JIP: Risk informed decision support in development projects (RISP)

Main report Workgroup 2 - Explosion

Report for:
Aker Solutions

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Summary

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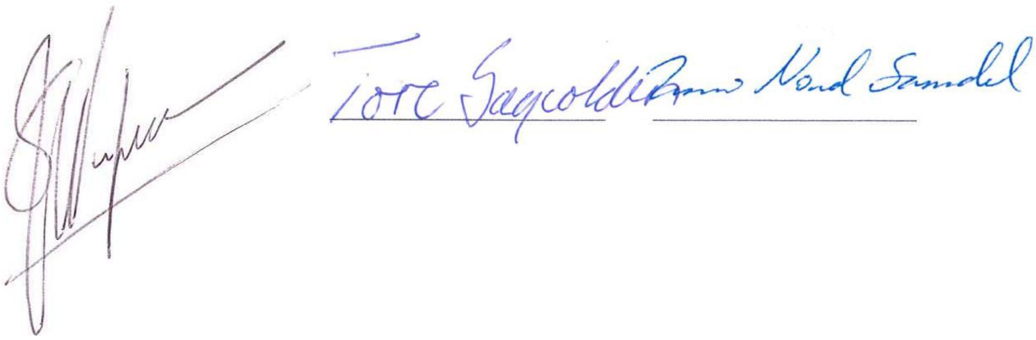

Document history

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Draft	7 December, 2018	Issued for RISP Steering Committee review	WG2
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Abbreviations

AC	Anticipated Congestion
ACM	Anticipated Congestion Method
ACH	Air Changes per Hour
AIT	Auto Ignition Temperature
ALARP	As low as reasonably practicable
API	American Petroleum Institute
ASAP	Computer analysis package calculating risk related to hydrocarbon leaks, fires and explosions, Lilleaker Consulting
BFETS	Blast and Fire Engineering for Topside Structures
BLEVE	Boiling Liquid Expanding Vapour Explosion
CAD	Computer-aided design
CFD	Computational Fluid Dynamics
CFX	General purpose CFD-tool
CMR	Christian Michelsen Research
COSAC	Computerised tool for risk assessment in the early project phases of a field development project, Lloyd's Register
CPU	Central Processing Unit
DAL	Design Accidental Load
DDT	Deflagration to detonation transition
DeAL	Design Accidental Load
DG2	Decision Gate 2
DiAL	Dimensioning Accidental load
DNV GL	Det Norske Veritas Germanischer Lloyd
EMERGE	Extended Modelling and Experimental Research into Gas Explosions (EU-supported project)
ERA	Explosion risk analysis
ExploRAM	Explosion Risk Assessment Model, Lloyd's Register
EXSIM	EXplosion SIMulator (dedicated CFD-tool), DNV GL
ESD	Emergency ShutDown
FEED	Front End Engineering and Design
FLACS	FLame ACceleration Simulator (dedicated CFD-tool), Gexcon
FLUENT	General purpose CFD-tool
GAME	Guidance for the Application of the Multi-Energy method
GoM	Gulf of Mexico
HC	HydroCarbon
HCR	Hydrocarbon releases
HHV	Higher Heating Value (combustion energy)
HPHT	High Pressure – High Temperature
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Organization for Standardization
JIP	Joint Industry Project
KFX	Kameleon FireEx (dedicated CFD-tool), DNV GL
LFL/LEL	Lower Flammability Limit/Lower Explosion Limit
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LQ	Living Quarters
WCE	Worst credible event
MEP	Model Evaluation Protocol
MERGE	Modelling and Experimental Research into Gas Explosions (EU-supported project)
MISOF	Modelling of Ignition Sources on Offshore oil and gas Facilities
MSF	Main Safety Function
NCS	Norwegian Continental Shelf
NFPA	National Fire Protection Association

