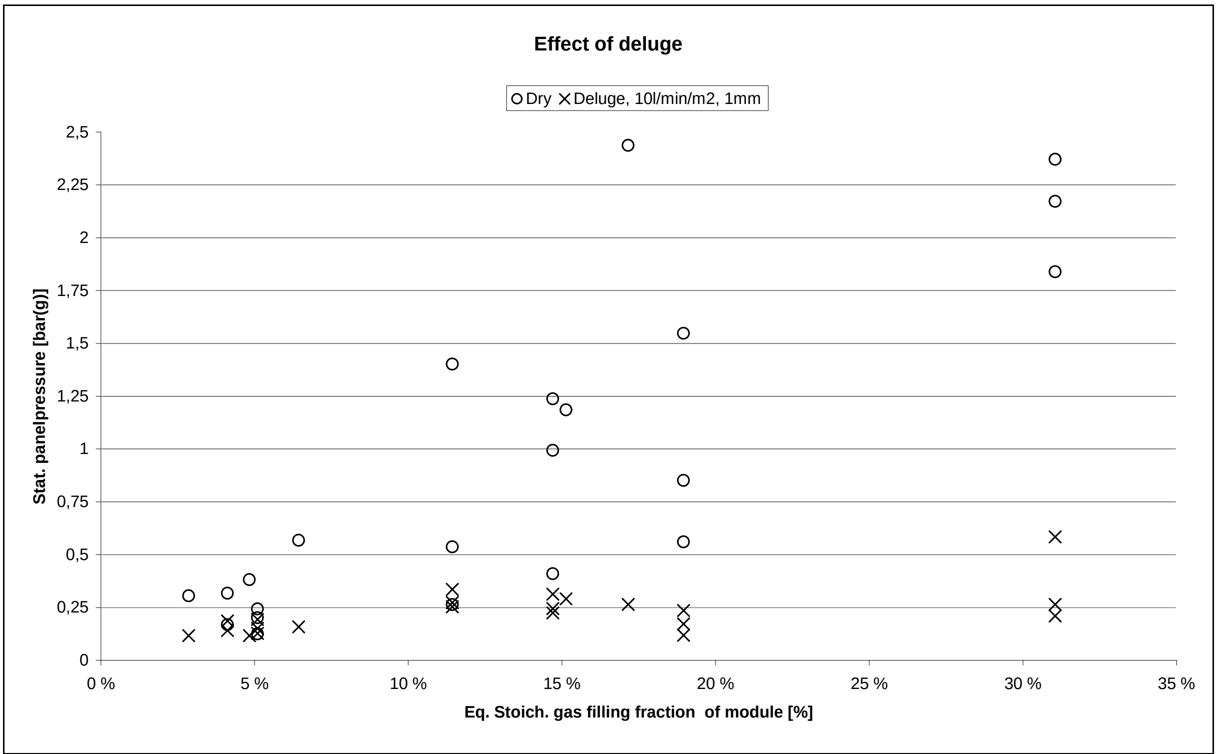


Figure 51: Effect of deluge plotted against degree of module filling for clouds < 35 % of module filling.

The effect of different ignition locations can be seen in the above diagram by comparing the results for clouds with identical degree of filling. The only difference between the simulations with identical size is their ignition location and whether deluge is activated or not. Typically three scenarios have been simulated for each cloud; two with end ignitions and one with central ignition. Based on the results displayed in figure 51, the effect of different ignition location is seen to be of great importance for simulations without deluge. It is also concluded that the effect of ignition location is of less importance when deluge is activated compared to scenarios without activated deluge.

The main reason for reaching different pressures with different ignition points can be explained with the Schelkin mechanism of turbulence generation. For example, end ignition often leads to high pressures due to a longer flame path during which the turbulence can be created and the flame accelerate. Turbulence generation is thus seen as the most likely explanation why the simulation results with-out deluge varies much more with ignition locations compared to simulations with deluge.

Figure 52 illustrates a typical comparison between to similar scenarios with the only difference that deluge is activated in one of them.

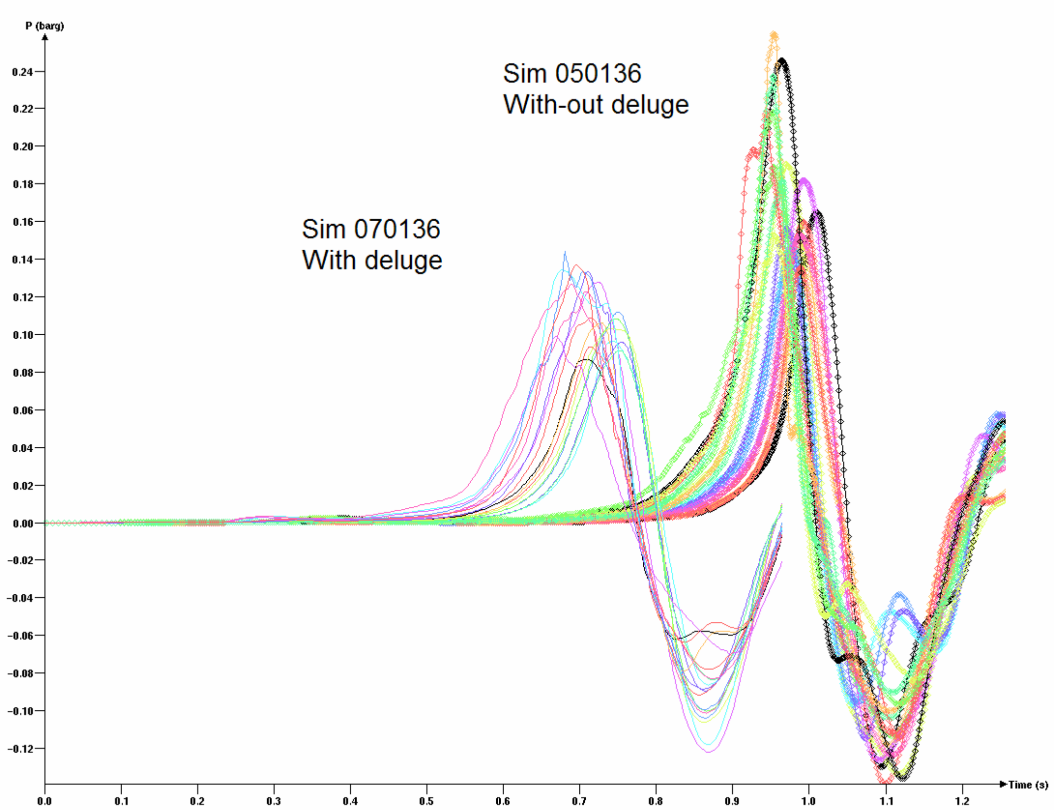


Figure 52: The pressure-time history at the measuring points for two simulations only different in the use of deluge in 070136 and no deluge in 050136. Note that the pressure is reduced from 0,25 bar(g) to approximately 0,14 bar(g) in this particular example.

Deluge is generally expected to increase the initial turbulence in the gas cloud and then decrease the turbulence generation process after the explosion reach such conditions that droplet break-up occurs. This also means that explosions with activated deluge have a higher burning velocity in the initial phase of the explosion. A higher initial burning velocity is also indicated in figure 48 above and explains why the explosion peak occurs faster than for with-out deluge.

The simulation results also show that deluge is generally more beneficial for large gas cloud explosions than for smaller clouds. This can also be explained by the turbulence generation and droplet break-up. Smaller clouds are more sensitive to differences in initial turbulence, while larger clouds are more dominated by the turbulence created during the explosion propagation. Hence, the downside of increased initial turbulence is more obvious for small gas cloud explosions. At the same time, the conditions for efficient droplet break-up may not develop in the small cloud explosions.

Dynamic explosion drag load
In chapter 3.1.5 the importance of the dynamic explosion drag load in relation to damage on small equipment and domino effect was discussed. However, little information was found on how equipment tolerates such a dynamic explosion drag load. Without the information needed to couple the dynamic explosion drag load to a corresponding consequence, it was seen to have limited value to the analysis. In the previous analysis a value of 0,2 bar was used as a threshold for domino effects, but how this value had been derived was unclear. It is therefore preferred to use the probit methodology presented in chapter 3.1.5. The methodology suggest that small equipment starts to collapse at a static pressure above 0,1 bar(g).

Dynamic structure response
No input was available on the ductility and natural frequency of the analysed object, and therefore a quantitative analysis of the dynamic response has not been possible. The explosion simulation durations were qualitatively compared between scenarios with and with-out deluge and it was found that the duration in most cases were rather similar and on the order of 100-200 ms. Based on the experimental evidence presented in chapter 3.1.5

above it assumed that the ratio between explosion load duration and natural frequency is on the order of 1 and typically in the range 0,5-2. Figure 25 in chapter 3.1.5 was then used to conclude that depending on the allowable ductility, the dynamic load factor can be assumed to be between 0,5-1,2.

7.3.7 Sensitivity analysis results

14 scenarios with gas cloud size between 600-4500 m^3 were chosen for the sensitivity studies, modified, and simulated to examine the effect of droplet size and water application rate.

14 simulations with 0,5 mm droplet size and water application rate $10L/m^2$/minute.
13 simulations with 0,1 mm droplet size and water application rate $10L/m^2$/minute.
14 simulations with 1 mm droplet size and water application rate $15L/m^2$/minute.

Hence, in total 41 simulations were conducted to examine the effect of droplet size and water application rate. The droplet size simulations are plotted in figure 53 together with the identical scenarios without deluge.

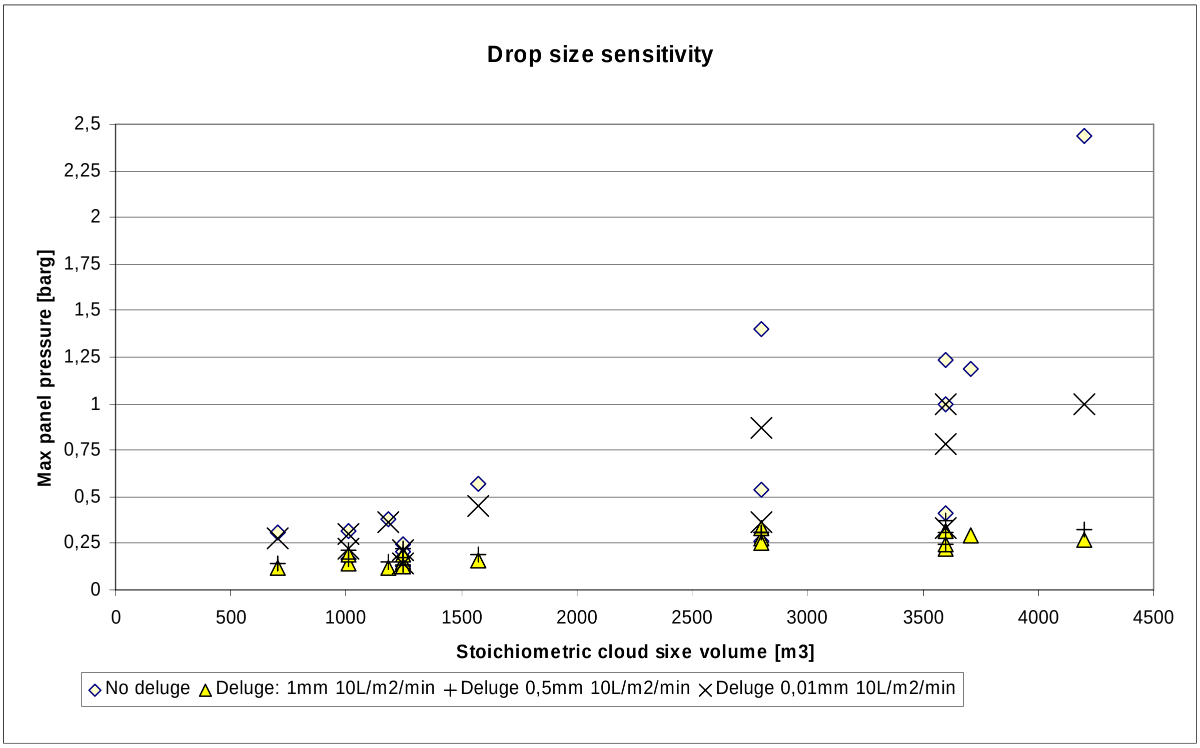


Figure 53: The results from the drop size sensitivity study. The Maximum recorded panel pressure in each simulation has been plotted against the stoichiometric cloud size volume.

The results indicate some interesting trends. It is seen that deluge is expected to have a positive effect for the majority of the simulations, especially for 0,5 and 1 mm drop sizes combined with medium and large clouds. For the 37 simulations with $10L/m^2$/minute and 1mm, deluge had a clear positive effect in all cases except two. The beneficial effect of deluge was seen to decrease with decreasing droplet sizes and gas cloud size. In scenarios combining small gas clouds with 0,1mm droplets, the effect of deluge was even seen to be negative for 4 of 12 simulations compared to simulations with-out deluge. This can be explained by the theories of droplet break-up. Smaller drops are more difficult to break-up and droplet break-up is necessary to achieve the mitigating effect.