NOROG	Norsk olje og gass
NORSOK	NORsk SOkkels Konkurranseposisjon
OGP	International Association of Oil and Gas Producers
OLF	Oljeindustriens Landsforening (now Norsk olje og gass (NOROG))
PDR	Porosity Distributed Resistance
PLOFAM	Process Leak for Offshore installations Frequency Assessment Model
PSA	Petroleum Safety Authority Norway
QA	Quality Assurance
QRA	Quantitative Risk Analysis
RAC	Risk Acceptance Criteria
RBM	Risk & Barrier Management (toolbox for QRA, DNV GL – ComputIT)
RISP	Risk informed decision support in development projects
RP	Recommended Practice
RPSEA	Research Partnership to Secure Energy for America
SoW	Scope of Work
SHLFM	Standardised hydrocarbon leak frequencies model
TDIIM	Time Dependent Internal Ignition probability Model
ThorExpressLite	Simplified tool to find DAL explosion pressures and optimise the design against explosions and select mitigating measures, DNV GL
TNO	Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
TNT	Trinitrotoluene (high explosive)
UFL/UEL	Upper Flammability Limit/Upper Explosion Limit
UKCS	United Kingdom continental shelf
VCE	Vapour Cloud Explosion
WG2	Work Group 2

1. Introduction

This report describes the work undertaken by Workgroup 2 as a part of the joint industry project RISP (Risk informed decision support in development projects).

A generic methodology has been developed and presented for estimating explosion design during an early design phase. Moreover, more advanced simple methodologies have been described in this document also for estimating explosion design loads during an early design phase. Validation approaches for these models have been described as well.

This report is one of the five workgroup reports constituting the basis for the overall RISP report, see also Ref. /2/.

1.1 RISP project

The RISP joint industry project is a continuation of the project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") run by Norwegian Oil and Gas, NOROG (Ref. /1/). RISP focuses on risk management in project development of topside facilities.

Seven offshore operator companies have initiated and sponsored the RISP work; Equinor, ConocoPhillips, Total E&P, ENI, Lundin, Wintershall and AkerBP.

The RISP project organisation is illustrated in Figure 1.

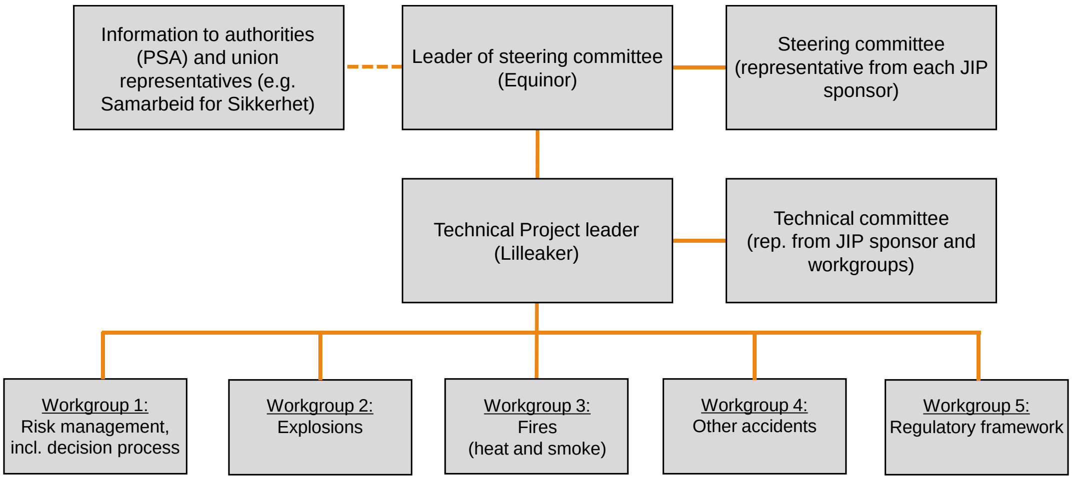


Figure 1 – The RISP project organisation overview

The five workgroups consist of representatives by consultants nominated by the sponsors, and different work packages are defined for the different workgroups.

This document describes the work undertaken by the Workgroup 2 (Explosion). The workgroup 2 consisted of representatives from Gexcon (lead), DNV GL, Lilleaker Consulting, Lloyd's Register Consulting and Aker Solutions.

A more detailed description of the RISP project and its context is given in the report issued by working group 1 (Ref./2/).