The effect of increasing the water application rate from 10 to 15 L/m^2/minute was very small in the simulations. A possible explanation why the simulation results with 15 L/m^2/minute were generally a little bit higher than the identical simulations with 10 L/m^2/minute may be that the increased turbulence had a slightly more impact than the mitigation effect. Another way of illustrating the effect of deluge and the how the results are effected by droplet size and water application rate is to plot the simulation scenario results with-out deluge against the sensitivity simulations. An example of such a diagram is given in figure 54.

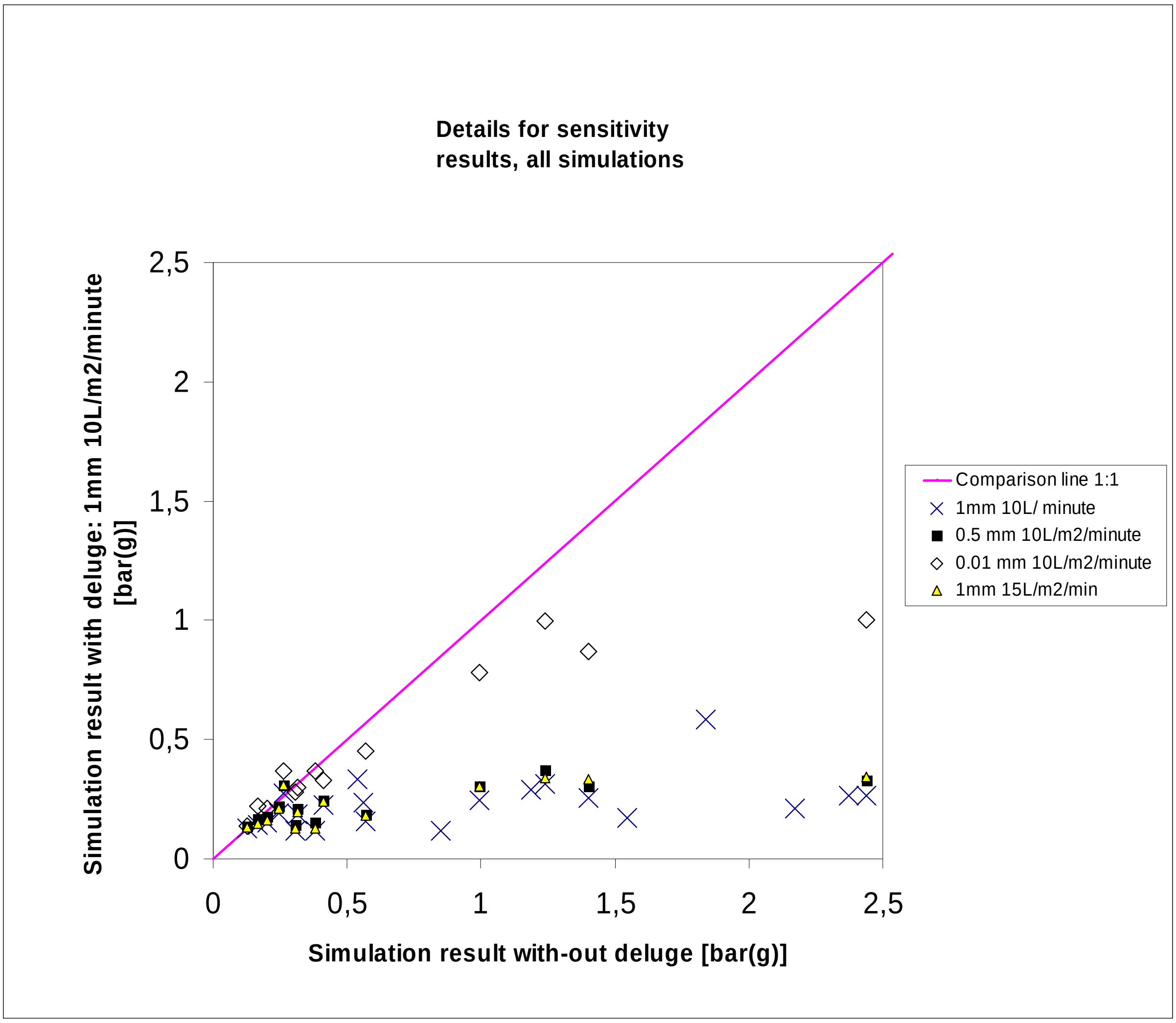


Figure 54: The diagram shows all sensitivity simulation results with different deluge configuration plotted against the results for identical simulations with-out deluge. Results located to the right of comparison line illustrate scenarios where deluge is beneficial. Note that the beneficial effect of deluge is seen to increase with increasing dry simulation pressure.

In figure 55 it can be seen that all of the simulations with pressures above 0,5 bar(g) with-out deluge were reduced significantly when deluge was used. There seems to be a trend that the effect is less beneficial until 0,25 bar(g) and thereafter increases more and more. In other words, the results indicate that efficient initiation of 1mm or 0,5 mm deluge can be expected to have a beneficial effect for explosions with pressures above 0,25 bar(g) without deluge.

As can be seen in figure 55, the simulations with 0,1 mm droplet size is quite different from the simulations with 0,5 and 1mm droplets. In the study of overpressure thresholds, it was found that the most interesting region was below 1 bar. It can also be seen in figure 55 that for some of the simulations in this particularly interesting area, deluge seems to have a negative effect on the explosion consequence.

7.3.8 Probabilistic analysis

As has been explained in earlier sections, it has not been possible in the present study to calculate the cumulative explosion load diagram with and with-out deluge. Since the cumulative explosion load diagram are necessary to proceed with the economical analysis, the results from the present study and a previous analysis has been semi-qualitatively compared to the to produce an coarse estimate. The curves are presented in figure 55.

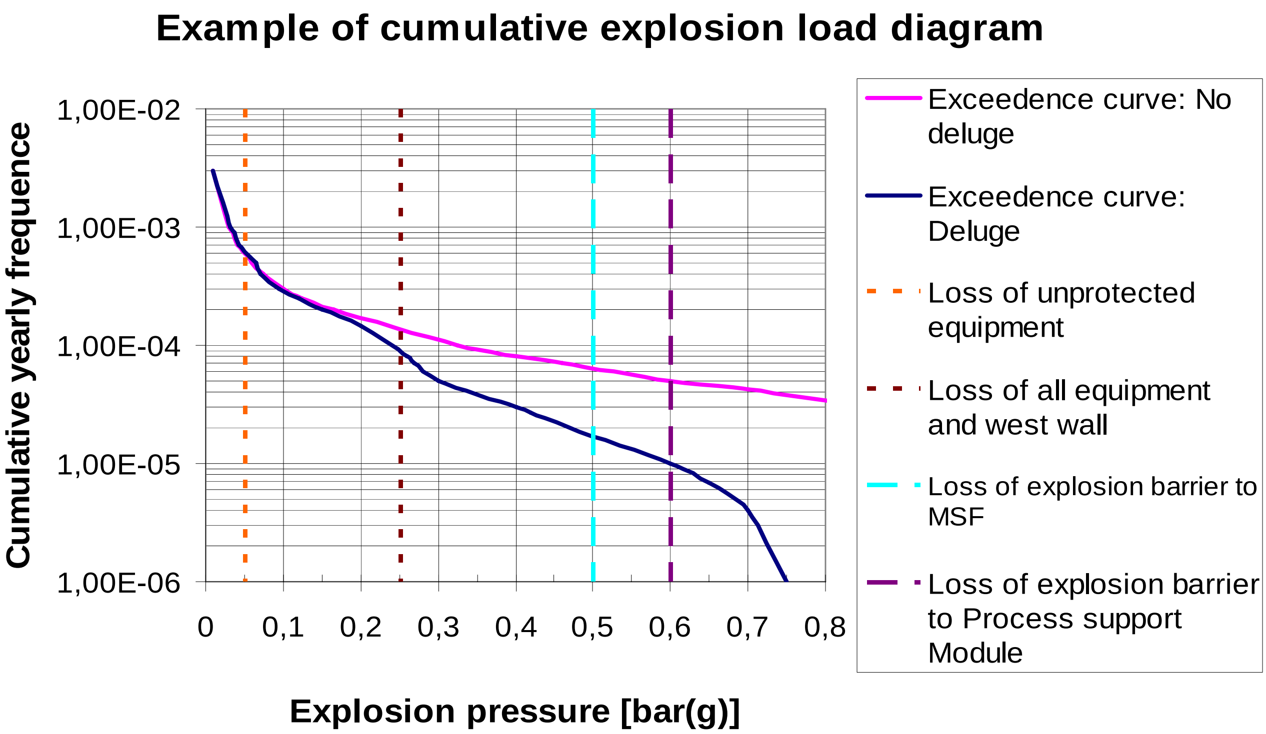


Figure 55: A coarse semi-qualitative estimate of the cumulative explosion load curves with and with-out deluge. Note that these curves are not are based on a full probabilistic Monte Carlo analysis of response surfaces, but on a qualitative discussion of the simulation results.. They should be considered as hypothetical examples rather than evidence. The curves must not be used for other purposes than illustrating the framework methodology

7.3.9 User dependency study

After all the simulations had been conducted, the explosion simulation results from both an earlier analysis and the present analysis were plotted in a diagram showing simulated pressure against stoichiometric equivalence cloud volume. This is presented in figure 56.

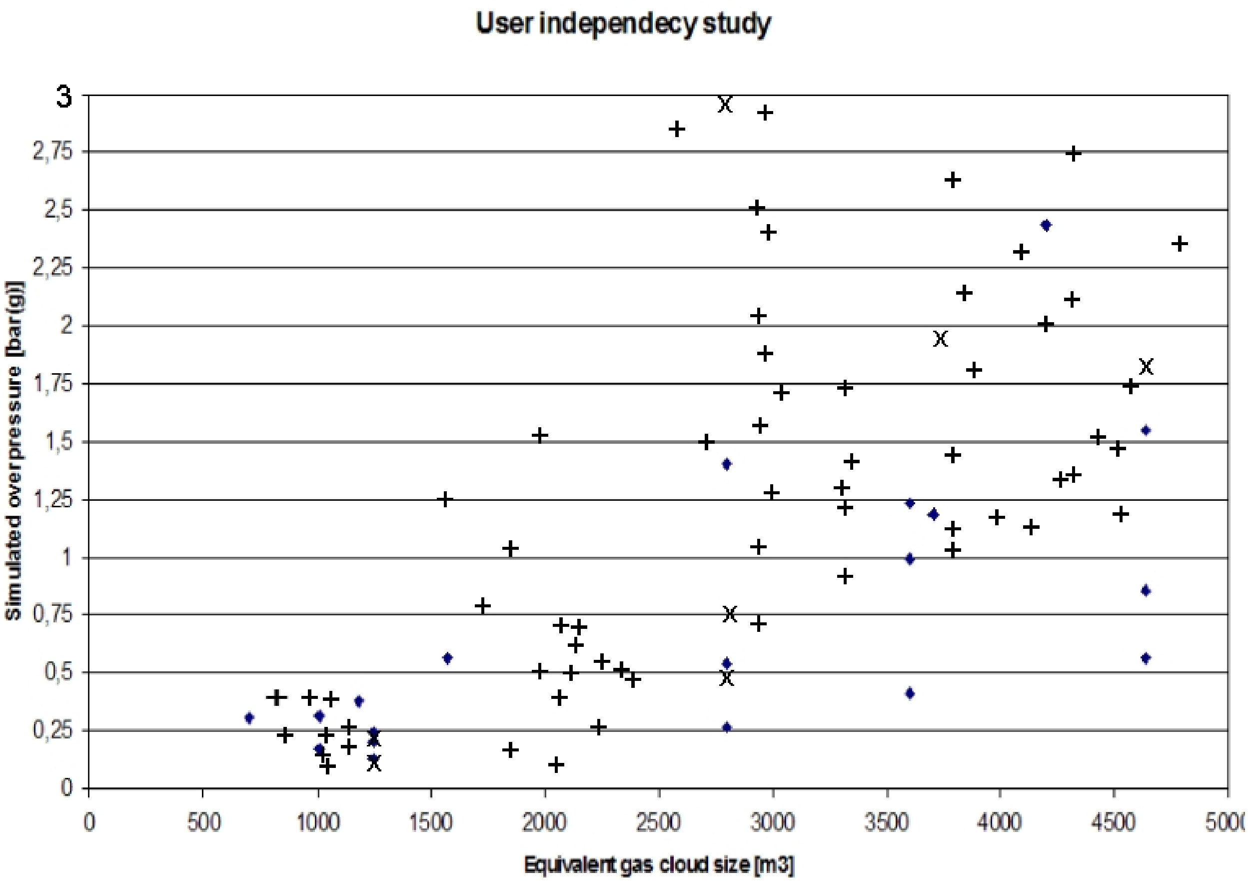


Figure 56: The diagram shows the results from two independent users. Results from the earlier study with a grid of 1meter was used are represented by (+). Diamonds represent simulation results from the present study using the finer 0,5meter grid, while (X) represent identical simulations using a 1meter.

In general, the results seem to be good agreement between the two studies. Slightly lower pressure values are seen for the finer grid simulations than for the coarser grid. A similar effect was shown in the grid dependency study when comparing the results between a 1 meter grid and 0,5 meter grid for identical scenarios in the present study. The user dependency study indicates that the FLACS results can be a considered rather user independent.

The similarities between the results also add some information on the objectivity and reliability of the analysis. It is seen that the selection and definition of scenarios are important for the objectivity and reliability of the analysis. The results in figure 56 show that there is a great spread in the pressures from different scenarios despite their similarity in gas cloud size. This can be explained to a large extent by scenario specific factors such as gas cloud and ignition location. This also indicates a need to run a large number of different simulation scenarios. With a larger number of scenarios, the importance in choice of each scenario will be reduced. The ability of the present risk analysis to correctly represent the underlying risk would also be significantly improved by simulating a larger number of scenarios than has been possible in the present analysis.

7.4 *Cost-benefit analysis*

In accordance to the framework, a net present value has been calculated. The input used in the calculation is first presented, and then the calculation details.

7.4.1 Input used in the analysis

G = Investment cost of installing automatic deluge on confirmed gas detection to mitigate explosion risk was estimated to 5 MNOK.

n = Expected platform life time has been estimated to 15 years.

i = Interest, assumed to be 8%

$a_{\mathrm{Re}gular}$ = The increase in regular maintenance costs has been estimated to be negligible.

$a_{DelugeDamage}$ = The increased costs associated with deluge damage on process equipment were estimated to 20 MNOK. The estimate is based on an incident at the platform in question, which led to spurious activation of deluge in M20 at the installation in question.

$fr_{FalseAlarm}$ = Expected yearly frequency of false alarms leading to initiated deluge due to spurious hydrocarbon gas detection. This has been estimated with the statistical failure rate data from the OREDA database, combined with platform specific observations. A priori, the frequency of spurious hydrocarbon gas detector operation is approximated with the mean failure rate of 2,44 per 10^6 hours operational time[205]. This is equivalent to a spurious operation failure rate of 0,021 per detector and year. To minimize spurious alarms it is normal to distinguish between detection and confirmed detection, where the latter requires two detections from the same module. There have never been any spurious alarms on Troll B during the 11 years the platform has been running. The expected yearly frequency have arbitrarily been assumed to be 0,02 spurious alarms per year, which corresponds to once every 20th year.

$a_{Downtime}$ = Costs associated with downtime was calculated based on the daily production volume of oil and gas multiplied with their respective costs and the downtime.

The prices of currencies, oil and gas is known to vary over time but in the present analysis only single values have been used. An oil-price of 60$/barrel was used in the present calculations. Stating that one barrel ≈ 159 litres and 1USD ≈ 6,50 NOK, the oil-price was estimated with ~2500 NOK /m^3. The price of natural gas was estimated with 1,50 NOK/m^3.[206]

Daily oil downtime cost ≈ 35 000 m^3/day x 2500 NOK/m^3	≈ 88 MNOK/day
Daily gas downtime cost ≈ 8 000 000 m^3 x 1,50 NOK/m^3	≈ 12 MNOK/day
Total estimated downtime cost ≈ (88 + 12) MNOK/day	≈ 100 MNOK/day

$f_{Difference}$ = Expected yearly difference in explosion frequency corresponding with the particular economic consequence, a_{Risk}.

a_{Risk} = Particular economic consequence of deluge in case of an explosion corresponding to a certain frequency. This means a decreased cost in cases of decreased explosion risk and vice versa. In cases the deluge has a beneficial effect a_{Risk} will have a negative sign to indicate cost reduction. The input used for a_{Risk} and f_{Diff} is summarized in figure 57.

[205] OREDA (2002) *"Offshore Reliability Data Handbook"* , 4th edition
[206] The input used in the calculation is based on the Statiol annual finance report from 2005 www.statoil.com

Scenario	Preference thresholds Pressure range [Range representative]	a_{Risk} Economic consequence	f_{Diff} Frequency difference
Damage to unprotected equipment	0,050 – 0,15 bar(g) [0,1 bar(g)]	1700 MNOK	Negligible
Loss of all equipment in module, loss of west wall in module.	0,15 – 0,35 bar(g) [0,25 bar(g)]	6000 MNOK	3 E-5
Total loss of module and eventually the whole installation	0,35-0,6 bar(g) [0,5 bar(g)]	30 000 MNOK	1 E-5
Total loss of module and eventually the whole installation	> 0,6 bar(g) [0,6 bar(g)]	30 000 MNOK	4 E-5

Figure 57: Summary of f_{Diff} and a_{Risk} for the thresholds defined in Figure 44 above. Note that the frequency differences have derived from the arbitrary example cumulative explosion load diagram presented in later sections. They are <u>not</u> results from a full Monte Carlo analysis, but only an example. Also note that the cumulative frequency distributions have been transferred from cumulative frequency function into a frequency distribution.

7.4.2 Calculations

The sum of reduced costs due to deluge mitigation was first calculated as:

$$\sum_{K=1}^{n=4}[fr_{Difference} \times (\pm a_{Risk})]_K = [0 + (-0{,}00003 \times 6000) + (-0{,}00001 \times 30000) + (-0{,}00004 \times 30000)]$$

= - <u>1,68 MNOK</u>

Note that the negative sign indicates a cost reduction. Then the total annual cost was calculated as:

$$a = [a_{Regular} + (fr_{FalseAlarm} \times a_{DelugeDamage}) + \sum(fr_{Difference} \times (\pm a_{Risk}))] =$$

= $[0 + (0{,}02 \times 20) - (1{,}68)]$ MNOK/year = -1,28 MNOK/year

(representing a annual risk cost reduction)

To account for the effect of an interest rate of 8%, the following factor was calculated.

$$\sum_{k=1}^{n}\frac{1}{(1+i)^k} = \frac{(1+i)^k - 1}{i(1+i)^k} = \frac{(1+0{,}08)^{15} - 1}{0{,}08(1+0{,}08)^{15}} \approx 8.56$$

Finally, everything was merged together in the net present value according to Eq. 4.

$$NPV = -G - a\sum_{k=1}^{n}\frac{1}{(1+i)^k} \approx -5 - (8{,}56 \times -1{,}28) \approx +\underline{\mathbf{6\ MNOK}}$$

The sensitivity of the cost-benefit result with oil price was examined by recalculating the NPV with a daily downtime cost reduced with 50% to 50 MNOK/day.
The NPV in such case is still positive (4,82 MNOK).

The calculations shows how the methodology can be used to calculate the net present value.

7.5 Time model analysis

In order to calculate the time to efficiently activated deluge, the suggested time model needed to be slightly modified in order to better represent the reality.

$$t_{Deluge} = t_{Confirmed\_Detection} + t_{Reaction} + t_{Response}$$

together with $t_{Deluge} < t_{Ignition}$ as a critical criteria for deluge to effective as a mitigation measure. The above parameters can be described as:

t_{Deluge} = Total time from gas leakage to effectively activated deluge. Effectively activated deluge is defined as water out of the nozzles at sufficient flow rate covering the whole module. It is recommended to measure t_{Deluge} directly in situ experiments with tracer gas.

$t_{Confirmed\ Detection}$ = Time from gas leakage to confirmed detection. According to a Troll B document[207] gas leakages >1,5 kg/s shall be detected within 20 seconds from initiated leak. This is based on the assumption that the gas cloud with concentration >20% LFL is equal of larger than 1000m^3 at this time. [208]

$t_{Reaction}$ = Time from receiving the first signal to initiating a response. $t_{Reaction}$ includes an operator judgement or automatic voting decision when to initiate the response.
For automatic initiated deluge $t_{Reaction}$ is negligible.
An operator on the other hand has the ability to be faster if the time between the first detection and confirmed gas alarm is sufficiently long, and it can be confirmed in other ways than automatic detection that there is a gas leakage. The operator will however need some time to react and respond. In most cases this means that automatic initiation will be faster than manual activation. Manual activation may also be needed in case the detection system fail.

In order to minimize $t_{Reaction}$, it is recommended to use both manual and automatic activation of deluge. Deluge buttons should be installed in the modules and in the control room if the automatic initiation should fail. At the same time, automatic activation is expected faster than manual activation. The initiation of deluge needs to be incorporated in the ESD hierarchy.

$t_{Response}$ = Time from initiation of the response until the response is successfully implemented.
According to the System Engineering Manual for the Fire-water and foam system, the response time varies between 26-44 seconds depending on where the area is located. For the deluge skids at the main and upper deck of the process module, 40 seconds seem to be a typical value. It takes approximately 15 seconds to open the valves and 25 seconds to fill the system.[209]

$t_{Ignition}$ = Time from gas leakage to effective ignition of gas cloud. This needs to be modelled based on each leakage scenario, since the gas cloud development is coupled to the probability of ignition.

t_{Deluge} has been estimated to 40- 70 seconds with automatic initiation of deluge. If the leakage is detected immediately, the time is approximately 40 seconds.

It has not been possible in the present study to fully analyse the criterion $t_{Deluge} < t_{Ignition}$ quantitatively since this would require a unified model for transient gas cloud development, ignition and detection probabilities. Some qualitative argumentation is nevertheless possible, by comparing the dispersion simulation results with the time to efficiently activated deluge.

Based on the gas dispersion scenarios simulated, the equivalent stoichiometric cloud size at the time of activated deluge is expected be to be typically 50kg ≈ 1500 m^3 or larger. Based on the results from the explosion analysis results, it is seen that clouds in this range typically results in pressures around 0,5 bar(g) when deluge is not activated. When comparing with identical scenarios with deluge, it is seen the effect of deluge can be expected to lower the pressures significantly. In many cases the reduction is such that it could mean the difference whether the explosion barriers survive the explosion or not.

[207] HYDRO (1993) *"SAFETY REQUIREMENTS TO SYSTEMS DURING ACCIDENTS"* 17-1A-NH-F15-00010
[208] HYDRO (1993) *"SAFETY REQUIREMENTS TO SYSTEMS DURING ACCIDENTS"* 17-1A-NH-F15-00010
[209] HYDRO (1998) *"System Engineering manual System 71 Brannvann og skumsystemet"*
Document reference number 17-1A-AE-F85-71000

For smaller leakages with slower cloud build-up time and smaller clouds at the time of activated deluge, the initiation is seen as helpful to dilute the cloud with air.

7.6 Uncertainties

As has already been discussed in earlier chapters, there are a lot of uncertainties attached to any attempt to conduct a probabilistic explosion risk analyse. In this section an attempt to identify, describe and discuss the uncertainties of the explosion risk analysis is presented. This is done by examining each part of the explosion risk analysis separately. This following section is largely based on earlier chapters. The reader is encouraged to revisit the discussions of uncertainties in the previous section 1.4 and 3.3.6 before reading the following chapter since section 7.3 is based on and meant to be read in the light of these earlier sections.

7.6.1 Ability of the chosen scenarios to represent the underlying risk

The uncertainty in the choice of representative scenarios is closely related to the limitations in time, computer power, storage space, risk analyst experience and other important resources. This is particularly true for the very computer resource demanding dispersion simulations. The number of dispersion simulations was limited to only 13 and it was not even possible to let all of them run until steady state was reached. The effect of deluge on dispersion has only been possible to evaluate qualitatively, since the model can not account for the effect of activated deluge. However, this effect is estimated to have a net beneficial impact on the total explosion risk.

7.6.2 Strategies used in the present analysis to handle the uncertainty in the ability of the chosen scenarios to represent the risk

To reduce the uncertainties in the ability of the scenarios to represent the risk a number of measures were taken. The choices of CFD scenarios have been discussed with an experienced risk analysis expert from DNV. The choices also followed the available guidelines from NORSOK Z-013 and the EXPRESS user manual as far as possible. In accordance to the NORSOK Z-013 standard a slightly conservative approach has been used to account for the uncertainties. Explosion and dispersion scenarios have been deliberately chosen to cover combinations of stochastic variables which could lead to worse-case scenarios.

For explosion simulations, it would have been interesting to simulate even more scenarios to examine sensitivities for variation of gas cloud and ignition location, droplet size, water application rate and other parameters in greater depth. More resources also would have enabled a more detailed analysis of the problems with extreme values and grid dependency in encountered in the analysis.

The use of consequence response surfaces combined with leakage frequency distribution, stoichastic input modelling and Monte Carlo analysis also would have been helpful in handling the uncertainties of choice of scenario representation if there had been more resources available.