1.2 Background

Explosion risk analyses (ERAs) play a key role in the safety work within the petroleum industry. The explosion risk analyses are widely used in the design phase of a development project, e.g. as input to design explosion loads and ALARP assessments.

The purpose of the NORSOK Z-013 standard (Ref./3/) is to establish requirements for effective planning and execution of risk and/or emergency preparedness assessment. Annex F of the NORSOK

Z-013 standard specify how a probabilistic explosion analysis can be performed. For many years, explosion risk analyses in development projects have been performed in compliance with these principles.

In the concept definition, optimization and detailed engineering phases, the analysis shall include an explosion risk assessment. In case of probabilistic assessment, calculations shall be performed according to the standard's Annex F.

Each of the large risk analysis consultant companies has developed their own model / tool based on the method description in NORSOK Z-013, annex F.

Although the ERA methodology as such was standardized by introduction of the standard, analysis results did not seem to converge. There are several reasons for this, for instance:

- Different initiatives among consultant companies to improve leak frequency modelling (leak frequencies)
- Different initiatives among consultant companies to improve ignition modelling (ignition probabilities)
- Different approaches among consultant companies with respect to describing gas cloud build-up (gas dispersion)
- CAD models have been more detailed over time, software for geometry import from CAD to the CFD tools has changed and various methods for modelling congestion at early phases have been introduced
- Since 2001 there has been no organized benchmarking of the ERA methodologies. The various models have to a varying degree been updated to reflect improved knowledge and to exploit increased computational capacity

1.2.1 Explosion risk analysis in a field development project

The current practice with probabilistic explosion analysis has in the past two decades provided important decision support to NCS development projects. The detailed transient modelling of relevant leak scenarios, effect of safety systems, gas cloud build-up, ignition probability and finally explosion loads, gives a very detailed description of the explosion risk picture for a specific area. This can be used to understand the main explosion risk drivers for the specific module, understand the residual risk as well as providing important information regarding how the design influences the explosion risk. The methodology is a very good tool for evaluation and comparison of the effect of different design changes, e.g. size of process segments, blow down system design, location of ignition sources, confinement of the module, location of equipment etc., with respect to explosion risk. The sensitivities that affect the module layout (and hence require CFD simulations to be rerun) will be more time-consuming, than those changes only implying changes in the probabilistic model.

It should be mentioned that the above-described use of the explosion risk analysis has not always been well communicated in the explosion risk analysis reports. This may be because the main focus in the explosion analysis, historically, has been to provide design explosion loads as well as to verify that the risk level is within the defined risk acceptance criteria. The challenges related to such use of the analysis are elaborated in the next section.

Design input from the explosion risk analysis in the different phases of a field development project is illustrated in Figure 2.

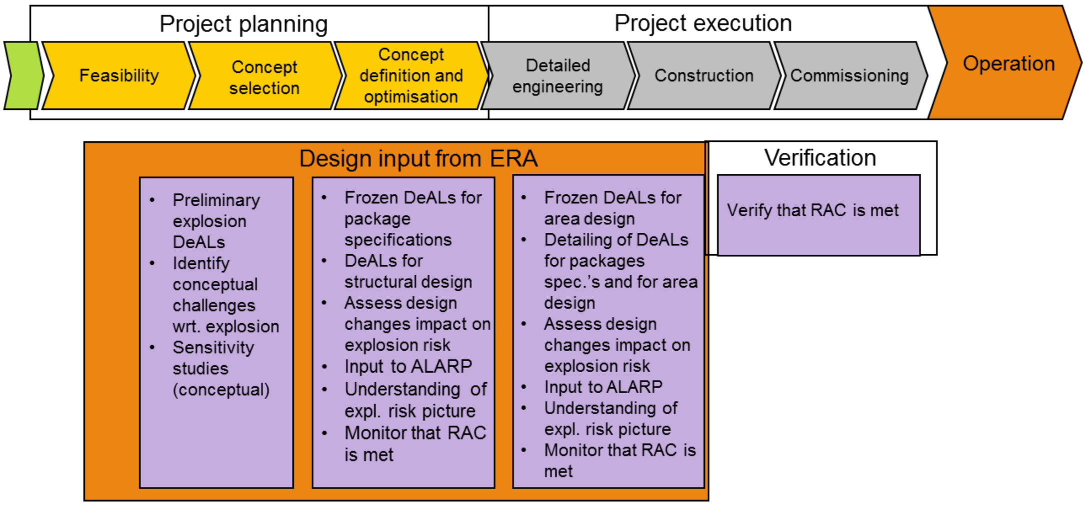


Figure 2: Design input from the probabilistic explosion analysis in different project stages (current approach)