7.6.3 Uncertainty of assumptions

Most of the assumptions used in the present analysis have not been introduced by the risk analyst. They are related to modelling explosions with FLACS and seen as part of the model. Three important assumptions that have been made in the present analysis are that:

i. FLACS is as an acceptable tool for simulation of explosion consequences with and without deluge.
ii. The ignition probability will not increase due to the use of automatically activated deluge as an explosion mitigation measure.
iii. The expected leakage frequencies will not increase due to the use of automatically activated deluge as an explosion mitigation measure.
iv. The effect of activation deluge will have a net beneficial effect on dispersion and gas cloud development.

For a full probabilistic explosion risk analysis the uncertainties related to assumptions would have been of greater importance.

7.6.4 Strategies used in the present analysis to handle the uncertainty in relation to the assumptions

As was already mentioned in section 1.4 above, standardised guidelines and risk analysis procedures such as NORSOK Z-013 and the aligned DNV EXPRESS methodologies are seen as possible means to reduce the uncertainties related to the use of assumptions in the analysis.

The three assumptions above proposed by the author have been discussed and accepted by the more experienced risk analysis experts and representatives of the decision maker. They are not expected to have any significant contribution to the overall uncertainty in the present analysis.

7.6.5 Uncertainty in FLACS simulation results

The general limitations in and short-comings of CFD modelling of explosion as well as a more specific description of FLACS have been discussed in section 3.3.6 and 4.1 above. According to the provider of the FLACS code, explosion simulation results are typically within ± 30% compared to experiments. In figure 59 the simulation results with-out deluge are plotted with a three time as broad uncertainty interval (± 100%) to illustrate a subjective estimate of the uncertainties in the explosion simulations in the present analysis.

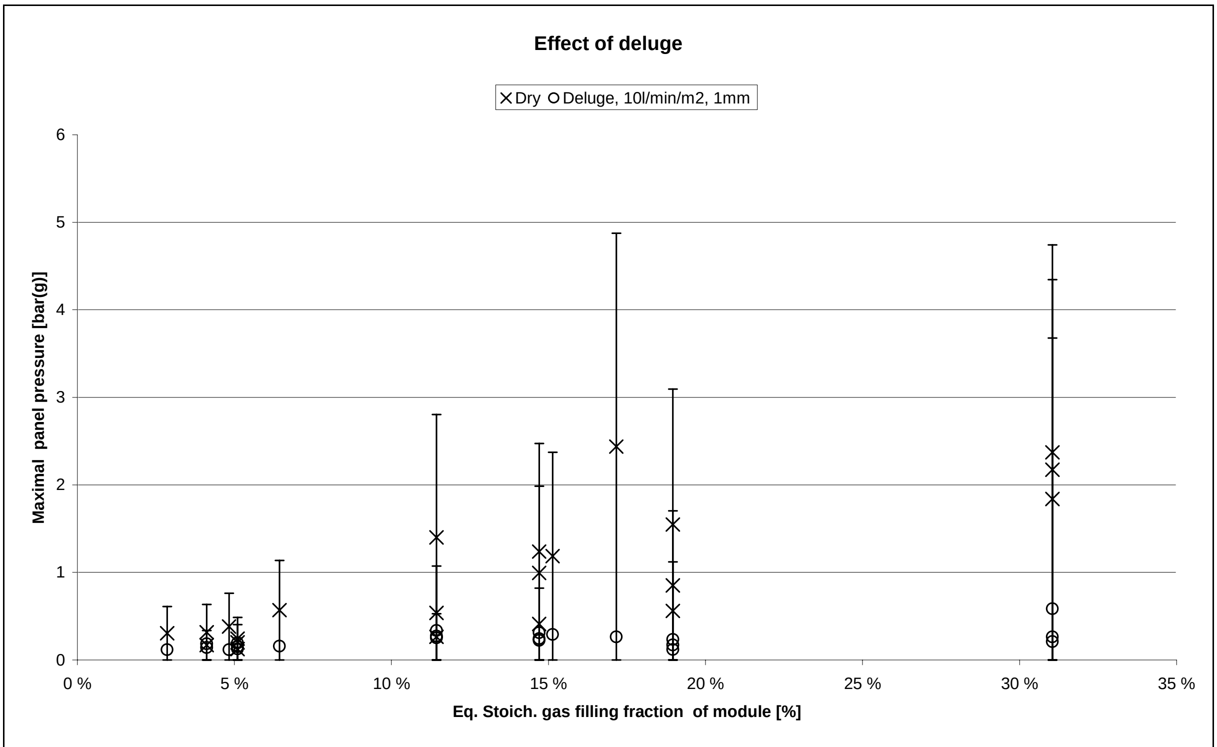


Figure 58: CFD results plotted together with an uncertainty interval factor of 2. Note that this illustrates the subjective estimate of the uncertainties based on the present study.

The chosen uncertainty interval is thought to reflect that the simulation solutions were not grid independent and that there have been some problems with extreme values. It is important to note that these difficulties should not be attributed to the deficiencies of the FLACS code alone but also the human factors: the risk analyst experience, the use of the model and the computer-user interface. Hence, in addition to the simulation code deficiencies there are always potential uncertainties in how the model has been used.

The results of simulations with the deluge model are regarded as even more uncertain than the simulations with-out deluge. No attempt has been made to try to estimate the uncertainties for the deluge simulations quantitatively in the present analysis. Even if there are large uncertainties in the exact values of the quantitative results, the general trends of using deluge compared to not using deluge are expected to be reproduced with an acceptable uncertainty.
The uncertainties in the ventilation and dispersion simulations are seen as less important in the present analysis, since the results could not be used to produce response surfaces and Monte Carlo analysis.

7.6.6 Strategies used in the present analysis to handle the uncertainties in the FLACS simulation results

To reduce the uncertainties attached to user competence and usage of FLACS the competence level has been raised by attending a three day FLACS course at Gexcon. Further, a lot of effort has been put to follow the latest available guidelines in detail. Considerable effort has to assure that the FLACS guidelines have been followed. More experienced risk analysis experts have also been consulted continuously throughout all parts of the project to compensate for the lack of FLACS experience by the author of this report. Still, the possibility to consult more experienced risk analysis expert has been limited.

Considerable time and resources have also been spent on systematic and continuous quality assurance efforts. The systematic quality work manifests itself in the present study as the grid dependency study, the sensitivity analyses and the comparisons between simulations and previous experimental experience to mention some examples. All simulated scenarios have been double-checked to avoid simple computer-user interfaces mistakes in defining the right input for each simulation scenario before simulation. This was done by using Linux commands to compare and control that the simulation control files were correctly defined. For example, the following command can be used to control that the ignition location is correctly defined.

```
grep POSITION_OF_IGNITION_REGION cs*
```

This command line in Linux can be used to display the ignition location for each cs-file. By comparing this with the list of the planned simulation scenarios, a lot simple mistakes with wrong input has been identified and corrected before the simulations were run. Two other useful commands, ‘diff’ and ‘tail’, in Linux were also used frequently to ensure as high scenario definition quality as possible and to eliminate simple user mistakes.

If there had been more resources it would have been possible to conduct the full probabilistic explosion analysis and include a model uncertainty factor such as proposed by Hjertager and discussed at the end of section 3.3.4 above. This means the uncertainties could be expressed as suitable probability distributions and incorporated in the Monte Carlo analysis model for the dispersion and explosion response surfaces.

7.6.7 Uncertainties in relation to input quality

While some input has been very hard to obtain, other has been easily available. The uncertainties related to the input quality for all parameters in the CFD simulations are hard to quantify but can be seen as part of the model uncertainty.

The input for the economical analysis was very hard to estimate. Any attempts to calculate such a measure will therefore be attached with extreme input uncertainties that need to be addressed.

7.6.8 Strategies used in the present analysis to handle the uncertainties due to input quality

The main strategy has been to search and search again for as good input as possible. Where object specific input has not been available, more general input has been used instead. The probit functions for quantifying threshold for equipment failure may serve as one example. More time and resources could easily have been spent to increase the quality of the input and thus reduce the input uncertainties. A full Monte Carlo analysis would also open for possibilities to account for much of the stochastic uncertainties in the input.

The results of the sensitivity study indicate that the Sauter mean droplet diameter is of outmost importance. In itself, the sensitivity study of droplet size has reduced this uncertainty a bit by providing additional information and thus eliminating some epistemic uncertainty.

To ensure as high traceability and transparency as possible, the most relevant input has been listed together with references, comments and/or recommendations on how to obtain even better input. An example of an explosion simulation control file has also been attached to allow for a thorough examination of the input used in the simulations.

7.7 Recommendation

7.7.1 Recommendation for Troll B

The total gathered evidence of the CFD simulations, calculations, experimental experience and earlier analyses indicates that deluge has a generally good effect on explosion at Troll B.
Based on this evidence, the use of automatic initiated deluge is recommended to be implemented if it can be confirmed that the Sauter mean diameter of the open sprinkler nozzles are 1 mm or above. In case the droplet size turns out to smaller than 1mm, a more detailed analysis is required.

A more detailed analysis is recommended with more accurate input on the droplet size Sauter mean diameter and a larger number of simulations than has been possible during the present study. The effect of deluge is also recommended to be analysed with a full probabilistic explosion risk analysis to examine how deluge will effect both the consequences as well as the total risk picture. In such a probabilistic analysis, the improved time model needs to be fully incorporated in the Monte Carlo simulations to reflect the probability of ignition before efficiently activated deluge. Based on the results of the present study, such analysis should be focused mainly on clouds below 30% of module filling.

More accurate input on the Sauter mean diameter of the deluge system is required before a decision can be made. This can be achieved by measuring the droplet size distribution in a laboratory or by possibly through further contact with the deluge nozzle supplier.

The time study reveals that the time for automatic activation of deluge on Troll B is in the range 40-60 seconds. The limited number of dispersion simulations suggests that the stoichiometric equivalent size of cloud at this time is typically as large as 1500 m^3 and that deluge can be expected to have a good effect in case ignition should occur.

The cost-benefit analysis indicates how large the economic values at stake are. Unsurprisingly, some of the largest costs are related to downtime and production loss. The uncertainties in the input to the cost-benefit are very large. This is particularly true for the estimates of costs for scenarios with extremely high consequences combined with extremely low frequencies. It should also be noted that the cost-benefit calculations presented were based on rather arbitrary cumulative explosion load curves. Nevertheless, the cost-benefit analysis indicates that deluge as an explosion mitigation measure is economically beneficial for the case study.

7.7.2 General recommendations for offshore installations

Based on the results from the first part and the case study, it is recommended to conduct an installation specific analysis. The suggested framework is seen as a good method of conducting such an analysis. Deluge can be expected to have a beneficial effect in modules which are not totally confined. The effect is dependent on deluge drop size and explosion scenario factors such as cloud size, ignition location, level of congestion etc. Scenarios with large deluge droplets, large clouds, high-congestion and end ignition typically lead to a substantial lower explosion loads with deluge than with-out. For smaller, low congested, central ignited clouds the effect of deluge is generally less beneficial or even negative due to the increase in initial turbulence.

8 Discussions and Conclusions

During the work with the case study, problems and opportunities of improvement were identified for the decision support framework. In this chapter these problems and opportunities are discussed in a systematic and constructive way. First, some general problems and improvements are discussed. Then each part of the framework is evaluated to identify specific problems and possibilities of improvements.

8.1 General improvements to the decision support framework

8.1.1 Problems of finding good input to the analysis

During the analysis finding good input were identified as a general problem. Two key strategies are suggested to minimize this problem. First of all, it is seen as helpful to define the required input as early as possible in the project. Secondly, the input used in the report has been carefully documented with as high traceability to enable re-use of good input for future similar analyses. Care must however always be taken to evaluate if new, better input is available rather than just using old input. Whenever available, object specific input is preferred in comparison to more general input.

8.1.2 Problems with high degree of uncertainty in the results

The risk and cost-benefit analyses were seen to have a high degree of uncertainty in the results. This is not unexpected given the topic and methods available to quantify the explosion risk. Some strategies for handling the uncertainties related to CFD modelling of explosions have already been presented in section 3.3.6. Further discussion and strategies on how the uncertainties were handled in the case study is found in chapter 7.6.

Two additional potential improvements of the decision support framework in relation to uncertainties are proposed. First, the decision analysis should provide information on the decision-makers requirements and preferences regarding uncertainties. This can be done by adding the following to the set of questions used in the decision analysis:

How should uncertainties be handled in the decision support?

When found valuable for the decision maker, the analysis could be extended to estimate the uncertainties quantitatively. The question should also ensure that the decision maker and risk analyst share the same definition of uncertainty.

Secondly, it is suggested that the cost-benefit analysis and time model can be combined with Monte Carlo simulation techniques to handle input uncertainties in a systematic way.

8.1.3 Opportunities in framework flexibility

It is recognised that CFD simulation, explosion risk modelling and explosion risk management are areas under fast continuous development and scientific research. It is seen as a problem that the suggested framework is limited to the present state of knowledge which may limit future analyses. At the same time this is seen as a possible opportunity provided that the framework can be flexible enough to capitalise on the benefits of the continuously improved methods, input, newer statistics, scientific research etc. available at the time of the analysis.