1.2.2 Challenges related to current practise with ERAs

The probabilistic explosion models and tools need input data on a very detailed level and, in many cases, there is a mismatch between a) the need for input and the time it takes to set up and use the tools, and b) the information and time available at the time of making key decisions. This applies in particular for design explosion loads. Normally, the design accidental explosion loads need to be "frozen" in FEED phase, and sometimes even before FEED (for critical Purchase Orders). At this stage, the 3D model is very immature and will lack a lot of details, and is, hence, not appropriate as basis for CFD explosion simulations. Ventilation and gas dispersion CFD simulations can in general be performed with a coarser 3D model basis than explosion simulations. In addition, the leak picture is not known in detail (e.g. segment inventories and number of leak sources). In short; the input with the right level of detail required to perform ERA according to current practice, is not available at the time the design explosion loads need to be frozen.

In current practice with ERAs, to mitigate this, contingency is added to the input parameters (e.g. leak frequency), and often also to the result, i.e. the basis used for design load. With respect to congestion, two different approaches to reflect the as built congestion in a module are:

1. Add anticipated congestion to reflect expected "as built" density factors
2. Aim to model the actual "as built" layout, based on experience from "as built" 3D models/actual designs for each type of equipment, e.g. separator.

Although time consuming, the latter method has been preferred in recent field development projects because it is considered to reflect the expected congestion in a better way (reduce the uncertainty). However, independent of method used, the associated uncertainty is considered to be significant.

Further, the probabilistic explosion models developed have become quite complex with many user-influenced input parameters. In many cases the transparency and traceability can be poor, in particular for the end user of the analysis. An overview of the most important uncertainty characteristics is discussed in chapter 2.

In summary, this may lead to one or several of the following consequences:

- Late design changes caused by either:
  - Too immature input to the explosion analysis used as basis for design loads (and not enough contingency added)
  - Inconsistent results among consultant companies and possibly also among different persons within the same company.
  - The complexity of the analysis in combination with poor transparency which makes it difficult for the user to understand and control the parameters that influence the

(calculated) explosion risk. I.e. it can be difficult to understand whether changes in the ERA results are caused by changes in design or analytical/method related.

- Too late decision support
- Much effort and cost spent on explosion analysis in detail engineering without really influencing the design (validation activity only)

Based on this a need has been identified for a new method for explosion analysis in the early phases of a development project, in particular for the purpose of specifying design explosion loads.

1.3 Requirements to the method or model

According to requirements in the scope of work of the RISP initiative the method or model:

- shall ensure **the same level of safety** as currently achieved
- shall be based on **best available knowledge**
- theoretical and empirical **basis shall be available for review**
- shall be **transparent**
- must be **traceable**
- shall be **openly available** to the industry

It is stated that when using RISP, we should (as a minimum) have the same safety level as before introducing RISP. We interpret this as a requirement for similar design blast loads as current practice when RISP is used. At the same time, we want new and updated knowledge reflected in the tools and methods. Furthermore, methods shall be simple, transparent and traceable.

The presumption seems to be that the current safety level is sufficient (or even optimal), and that this can be obtained without much analysis work being performed. So, the contribution from the new RISP methods is to provide a simple and fast model that will provide the same design load whoever use it. Simple sensitivities should be possible.

The scope of work also states that rather than to seek very detailed risk descriptions, the aim should be to provide better decision support at the right time when the developed concept is well known.

The methods applied should be based on our best knowledge of the phenomena involved. A brief overview of our basic knowledge is included in chapter 2. References to literature, databases and central studies should be included as part of the documentation.