An example of such improvements under development is an improved, more physically based deluge model for CFD simulation of explosions which accounts for droplet size distribution instead of using a single value. The potential of research progress in the area of deluge effect on dispersion is another example of a research area of outmost importance to a decision support frame for explosion risk and deluge.

These opportunities can be captured by the framework by starting each new decision support analysis with a review and update of best available methodologies, models and recent research results.

8.2 Evaluation and improvements: Decision Analysis

The suggested coarse decision analysis approach based on five questions was found to give rather vague results, partly due to lack of decision maker involvement in the analysis. More advanced methods to analyse the decision-makers preferences could be helpful to avoid this problem. Such methods are however more resource demanding which is the reason why the coarse decision analysis approach was chosen in the first place.

For oil companies with many installations that need to consider deluge as an explosion mitigation measure for many cases it is recommended that the preferences are analysed in depth once and for all. The findings of such an analysis could then be expressed as a company 'best praxis philosophy' applied to all installations. This would also lead to a more uniform strategy throughout the company on how to evaluate deluge and explosion risk. The present report is however seen as a good starting point for such analyses. An introduction to scientific methods to analyse the preferences with quantitative methods based on regression analysis are given by Aiman-Smith[210].

An alternative, more philosophical approach would be to take a theoretical ethical theory such as utilitarianism as the starting point and then derive preferences and policies for the decision problem in question from first principle.

During the work with the case study the need of defining key concepts such as risk, probability and uncertainty became obvious. It is seen as very important that the risk analyst and decision-maker share the same understanding and definitions of these key concepts to avoid misunderstandings and communication problems. A more detailed discussion of different approaches to these concepts was added in chapter 1.4. and 1.5 during the work of the case study. A similar clarification is recommended to be included in future analyses where the decision support framework is used.

8.3 Evaluation and improvement: Risk Analysis

Although the case study proved that the framework to be very useful, it also revealed two main flaws with the risk analysis method: large uncertainties and large resource demands. Since the handling of uncertainties was handled in earlier chapter, this chapter concentrates on ways to improve the framework by increasing the efficiency when conducting the risk analysis part.

i. **Conduct the risk analysis by stages**.
The idea is to divide the risk analysis into a number of stages with increasing level of sophistication and resource demand. After each stage a Managerial review and judgement process is conducted to evaluate if the evidence is sufficient to make the decision or if more information is needed. If the decision can be reached without a full analysis, substantial resources can be saved. The stages could include:

a) Qualitative screening checklists: Is deluge expected to be beneficial?
b) Explosion consequence analysis with and with-out deluge.
c) Sensitivity analysis of the explosion consequences with/with-out deluge.
d) Time model analysis combined with full probabilistic explosion risk analysis with and with-out deluge in accordance with NORSOK.
e) Full Cost-benefit analysis.

ii. **Avoid unnecessary CFD re-runs**
By working systematically with quality assurance, simple mistakes can be eliminated before the simulations are run to avoid unnecessary re-runs. The quality work should always be conducted by an experienced FLACS user. Four of the most important steps to avoid unnecessary CFD re-runs include the following measures:

a) Verify that the geometry model is detailed enough.
b) Control that the grid is in accordance with guidelines and optimal for the problem to be solved.
c) Control that the scenario has been correctly defined before starting the simulation.

---

[210] Aiman-Smith, Lynda, et al, (2002) *"Conducting studies of decision making in organizational contexts: A tutorial for policy-capturing and other regression-based techniques*", Organizational Research Methods, Oct 2002, Volume 5, No 4, page 388

d) During simulation, check continuously that the simulation runs smoothly with-out large mass residual errors or unphysical results.

iii. **Concentrate resources at the most interesting scenarios**
During the work with the case study, it was realised that important resources could and should be used more efficiently by concentrating the simulation efforts to the most interesting scenarios. Explosion results in the range between 0,1-1 bar was found to be of key interest, corresponding to gas cloud sizes typically below 5000 m^3 for the specific case study.

iv. **Capitalize on synergy effects**
By coordinating the analysis of the effect of deluge with CFD explosion risk analyses conducted for other purposes there are great opportunities to capitalize on synergy effects. Much of the work with the CFD geometry model, choice and preparation of scenarios can be saved and re-used. The scenario files with-out deluge can easily be modified and simulated with activated deluge. It is recommended to start by conducting a probabilistic explosion risk analysis. Then the explosion scenarios with emphasis on the more probable small gas clouds and then increase the gas cloud size. When available, use previous analyses as guiding input when selecting scenarios to concentrate the simulation effort to the gas cloud sizes most interesting to the analysis.

v. **Document and share the experience gained**
By documenting and sharing the relevant experience gained each time an analysis of deluge and explosion risk is conducted the framework can be continuously improved. Sharing experience with mutually with others means that pitfalls and resource losses can be minimized. In the long run this will lead to increasingly efficient analyses.

8.4 Evaluation and improvements: Time model

The suggested time model is seen as a good first step. It was successfully used to estimate the time to initiated deluge based on the available input.

The time model can be improved by incorporating it in a Monte Carlo simulation model for probabilistic explosion risk analysis. Ideally, it should to be coupled to the ignition model, the dispersion response surface and two different explosion response surfaces: one based on explosions with deluge and one with-out. For each iteration, the time to efficiently activated deluge needs to be compared with the time to ignition, so that the effect of deluge is **only** accredited when $t_{Deluge} < t_{Ignition}$. For cases $t_{Deluge} < t_{Ignition}$, the model uses the explosion responses surface based on simulations with deluge. If on the other hand $t_{Deluge} > t_{Ignition}$, the response surface based on simulations with-out deluge should be used. To incorporate the time model in a Monte Carlo simulation model for probabilistic explosion risk analysis, substantial research and model development is required.

The possibilities of using CFD dispersion simulations to estimate time to detection should also be further investigated. This could reveal object specific information on the transient relation between the explosive cloud size development in relation to time until confirmed detection occurs and deluge can be efficiently activated. The time to detection can also be estimated by CFD simulation. A way to do this in an effective way is by locating measure points to represent the detectors in the module before the dispersion scenarios are simulated.

8.5 Evaluation and improvements: Cost-benefit model

In general, the cost-benefit model was seen as an efficient and useful tool in quantifying the economic dimension of the decision problem. The three largest difficulties with the cost-benefit were:

i. The uncertainties in the input used in the analysis.
ii. The difficulties in finding good input.
iii. The question on what to include in the analysis.

The two first difficulties are partly covered by section 8.1. An additional possibility to handle these problems is to use Monte Carlo analysis. This way, input could be entered to the analysis as probability weighted intervals instead of single values.

The last difficulty with the cost-benefit is the question on what to include in the analysis. In the case study the explosion effects on the environment, occupational health and company reputation was ignored and argued not to be included in the analysis. Further, based on the preferences of the decision-maker, fatalities were not included in the cost-benefit analysis. The arguments and assumptions used to support this approach have been revisited based on the hindsight of the case study.

In retrospective with the hindsight of the case study, this approach of ignoring the direct risk reduction of fatalities, occupational health and environment is seen as an unnecessary simplification that needs to be corrected. Based on this hindsight, it is recommended that the CBA methodology in framework should be expanded to harmonise with the NORSOK guidelines. This approach includes the use of VOSL or ICAFS. The most important argument for this approach is that in a more standardised cost-benefit analysis, the choices of what to include is seen as less arbitrary. It is also argued that the harmonisation will ease the possibilities to compare deluge with other risk reduction measures and provide a better decision support for the decision maker. Although this is the recommended general practice, exceptions may still be made if the decision-maker has strong preferences against the use of VOSL, ICAFS or the NORSOK CBA guideline in general.

Hence, it is seen as an improvement opportunity to allow for the above effects to be entered in the cost-benefit analysis. This means that an extended cost-benefit methodology is recommended to be used in the framework.

8.6 Conclusions

A decision support framework has successfully been derived, tested, evaluated and improved as an answer to the questions raised in chapter 1. During this work, it became obvious that the questions will need to be analysed and addressed for the individual installation modules because of the complexity of the problem. Hence, a separate analysis needs to be done for each installation to account for the ventilation, dispersion and explosion phenomena. CFD is argued to be the best available tool to conduct such an analysis.

Nevertheless, some general answers to the questions are given below. Concerning the answer of the first question the aspects seen as most important were simply listed in falling order:

What aspects are important to take into consideration when making the decision whether to use deluge as an explosion risk reduction measure or not?

i. The legal requirements.
ii. The preferences of the decision-maker and relevant stakeholders in how to express the net effect of deluge on the explosion risk to be suitable for decision making.
iii. The analysis results describing how deluge can be expected to effect the explosion risk, expressed as a decision support for the specific installation in question.
iv. The costs compared to the risk reduction benefits.
v. The large amount of uncertainties and flaws in the available methods to quantify explosion risk and the effect of deluge.

When should deluge be used as an explosion risk reduction measure in the offshore industry?

i. When the analysis results show that automatically activated deluge can be expected to have a net positive effect on the explosion risk as it is required by law for all new installations, modules as well as major re-buildings or modifications of existing facilities on the Norwegian shelf built after 2002.
ii. When the decision support based on an installation specific analyis shows that activated deluge can be expected to have positive effect on the explosion risk which outweighs the downsides and costs in accordance with the preferences of the decision maker.

Generally, deluge activation on detected gas can be expected to have a net positive effect on the explosion risk in high congestion areas which are not totally confined. This is often the situation for process modules at offshore installations. Deluge activation on gas detection is **not** recommendable in fully confined modules and areas. It must be noted that activation of deluge can lead to increased explosion loads. It is therefore always highly recommended to analyse the effect of deluge for the specific installation module with CFD simulations. For such analyses it is recommended to use the improved framework presented in previous chapters of this report. The result of the case study cost-benefit analysis also indicates that the use of deluge had an expected positive economical effect.

Based on the gathered evidence presented the following practical recommendations can be given on how deluge should be used:

i. General area deluge should be used rather than equipment specific protection or water curtains.
ii. The water application rate should be at least 10 liter/m^2/minute
iii. The use of foam such as AFFF is **not** recommended to be used for explosion mitigation until more experimental experience have been gained and it can be proved that there is no conflict with exhausting the fire-fighting system capacity.
iv. The same nozzles can be used for both fire fighting and explosion mitigation as long as the Sauter mean droplet diameter of the produced spray is not to small. A Sauter mean diameter larger than at least 0.5 mm is recommended.
v. It is recommended that a combination of both manual and automatic initiation of deluge on confirmed gas detection in used in order to minimize the time to efficiently activated deluge.
vi. The potential increase in ignition probability due to water ingress in electrical equipment needs to be controlled.

8.7 Suggestions on future research

Suggestions for future research would be to fully incorporate the time model in Monte Carlo model to be able to better account the relations between the transient phenomena of gas dispersion, cloud development, ignition probability, detection and effective initiation of deluge. The possibility of using CFD dispersion simulations to estimate the time to gas detection should also be investigated and included in the framework. . Research efforts are also needed to improving the CFD modelling capabilities, especially in respect of the deluge models. The effects of deluge on ventilation and gas dispersion are still rather unknown phenomena that need to be investigated experimentally. A more theoretically founded analysis of the decision-makers preferences could be useful.

9 References

Aiman-Smith, Lynda, et al, (2002) *"Conducting studies of decision making in organizational contexts: A tutorial for policy-capturing and other regression-based techniques*", Organizational Research Methods, Oct 2002, Volume 5, No 4, page 388

Andersson, P. (1997) *"Evaluation and Mitigation of Industrial Fire Hazards"*

Arvidsson et al (2001) *"Släcksystem med vattendimma – en kunskapssammanställning"*

Arntzen, B. J. (1998) *"Modelling of turbulence and combustion for simulation of gas explosions in complex geometries"*
Thesis for doctoral degree at the Norwegian University of Science and Technology

Aven T. et al (2005) *"On the use of risk acceptance criteria in the offshore oil and gas industry"*

Aven T. et al (2005) *"A decision framework for risk management, with the application to the offshore oil and gas industry"*

Bolsover A. , Wheeler M. (1999) *"Decision-making to treat an explosion hazard"*
Paper presented at the Conference on Safety on Offshore Installations, 1999

Bjerkevendt et.al. (1997) *"Gas Explosion Handbook"*
Available at www.gexcon.com

Bull (2004) *"A critical review of post Piper Alpha developments in explosion science for the offshore industry"*

CMR/Gexcon (2006) *"FLACS Training"*
Course material for FLACS user course

Corr, R. B. et. al. (1998) *"Gas explosion generated drag loads in offshore installations"*

Cozzani V. et. al. (2006) *"Quantitative assessment of domino scenarios by a GIS-based software tool"*

Cozzani V. et. al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part I. Probit models"*

Cozzani, V. et al. (2004) *"The quantitative assessment of domino effects caused by overpressure Part II. Case studies"*

Dale, E. (2004) *"Simulation and modelling of waterspray in the 3D explosion simulation program FLACS"*
Master thesis at the University of Bergen

DNV (2006) *"Teknisk undersøkelse i forbindelse med gasslekkasje fra fakkelrøret på Visund 2006-01-19"*

DNV (2006) *"Introduksjon til risikostyring og ledelse"*,
Coarse compendium for Uib/DNV course 2006

DNV (1997) *"Värdering av risk"*

DNV , RF (2002) *"Årsaksanalyse av prosesslekkasjer"*

Drysdale, D (1998) *"An introduction to fire dynamics"* 2nd edition, page 11

Eckhoff (2003) *"Dust explosions in the process industries"* 3rd edition, pages 15-20

Ersdal (2005) *"Risk management and its ethical basis"*

Part of his Ph.D thesis, Stavanger Univeristy

FABIG (2003) *"Water deluge and influence of dispersion"*, FABIG Newsletter August 2003, Issue No 36 Article R485

FOA (1998) *"Toxic and inflammable/explosive chemicals – a Swedish Manual for Risk Assessment"* , rev. 2

Frantzich (1994) *"A model for performance-based design of escape routes"*

Grimvall G. et al (red), (1998) *"Risker i tekniska system"*

Hanna S. et. al. (2004) *"FLACS CFD air quality model preformance evaluation with Kit Fox, MUST, Praire Grass, and EMU observations"*

Hogarth (1987) *"Judgement of Choise: the Psychology of Decision"*

HSE (1996) *"An investigation of factors of relevance during explosion suppression by water sprays"*

HSE (2006) "*Design, materials and connections for blast-loaded structures"*,
RR405

HSE (1995) *"Electrostatic hazards associated with water deluge and explosion systems offshore"*

HSE (2000) *"Explosions in Full Scale Offshore Module Geometry Main Report"*
OTO 99 043

HSE (2006) "*Improved simplified response methods to blast loading"*,
RR435

HSE (2005) *"Natural ventilation on offshore platforms"*

HSE (2001) *"Reducing Risks, Protecting People"*

HSE (1999) *"The Repeatability of Large Scale Explosion Experiments"*
HSE (2000) *"Screening study to assess the relative importance of factors the decision to activate deluge on gas detection"*

HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"*

HSE/UKOOA (2002) *"Updated guidance for fire and explosion hazards CTR 104 – Management of explosion hazard - rev A2"*

HSL (2002) *"A Review of the State-of-the-art in Gas Explosion Modelling"*

HSL (2005) *"Offshore ignition probability arguments"*

Hume D. (1739) *"Treatise of Human Nature"*

Huser, A et al (2000) *"EXPRESS- cost effective explosion risk management"*

HYDRO (2005) *"Weight and cost estimates Camilla Belinda (CB) to Troll B"* , Hydro internal note TFD0500007

HYDRO (1993) *"SAFETY REQUIREMENTS TO SYSTEMS DURING ACCIDENTS"*
Document reference number 17-1A-NH-F15-00010

HYDRO (1998) *"System Engineering manual System 71 Brannvann og skumsystemet"*
Document reference number 17-1A-AE-F85-71000

Høiset S. (1997) *"Statistical estimation of loads from gas explosions"*

IEC (1995)*"International standard 60300-3-9, Dependability Management – Part 3: Application Guide – Selection 9; Risk analysis of technological systems"*, Genéve,

ISO (1999) *"Petroleum and natural gas industries – Control and mitigation of fires and explosion on offshore production installations – Requirement and guidelines"*

Johansson, H (2003) *"Decision Analysis in Fire Safety Engineering – Analysing investments In Fire Safety"*

Jones. J. C. et. al. (1997) *"PLATO© software for offshore risk assessment: a critique of the combustion features incorporated"*

Kaplan S. et. al. (2001) *"Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and Result Refinement to the Quantitative Definition of Risk"*

Makarov et. al. (2004) *"Modeling and Large Eddy Simulation of Deflagration Dynamics in a Closed Vessel"*

Mattsson B. , (2000) *"Riskhantering vid skydd mot olyckor- problemlösning och beslutsfattande"*

Miura, K et al (2006) *"Characterization of operational safety in offshore oil wells"*

NSF (1997) *"Explosive atmospheres Explosion prevention and protection Part 1: Basic concepts and methodology",* NS-EN 1127-1

NORSOK (2000) *"S - 001 Technical Safety"*
Free to download at www.standard.no

NORSOK (2004) *"D – 010 Well integrity in drilling and well operations"*
Free to download at www.standard.no

NORSOK (2001) *"Z - 013 Risk and Emergency preparedness analysis"*
Free to download at www.standard.no

OREDA (2002) *"Offshore Reliability Data Handbook"* , 4th edition
Prepared by SINTEF and distributed by DNV
ISBN 82-14-02705-5
See also the webpage www.oreda.com

Persson I. et al. (2001) *"Investeringsbedömning"*

Popat et. al (1996) *"Investigations to improve and assess the accuracy of computational fluid dynamics explosion models"*

PTIL (2006) *"ALARP-prosesser – Gjennomgang og dröfting av erfaringer og utfordringer"*

PTIL (2006) *"Granskning av alvorlig gasslekkasje fra trykkavlastningssystemet på Visund den 19.1.2006"*

PTIL (2005) *"Gransking av gassutblåsning på Snorre A, brønn 34/7-P31 A 28.11.2004"*

PTIL (2004) *"Granskingsrapport etter hendelse knyttet til gasslekkasje fra 6" eksport rørledning fra Jotun A"*

PTIL (2005) *"Trends in risk level 2004 – Summary report"*
The report is free to download at:
www.ptil.no/English/Helse+miljo+og+sikkerhet/Risikonivaa+paa+sokkelen/RNNS+Fase+5+%282004%29+Sammendragsrapport/Coverpage.htm

PTIL (2005) *"Utvikling i risikonivå - norsk sokkel Fase 5 hovedrapport 2004*"

Riddle (2003) *"Comparisons between FLUENT and ADMS for atmospheric dispersion modelling"*

Savvides C. et. al. (2001) *”DISPERSION OF FUEL IN OFFSHORE MODULES: Comparison of Prediction Using FLACS and Full Scale Experiments”*
Available at www.gexcon.com

Scandpower (2003) report 27.101.487/R1, page 27

Scandpower (2003) *”Troll B – Risikoanalyse”*

Sklavounos (2006) “*Simulation of Coyote series trials—Part I: CFD estimation of non-isothermal LNG releases and comparison with box-model predictions”*

Singer (1996) *“Praktisk etik – Andra upplagan”*

Särdqvist (2002) ”Vatten och andra släckmedel”

Thomas, G.O. (2002) *“On the conditions required for explosion mitigation by water sprays”*

Tolson (1989) *“Examination of possible hazards arising form the use of water spray barriers to disperse flammable vapours”*

Van Wingerden, K. et. al. (1998) *“Effect of deluge on explosions: FLACS simulations compared to full-scale experiments”* Downloaded from www.gexcon.com

Van Wingerden, K. (1995) *“Gas explosion in vented enclosures and in the open: mechanisms, prediction methods and mitigation”*

Wingerden K. (2000) *”Mitigation of Gas Explosions Using Water Deluge”*

Appendix:

A: Input list
B: Scenario definitions
C: Example of explosion control file

Appendix A: Input checklist

Ventilation analysis input

CFD geometry.

The geometry model can be constructed from scratch, but it if CAD drawings it is recommended to try to import the geometry using the import script GEO2FLACS. In some cases there might be an old model available that can be used after it has been updated and verified.

Wind statistics (direction and speed frequencies)
Platform coordinates relation to wind directions. It is worth noting that while installations are often constructed on strict Carteisan grid-lines, it is often the case that these gridlines deviate from "true north" with some degrees. In the case study, the deviation between 'true north' and 'platform north' is 15 degrees. The deviation is handled by recalculating the wind frequencies before entering them into the probabilistic Monte Carlo model.

Ventilation system

In modules where there are ventilation systems, these will effect the flow pattern in the module. It is possible to model fans in FLACS. In the present analysis, there is no forced ventilation in analysed the process module since the natural ventilation is so good.

Dispersion analysis input

Gas composition:

In the present analysis a mixture of 70% CH_4, 10% C_2H_6 , 10% C_3H_8, 10% C_4H_{10} based on object specific input. A representative gas composition mixture can be found by analysing the process flows.

Segment sizes: Segment sizes are needed to calculate how the leakage mass flux decreases with time. It is used in the Monte Carlo analysis model combining the dispersion response surfaces, gas cloud development and ignition modelling. Segment sizes can be found by identifying the isolating valves, check valves and equipment sizes on object specific drawings, and then calculating the hydrocarbon volume for each segment. Process data such as pressure, temperature and gas composition also need to be taken into account.

Leakage size frequency distribution:
The leakage size frequency distribution can be achieved by calculating all equipment, piping, flanges, valves, gauges etc, in a module and then use statistics to attribute each specific item a contribution to the over all leakage frequency. The sum of all contribution from different leakage classes then add up to a leakage size frequency distribution. By conducting such an analysis, it is also possible to identify large contributions to the leakage frequency and make sensitivity analysis on risk mitigating measures such using double-walled pipes or, welding instead of flanges. It is recommended to use the nine leakage classes defined by NORSOK Z-013, Annex G. In the present study, leakage size frequencies were available from previous analyses. Since it was not possible to conduct the Monte Carlo analysis, the leakage frequencies were never used quantitatively in the present analysis.

Ventilation simulation results
The ventilation simulation results are used to identify dispersion scenarios with-in a specified range of the non-dimensional leakage rate, and to choose dispersion scenarios where ventilation patterns may lead to gas build-up.

Location of gas detectors
It is recommended to identify the number and locations of gas detectors in the module to enable an analysis of how fast the different simulation scenarios can be detected. This can be done by defining measure points in CASD to represent the gas detectors. At the measure points, the gas concentration over time is the recorded for the simulations.

Explosion analysis input

Dispersion results:
The dispersion results are used to identify explosion scenario parameters such as gas cloud size and location. Even if it is recommended to put the most of the computational efforts on smaller clouds, it may be interesting to conduct a small number of simulations with large clouds as well to examine the effect.

Detailed CFD geometry model:
A very detailed CFD geometry model is needed to simulate explosion scenarios, since it is the small details that contribute a lot to turbulence generation and the Schelkin mechanism. The geometry also needs to be verified.

Main safety functions, barriers, pressure relief panels, important equipment etc
Drawings on the important explosion targets are needed to define suitable measure points and panels to record the explosion load. Both pressure panels and monitor points can be used. Information on the pressure relief panels is required to account for the effect of pressure relief venting. In the present analysis, a value of 0,05 bar(g) was used based on object specific data and the previous analysis. The most important explosion targets were identified by analysing object specific drawings on the fire and explosion barriers. The probit functions presented in chapter 3 can be used to estimate the damage to equipment and risk of escalation. Typically the most interesting range is between 0,1 – 1 bar(g).

Dynamic response
The dynamic response and ductility to explosion walls can be included in the analysis by using the generic response spectra presented in chapter 3. Input needed for the analysis is the ductility, explosion duration and natural frequency of the construction. The explosion duration can be estimated from CFD simulation, while ductility and natural frequency needs to be calculated by structural computer programs, models or analytical solutions. In the present analysis, no object specific data on natural frequency and ductility were available. Based on experimental measurements, the natural frequency was estimated to be on the same order as the explosion duration (100-250 ms) which corresponds to a dynamic load factor of 0,5-1,2.

Explosion analysis with deluge

Droplet size, expressed as Sauter mean diameter
This is seen as a very important parameter. It is typically in the range between 0,1 – 2 mm. Three different ways of estimating the droplets size are listed below in falling priority:

i. Direct measurement.
ii. Data sheets from manufacturer.
iii. Empirical correlations, such as the one presented in chapter 4.

In the present study, no information was available on the droplet size. In the calculations, 1 mm was seen as a typical size based on experiments. Sensitivity runs were conducted with 0,5 and 0,1 mm droplet sizes.

Water application rate and coverage
The water application rate is typically 10 Litre/minute/m^2 for process areas based on NORSOK standard S-001, which also prescribes water application rates for other kinds of areas such as manifold area, well-head area etc[211]. HSE/UKOOA recommends at least 13-15 Litre/minute/m^2 since this was the lowest water application used in the JIP experiment series.[212] The water application rate is used to calculate the factors using the correlations presented in chapter 4 that incorporate the effect of deluge into FLACS.

Time to efficiently activated deluge
This has been estimated to 60-90 seconds by HSE/UKOOA[213] which may be used if other input is not available. To be able to calculate a more object specific value, a model has to calculate the time to efficiently activated deluge has been presented. This requires further input on time to detection, confirmed detection, reaction and response.