An important aspect of the chosen methodology for explosion risk assessment is to establish a framework in which the available knowledge, data and experience can be comprised.

How the documented knowledge is applied in establishing models and methods must be evident. The link between this knowledge and data and the results of analysis should be transparent. In this way the credibility of the methods and model is ensured.

To the extent possible, models and methods should match the complexity of the problem. The model should not be more complex than necessary to improve the credibility of explosion risk assessments.

The methods or models shall be openly available for the industry. This can be done by including the method description in a standard (e.g. NORSOK Z-013) or by making a common software / model open or available for relevant companies.

In addition the method or model shall, according to requirements in the scope of work:

- be based on input available in early phase (before DG2)
- avoid late design changes

- give decision support at the right time
- focus on individual decisions
- be based on principles in ISO 17776 {Ref. /4/)
- utilize knowledge and experience in the industry
- give consistent results independent of individual / Company

Repeatedly, the RISP scope of work state the need for timely decision support specific to each individual decision. A simple, robust and fast model may give reasonable design loads for explosion, but it is hard to see how a coarse model can support the broad spectrum of decisions that comprise an offshore development project (see also Figure 2). A versatile explosion model with many input parameters will normally be required to support specific decisions. But this conflicts with other RISP requirements to e.g. fastness and robustness.

A common and openly available model (or at least a framework) for explosion risk analysis should be established in the RISP project. This will facilitate verification of analyses and proposed design loads (and other solutions) and improve the credibility of explosion risk assessments.

1.4 Objective and Scope of work

The objective of the work in WG2 is to describe and evaluate different approaches for early phase explosion analyses, and to recommend a way forward for a common industry method for early phase explosion analyses. The different methods or models shall be evaluated versus the predefined requirements in the scope of work as well as the potential use of the method/model as decision support.

The ultimate goal is a method or model for early phase explosion analysis that fulfils the predefined requirements and where the above described challenges with current probabilistic explosion analysis are solved. Ideally the new method should provide the same important safety design input as current practice with ERAs (i.e. possibility for sensitivity studies, understanding of risk picture), but this is most likely not possible and at the same time fulfilling the RISP method requirements.

The scope of work has been split in the following main activities:

- Describe the industry knowledge on explosion risk for offshore installations and the main parameters influencing the explosion risk
- Map the historical (calculated) explosion risk and the design explosion loads in recent development projects for different types of modules and areas, including the values of the main parameters.
- Describe (on a principal level) different approaches for early phase explosion analysis
- Develop a generic method for early phase explosion analysis (Generic explosion loads)
- Demonstrate an example of a more advanced simple explosion model
- Describe pros and cons with the different approaches, evaluate the methods vs. the predefined requirements and map the potential usage of the methods
- Conclusion and recommendations for further work, i.e. a recommended way forward.

1.5 Limitations

A coarse framework for the new potential methods or models will be developed only. I.e. the method/model will not be finalised and ready for digitalisation as part of this subproject.

2. Key risk drivers of gas explosions at offshore installations and their modelling

This chapter summarizes key risk drivers of gas explosions at offshore installations. Some of the elements described is more relevant for explosion risks following process leaks, but the phenomena description is mostly relevant for all type of hydrocarbon releases at an offshore installation.

The chapter is a summary of what is presented in Appendices B and C.

Explosion loads are the result of a sequence of events where each of these are influenced by many factors. The event starts with a hydrocarbon release followed by a dispersion process where the flammable material mixes with air resulting in a flammable cloud. Next ignition of this flammable cloud occurs resulting in a combustion event, often an explosion.

A release is the first event in the chain of events leading to blast loading of structures and equipment and is probably best described by a rate with which gas, vapour or mist is being released into the atmosphere and the associated fluid dynamic disturbance of the atmosphere. Additional but not less important is the development of this release in time.

Important factors influencing the release are therefore the pressure of the released substance inside the segment, its temperature, its composition and the hole size. Additional factors include the shape of the point of release (flange seal, hole in pipe, etc.), the leak direction and the surrounding environment. The environment can be module size, confinement (walls or decks) and congestion (equipment) and will influence the probability whether jets from pressurized releases will impinge and losing momentum or be sent directly out of the module. Flammable liquids and multiphase releases may generate a mist in case of a pressurized release. The inventory and any mitigation actions upon a release (activated by gas detectors) determine how the release develops in time.