[211] NORSOK (2000) *"S - 001 Technical Safety"* page 29
[212] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"* page 44
[213] HSE/UKOOA (2003) *"Fire and explosion guidance Part 1: Avoidance and mitigation of explosions"* page 77

Three different ways to estimate the time to detection is presented, in falling order of priority:

i. In situ measurements with tracer gas.
ii. The time to detection can also be estimated by CFD simulation. A way to do this in an effective way is by locating measure points to represent the detectors in the module before the dispersion scenarios are simulated.
iii. Design document and previous analyses

A similar approach is possible can be adopted to estimate the time of response.

i. In situ measurements by activating the deluge system.
ii. Design document and previous analysis

The reaction time is negligible for automatic activation, but may be substantial for manually activated deluge. The time for manual reaction is dependent on the routines and education of the operators, the alarm presentation in the control room and many other factors and needs to be evaluated in each specific case.

Time to ignition
The time to ignition needs to be modelled with a ignition model.

Appendix B: Simulated scenarios

Fill fraction		Case no.	Cloud mass, E, (kg)	Cloud volume (m3)	Gas cloud position			size gas cloud			Ignition location		
					x	y	z	dx	dy	dz	x	y	z
0,467	1	A,B,C	342,7	11424	341,5	507,0	221,6	32,0	51,0	7,0	357,0	551,5	225,1
0,467	2	A,B,C	342,7	11424	341,5	507,0	221,6	32,0	51,0	7,0	357,0	511,5	225,1
0,467	3	A,B,C	342,7	11424	341,5	507,0	221,6	32,0	51,0	7,0	373,0	551,5	225,1
0,190	4	A,B,C,D,E,F	139,2	4641	359,5	507,0	221,6	13,0	51,0	7,0	366,0	507,5	225,1
0,190	5	A,B,C	139,2	4641	359,5	507,0	221,6	13,0	51,0	7,0	366,0	532,5	225,1
0,190	6	A,B,C,D,E,F	139,2	4641	359,5	507,0	221,6	13,0	51,0	7,0	366,0	557,5	225,1
0,114	7	A,B,C,D,E,F	84,0	2800	341,5	522,0	221,6	20,0	20,0	7,0	370,0	532,5	225,1
0,114	8	A,B,C,	84,0	2800	341,5	522,0	221,6	20,0	20,0	7,0	356,0	532,5	225,1
0,114	9	A,B,C,D,E,F	84,0	2800	341,5	522,0	221,6	20,0	20,0	7,0	342,0	532,5	225,1
0,417	10	A,B,C	306,0	10200	348,5	507,0	213,6	25,0	51,0	8,0	373,0	507,5	217,1
0,417	11	A,B,C	306,0	10200	348,5	507,0	213,6	25,0	51,0	8,0	366,0	532,5	217,1
0,417	12	A,B,C	306,0	10200	348,5	507,0	213,6	25,0	51,0	8,0	342,0	532,5	217,1
0,051	13	A,B,C,D,E,F	37,4	1248	359,5	519,0	213,6	13,0	12,0	8,0	371,0	519,5	217,1
0,051	14	A,B,C,D,E,F	37,4	1248	359,5	519,0	213,6	13,0	12,0	8,0	366,0	532,5	217,1
0,051	15	A,B,C,D,E,F	37,4	1248	359,5	519,0	213,6	13,0	12,0	8,0	366,0	342,5	217,1
0,310	16	A,B,C,	228,0	7600	348,5	507,0	213,6	25,0	38,0	8,0	373,0	507,5	217,1
0,310	17	A,B,C,	228,0	7600	348,5	507,0	213,6	25,0	38,0	8,0	366,0	526,5	217,1
0,310	18	A,B,C,	228,0	7600	348,5	507,0	213,6	25,0	38,0	8,0	342,0	526,5	217,1
0,151	19	A,B,C,D,E,F	111,2	3705	359,5	531	213,6	13,0	19,0	15,0	366,00	543,50	214,10
1,000	20	A,B,C	734,4	24480	341.5	507,0	213,6	32,0	51,0	15,0	373,25	507,25	227,35
1,000	21	A,B,C	734,4	24480	341,5	507,0	213,6	32,0	51,0	15,0	373,25	532,75	225,85
1,000	22	A,B,C	734,4	24480	341,5	507,0	213,6	32,0	51,0	15,0	373,25	557,75	227,35
1,000	23	A,B,C	734,4	24480	341,5	507,0	213,6	32,0	51,0	15,0	341,25	532,75	213,85
1,000	24	A,B,C	734,4	24480	341,5	507,0	213,6	32,0	51,0	15,0	357,25	557,75	221,25
1,000	25	A,B,C	734,4	24480	341,5	507,0	213,6	32,0	51,0	15,0	350,25	507,25	213,85
0,765	26	A,B,C	561,6	18720	341,5	507,0	213,6	32,0	39,0	15,0	341,75	545,25	221,35

0,765	27	A,B,C	561,6	18720	341,5	519,0	213,6	32,0	39,0	15,0	363,25	555,25	215,35
0,765	28	A,B,C	561,6	18720	341,5	519,0	213,6	32,0	39,0	15,0	357,25	532,75	225,85
0,147	29	B,C,D,E,F	108,0	3600	350,5	519,0	213,6	15,0	16,0	15,0	355,25	542,75	214,85
0,147	30	B,C,D,E,F	108,0	3600	358,5	542,0	213,6	15,0	16,0	15,0	360,75	536,75	227,25
0,147	31	B,C,D,E,F	108,0	3600	350,5	536,0	213,6	15,0	16,0	15,0	363,25	536,75	221,85
0,041	32	B,C,D,E,F	30,2	1008	350,5	519,0	213,6	12,0	12,0	7,0	363,25	517,75	222,85
0,048	33	B,C,D,E,F	35,5	1183	360,5	507,0	213,6	13,0	13,0	7,0	363,25	517,75	222,85
0,172	34	B,C,D,E,F	126,0	4200	341,5	517,0	221,6	30,0	20,0	7,0	363,25	555,75	222,85
0,029	35	B,C,D,E,F	21,0	700	341,5	535,0	221,6	10,0	10,0	7,0	341,75	531,25	222,85
0,041	36	B,C,D,E,F	30,2	1008	341,5	531,0	221,6	12,0	12,0	7,0	373,25	557,75	213,85
0,064	37	B,C,D,E,F	47,3	1575	348,5	531,0	213,6	15,0	15,0	7,0	341,75	507,25	215,85

Appendix C: Example of cs-file

```
VERSION 0.5
%TEMPLATE="_v8.1/scenario/default"

SINGLE_FIELD_VARIABLES
 NH      "H      " 1 "(J/kg)         "  N
  "Enthalpy"
 NFUEL   "FUEL   " 1 "(-)            "  N
  "Fuel mass fraction"
 NFMIX   "FMIX   " 1 "(-)            "  N
  "Mixture fraction"
 NFVAR   "FVAR   " 1 "(-)            "  N
  "Mixture variance"
 NK      "K      " 1 "(m2/s2)        "  N
  "Turbulent kinetic energy"
 NEPK    "EPK    " 1 "(1/s)          "  N
  "Turbulence ratio"
 NEPS    "EPS    " 1 "(1/(m2*s3))    "  N
  "Dissipation rate of turbulent kinetic energy"
 NGAMMA  "GAMMA  " 1 "(-)            "  N
  "Isentropic gas constant"
 NLT     "LT     " 1 "(m)            "  N
  "Turbulent length scale"
 NMU     "MU     " 1 "(kg/(m*s))     "  N
  "Effective dynamic viscosity"
 NOX     "OX     " 1 "(-)            "  N
  "Oxygen mass fraction"
 NP      "P      " 1 "(barg)         "  N
  "Pressure"
 NPIMP   "PIMP   " 1 "(Pa*s)         "  N
  "Pressure impulse"
 NPROD   "PROD   " 1 "(-)            "  N
  "Combustion product mass fraction"
 NRET    "RET    " 1 "(-)            "  N
  "Turbulent Reynolds number"
 NRFU    "RFU    " 1 "(kg/(m3*s))    "  N
  "Combustion rate"
 NRHO    "RHO    " 1 "(kg/m3)        "  N
  "Density"
 NT      "T      " 1 "(K)            "  N
  "Temperature"
 NTURB   "TURB   " 1 "(m/s)          "  N
  "Turbulence velocity"
 NTURBI  "TURBI  " 1 "(-)            "  N
  "Relative turbulence intensity"
 NVVEC   "VVEC   " 3 "(m/s)          "  N
  "Velocity vector"
 NU      "U      " 0 "(m/s)          "  N
  "Velocity component x-direction"
 NV      "V      " 0 "(m/s)          "  N
  "Velocity component y-direction"
 NW      "W      " 0 "(m/s)          "  N
  "Velocity component z-direction"
 NUVW    "UVW    " 1 "(m/s)          "  N
  "Velocity value"
 NUDRAG  "UDRAG  " 1 "(Pa)           "  N
  "Drag component x-direction"
 NVDRAG  "VDRAG  " 1 "(Pa)           "  N
  "Drag component y-direction"
 NWDRAG  "WDRAG  " 1 "(Pa)           "  N
  "Drag component z-direction"
 NDRAG   "DRAG   " 1 "(Pa)           "  N
  "Drag value"
 NUDIMP  "UDIMP  " 1 "(Pa*s)         "  N
  "Drag-impulse component x-direction"
 NVDIMP  "VDIMP  " 1 "(Pa*s)         "  N
  "Drag-impulse component y-direction"
 NWDIMP  "WDIMP  " 1 "(Pa*s)         "  N
  "Drag-impulse component z-direction"
 NDIMP   "DIMP   " 1 "(Pa*s)         "  N
  "Drag-impulse value"
 NUFLUX  "UFLUX  " 1 "(kg/(m2*s))    "  N
  "Flux component x-direction"
 NVFLUX  "VFLUX  " 1 "(kg/(m2*s))    "  N
  "Flux component y-direction"
 NWFLUX  "WFLUX  " 1 "(kg/(m2*s))    "  N
  "Flux component z-direction"
 NFLUX   "FLUX   " 1 "(kg/(m2*s))    "  N
  "Flux value"
 NUMACH  "UMACH  " 1 "(-)            "  N
  "Mach number component x-direction"
 NVMACH  "VMACH  " 1 "(-)            "  N
  "Mach number component y-direction"
 NWMACH  "WMACH  " 1 "(-)            "  N
  "Mach number component z-direction"
 NMACH   "MACH   " 1 "(-)            "  N
  "Mach number value"
 NCS     "CS     " 1 "(m/s)          "  N
  "Sound velocity"
 NTAUWX  "TAUWX  " 1 "(-)            "  N
  "Wall shear force tauwx"
 NTAUWY  "TAUWY  " 1 "(-)            "  N
  "Wall shear force tauwy"
 NTAUWZ  "TAUWZ  " 1 "(-)            "  N
  "Wall shear force tauwz"
 NNUSSN  "NUSSN  " 1 "(-)            "  N
  "Nusselt number"
 NRESID  "RESID  " 1 "(-)            "  N
  "Mass residual in continuity equation"
 NER     "ER     " 1 "(-)            "  N
  "Equivalence ratio"
 NERLFL  "ERLFL  " 1 "(-)            "  N
  "Equivalence ratio, %LFL"
 NERNFL  "ERNFL  " 1 "(-)            "  N
  "Equivalence ratio, normalized flammable range"
 NEQ     "EQ     " 1 "(-)            "  N
  "Equivalence ratio, finite bounded"
 NEQLFL  "EQLFL  " 1 "(-)            "  N
  "Equivalence ratio, %LFL"
 NEQNFL  "EQNFL  " 1 "(-)            "  N
  "Equivalence ratio, normalized flammable range"
 NPPOR   "PPOR   " 1 "(-)            "  P
  "Panel average area porosity"
 NPP     "PP     " 1 "(Pa)           "  P
  "Panel average pressure"
 NPPIMP  "PPIMP  " 1 "(Pa*s)         "  P
  "Panel average pressure impulse"
 NPDRAG  "PDRAG  " 1 "(Pa)           "  P
  "Panel average drag"
 NPDIMP  "PDIMP  " 1 "(Pa*s)         "  P
```

```
  "Panel average drag impulse"
EXIT SINGLE_FIELD_VARIABLES

MONITOR_POINTS
 INSERT 1   343     555.5    217.6
 INSERT 2   357.5   549.5    217.6
 INSERT 3   368.2   549.5    217.6
 INSERT 4   346.8   532.5    217.6
 INSERT 5   357.5   532.5    217.6
 INSERT 6   368.2   532.5    217.6
 INSERT 7   350     509.5    217.6
 INSERT 8   360.2   509.5    217.6
 INSERT 9   368.2   515.5    217.6
 INSERT 10  343     549.5    225.1
 INSERT 11  357.5   549.5    225.1
 INSERT 12  368.2   549.5    225.1
 INSERT 13  343     532.5    225.1
 INSERT 14  357.5   532.5    225.1
 INSERT 15  368.2   532.5    225.1
 INSERT 16  350     509      225.1
 INSERT 17  357.5   515.5    225.1
 INSERT 18  368.2   515.5    225.1
EXIT MONITOR_POINTS

PRESSURE_RELIEF_PANELS
 INSERT          1
 POSITION          342.5 507 213.6
 SIZE          11 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          2
 POSITION          342.5 519 213.6
 SIZE          11 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          3
 POSITION          342.5 531 213.6
 SIZE          11 13 0
 MATERIAL          "DefaultMaterial"
 INSERT          4
 POSITION          342.5 544 213.6
 SIZE          11 14 0
 MATERIAL          "DefaultMaterial"
 INSERT          5
 POSITION          353.5 507 213.6
 SIZE          11 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          6
 POSITION          353.5 519 213.6
 SIZE          11 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          7
 POSITION          353.5 531 213.6
 SIZE          11 13 0
 MATERIAL          "DefaultMaterial"
 INSERT          8
 POSITION          353.5 544 213.6
 SIZE          11 14 0
 MATERIAL          "DefaultMaterial"
 INSERT          9
 POSITION          364.5 507 213.6
 SIZE          10 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          10
 POSITION          364.5 519 213.6
 SIZE          9 12 0
 MATERIAL          "DefaultMaterial"
 INSERT          11
 POSITION          364.5 531 213.6
 SIZE          9 13 0
 MATERIAL          "DefaultMaterial"
 INSERT          12
 POSITION          364.5 544 213.6
 SIZE          9 14 0
 MATERIAL          "DefaultMaterial"
 INSERT          13
 POSITION          348.5 507 213.6
 SIZE          0 12 8
 MATERIAL          "DefaultMaterial"
 INSERT          14
 POSITION          348.5 519 213.6
 SIZE          0 12 8
 MATERIAL          "DefaultMaterial"
 INSERT          15
 POSITION          341.5 531 213.6
 SIZE          7 0 8
 MATERIAL          "DefaultMaterial"
 INSERT          16
 POSITION          341.5 531 213.6
 SIZE          0 13 8
 MATERIAL          "DefaultMaterial"
 INSERT          17
 POSITION          341.5 544 213.6
 SIZE          0 14 8
 MATERIAL          "DefaultMaterial"
 INSERT          18
 POSITION          348.5 507 221.6
 SIZE          0 12 7
 MATERIAL          "DefaultMaterial"
 INSERT          19
 POSITION          341.5 520 221.6
 SIZE          7 0 7
 MATERIAL          "DefaultMaterial"
 INSERT          20
 POSITION          341.5 519 221.6
 SIZE          0 12 7
 MATERIAL          "DefaultMaterial"
 INSERT          21
 POSITION          341.5 531 221.6
 SIZE          0 13 7
 MATERIAL          "DefaultMaterial"
 INSERT          22
 POSITION          341.5 544 221.6
 SIZE          0 14 7
 MATERIAL          "DefaultMaterial"
 INSERT          23
 POSITION          347.5 513 213.6
 SIZE          3 3 0
 MATERIAL          "DefaultMaterial"
 INSERT          24
 POSITION          347.5 525 213.6
 SIZE          3 3 0
```

```
MATERIAL                "DefaultMaterial"
INSERT              25
POSITION              347.5 537 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              26
POSITION              347.5 550 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              27
POSITION              358.5 513 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              28
POSITION              358.5 525 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              29
POSITION              358.5 537 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              30
POSITION              358.5 550 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              31
POSITION              369.5 513 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              32
POSITION              369.5 525 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              33
POSITION              369.5 537 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              34
POSITION              369.5 550 213.6
SIZE              3 3 0
MATERIAL                "DefaultMaterial"
INSERT              35
POSITION              348.5 513 216.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              36
POSITION              348.5 525 216.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              37
POSITION              344.5 531 216.6
SIZE              3 0 3
MATERIAL                "DefaultMaterial"
INSERT              38
POSITION              341.5 537 216.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              39
POSITION              341.5 550 216.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              40
POSITION              348.5 513 223.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              41
POSITION              344.5 520 223.6
SIZE              3 0 3
MATERIAL                "DefaultMaterial"
INSERT              42
POSITION              341.5 525 223.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              43
POSITION              341.5 537 223.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              44
POSITION              341.5 550 223.6
SIZE              0 3 3
MATERIAL                "DefaultMaterial"
INSERT              45
POSITION              348.5 507 214.6
SIZE              25 0 5
MATERIAL                "DefaultMaterial"
PANEL_TYPE                POPOUT
OPENING_PRESSURE_DIFFERENCES  -0.05
0.05
INITIAL_AND_FINAL_POROSITY    0 0.85
WEIGHT              5
PANEL_SUBSIZES              2.5 2.5
INSERT              46
POSITION              373.5 507 214.6
SIZE              0 51 5
MATERIAL                "DefaultMaterial"
PANEL_TYPE                POPOUT
OPENING_PRESSURE_DIFFERENCES  -0.05
0.05
INITIAL_AND_FINAL_POROSITY    0 1
WEIGHT              5
PANEL_SUBSIZES              2.5 2.5
INSERT              47
POSITION              341.5 558 214.6
SIZE              32 0 5
MATERIAL                "DefaultMaterial"
PANEL_TYPE                POPOUT
OPENING_PRESSURE_DIFFERENCES  -0.05
0.05
INITIAL_AND_FINAL_POROSITY    0 0.85
WEIGHT              5
PANEL_SUBSIZES              2.5 2.5
INSERT              48
POSITION              348.5 507 222.6
SIZE              25 0 3.5
MATERIAL                "DefaultMaterial"
PANEL_TYPE                POPOUT
OPENING_PRESSURE_DIFFERENCES  -0.05
0.05
INITIAL_AND_FINAL_POROSITY    0 0.85
WEIGHT              5
```

PANEL_SUBSIZES 2.5 2.5
INSERT 49
POSITION 373.5 507 222.6
SIZE 0 51 3.5
MATERIAL "DefaultMaterial"
PANEL_TYPE UNSPECIFIED
OPENING_PRESSURE_DIFFERENCES -0.05 0.05
INITIAL_AND_FINAL_POROSITY 0 0.85
WEIGHT 5
DRAG_COEFFICIENT 1
MAXIMUM_TRAVEL_DISTANCE 0
INSERT 50
POSITION 341.5 558 222.6
SIZE 32 0 3.5
MATERIAL "DefaultMaterial"
PANEL_TYPE POPOUT
OPENING_PRESSURE_DIFFERENCES -0.05 0.05
INITIAL_AND_FINAL_POROSITY 0 0.85
WEIGHT 5
PANEL_SUBSIZES 2.5 2.5
INSERT 51
POSITION 364.5 544 228.6
SIZE 9 14 0
MATERIAL "DefaultMaterial"
INSERT 52
POSITION 364.5 531 228.6
SIZE 9 13 0
MATERIAL "DefaultMaterial"
INSERT 53
POSITION 364.5 519 228.6
SIZE 9 12 0
MATERIAL "DefaultMaterial"
INSERT 54
POSITION 364.5 507 228.6
SIZE 10 12 0
MATERIAL "DefaultMaterial"
INSERT 55
POSITION 353.5 544 228.6
SIZE 11 14 0
MATERIAL "DefaultMaterial"
INSERT 56
POSITION 353.5 531 228.6
SIZE 11 13 0
MATERIAL "DefaultMaterial"
INSERT 57
POSITION 353.5 519 228.6
SIZE 11 12 0
MATERIAL "DefaultMaterial"
INSERT 58
POSITION 353.5 507 228.6
SIZE 11 12 0
MATERIAL "DefaultMaterial"
INSERT 59
POSITION 342.5 544 228.6
SIZE 11 14 0
MATERIAL "DefaultMaterial"
INSERT 60
POSITION 342.5 531 228.6
SIZE 11 13 0
MATERIAL "DefaultMaterial"
INSERT 61
POSITION 342.5 519 228.6
SIZE 11 12 0
MATERIAL "DefaultMaterial"
INSERT 62
POSITION 342.5 507 228.6
SIZE 11 12 0
MATERIAL "DefaultMaterial"
INSERT 63
POSITION 369.5 550 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 64
POSITION 369.5 537 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 65
POSITION 369.5 525 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 66
POSITION 369.5 513 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 67
POSITION 358.5 550 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 68
POSITION 358.5 537 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 69
POSITION 358.5 525 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 70
POSITION 358.5 513 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 71
POSITION 347.5 550 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 72
POSITION 347.5 537 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 73
POSITION 347.5 525 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
INSERT 74
POSITION 347.5 513 228.6
SIZE 3 3 0
MATERIAL "DefaultMaterial"
EXIT PRESSURE_RELIEF_PANELS

```
SINGLE_FIELD_SCALAR_TIME_OUTPUT
 NP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
 NPIMP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18
 NVVEC 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18
 NU 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
 NV 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
 NW 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
 NDRAG 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18
 NERLFL 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
17 18
 NPP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
19 20 21
 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
38 39 40 41
 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57
58 59 60 61
 62 63 64 65 66 67 68 69 70 71 72 73 74
 NPPIMP 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18 19 20 21
 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
38 39 40 41
 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57
58 59 60 61
 62 63 64 65 66 67 68 69 70 71 72 73 74
EXIT
SINGLE_FIELD_SCALAR_TIME_OUTPUT

SINGLE_FIELD_3D_OUTPUT
 NFUEL
 NP
 NPROD
 NRHO
 NVVEC
 NU
 NV
 NW
EXIT SINGLE_FIELD_3D_OUTPUT

SIMULATION_AND_OUTPUT_CONTROL
        TMAX                 999999
        LAST                 999999
        CFLC                 5
        CFLV                 0.5
        SCALE                1
        MODD                 1
        NPLOT                10
        DTPLOT               999999
        GRID                 "CARTESIAN"
        WALLF                1
        HEAT_SWITCH          0
EXIT
SIMULATION_AND_OUTPUT_CONTROL

BOUNDARY_CONDITIONS
        XLO                  "EULER"
        XHI                  "EULER"
        YLO                  "EULER"
        YHI                  "EULER"
        ZLO                  "EULER"
        ZHI                  "EULER"
EXIT BOUNDARY_CONDITIONS

INITIAL_CONDITIONS
        UP-DIRECTION         0       0
1
        GRAVITY_CONSTANT          9.8
        CHARACTERISTIC_VELOCITY       0
        RELATIVE_TURBULENCE_INTENSITY
0
        TURBULENCE_LENGTH_SCALE       0
        TEMPERATURE          20
        AMBIENT_PRESSURE          100000
        AIR                  "NORMAL"
        GROUND_HEIGHT             0
        GROUND_ROUGHNESS          0
        REFERENCE_HEIGHT          0
        LATITUDE             0
        SURFACE_HEAT_P1           0       0
0
        SURFACE_HEAT_P2           0       0
0
        MEAN_SURFACE_HEAT_FLUX       0
        PASQUILL_CLASS            "NONE"
        GROUND_ROUGHNESS_CONDITION
"RURAL"
EXIT INITIAL_CONDITIONS

GAS_COMPOSITION_AND_VOLUME
        POSITION_OF_FUEL_REGION       341.5
532     221.6
        DIMENSION_OF_FUEL_REGION      15
15      8

VOLUME_FRACTIONS
        METHANE              0.7
        ACETYLENE            0
        ETHYLENE             0
        ETHANE               0.1
        PROPYLENE            0
        PROPANE              0.1
        BUTANE               0.1
        PENTANE              0
        HEXANE               0
        HEPTANE              0
        OCTANE               0
        NONANE               0
        DECANE               0
        HENDECANE            0
        DODECANE             0
        HYDROGEN             0
        CO                   0
        H2S                  0
        H2O                  0
        CO2                  0
        USERSPEC_1           0
        USERSPEC_2           0
        USERSPEC_3           0
```

EXIT VOLUME_FRACTIONS
EQUIVALENCE_RATIOS_(ER0_ER9) 1
0
EXIT GAS_COMPOSITION_AND_VOLUME

LEAKS
EXIT LEAKS

IGNITION
POSITION_OF_IGNITION_REGION 342
533 222
DIMENSION_OF_IGNITION_REGION 0
0 0
TIME_OF_IGNITION 0
RADMAX 0
EXIT IGNITION

WATERSPRAY
INSERT 1
POSITION 341.5 505
213.6
SIZE 34 55 15
VOLUME_FRACTION 0.2
MEAN_DROPLET_DIAMETER 1000
NOZZLE_TYPE "FACTORS:
3.5, 0.3"
EXIT WATERSPRAY

LOUVRE_PANELS
EXIT LOUVRE_PANELS

GRATING
EXIT GRATING

GAS_MONITOR_REGION
POSITION 341.5 507
213.6
SIZE 32 51 15
EXIT GAS_MONITOR_REGION

SPECIES
EXIT SPECIES
EXIT