The probability of a release of a certain size depends on the design of the installation, its age, its maintenance and its operation (human factor).

The industry has systematically collected data for hydrocarbon leaks at North Sea offshore installations since 1992. Main conclusions from these data include:

- There is a direct relationship between leak frequencies and number of equipment items.
- A high fraction of the leaks is caused by or related to maintenance work or other activities.
- The number of leaks is sufficiently high to establish very reliable frequencies for small and medium leaks (0.1 kg/s to, say, 10 kg/s), and a quite accurate estimate of the frequency for larger leaks (uncertainty interval less than a factor of two).

The statistics of the collected data is an important input parameter for ERAs.

The subsequent dispersion process is closely related to the momentum due to the release (in case of pressurized releases) causing mixing with air and the ventilation. The turbulence caused by the momentum of the release itself causes this mixing. In case of an impinging jet the mixing/dilution in air is strongly reduced affecting the dispersion process. Condensate and two-phase releases will have lower release velocity, will show dense gas behaviour and may represent a somewhat more complex dispersion process due to two-phase phenomena.

Natural ventilation is primarily wind-driven, but there are also thermal contributions from hot surfaces of piping and equipment which become important during calm conditions and in very confined modules. Natural ventilation is determined by the location specific wind conditions, confinement (walls, wind walls and decks), congestion and geometry (module size). The ventilation dilutes the gas/vapour/mist cloud, i,e. reducing the concentration. This can cause parts of the cloud which have a concentration higher than the upper explosion limit to become flammable and parts that are flammable to drop below the lower explosion limit. Natural ventilation is often simulated using computational fluid dynamics (CFD).

The probability of a certain cloud (size, shape) arising depends on probability aspects related to the release including its direction, its location and possibility of impinging. The wind (direction and speed) is the second factor affecting the probabilistic aspects of the dispersion process.

The most important mechanisms for dispersion in a semiconfined offshore platform include release momentum, gravity and natural ventilation. For open modules of limited size there is a significant possibility that releases may leave the module due to release momentum, and natural ventilation will be significant and may push flammable gas efficiently out of the module. For more enclosed modules both these mechanisms will be weaker and significant gas clouds can be expected for smaller release rates compared to more open designs.

In traditional ERA studies the dispersion process is modelled with CFD. To get a representative distribution of outcomes a significant number of scenario variations must be modelled. CFD tools have been shown to give fairly good predictions of dispersion processes in offshore module test geometries. To avoid a very high number of explosion calculations, and improve precision (explosions in non-homogeneous clouds are challenging to model properly), the non-homogeneous clouds from a dispersion study are linearized and represented by equivalent stoichiometric clouds. This way a non-homogeneous cloud is represented by a smaller, maximum reactivity cloud estimated to give the same explosion load. In an ERA a number of these idealised clouds are located and ignited at different representative locations in the geometry.

Ignition is the next risk driver in the chain of events. The ignition source will affect explosions because of its location and moment of becoming effective. The probability of ignition depends on presence of an ignition source, the incendivity of the ignition source itself, the local concentration of the gas/vapour/mist cloud and level of turbulence. Ignition sources can be hot surfaces, electric sparks, electrostatic sparks and discharges, mechanical sparks, open flames etc. Choice of equipment, hot work operations, maintenance and ignition control measures (again depending on gas detection) are contributing factors determining the ignition probability.

It is expected that there is a relation between ignition probability and the extent (volume) and duration of flammable gas exposure. CFD-modelling can therefore help establishing ignition probability.

In the chain of events the explosion and its strength are directly dependent on the processes occurring before the combustion process starts: the cloud formation and the time and location of ignition. In addition, the strength of the explosion is directly related to geometrical aspects: congestion density, dimensions of the congested area, degree of confinement and combustion properties of the fuel. This has been elaborated more below:

- Confinement: With significant vent areas, preferably well distributed across the module, overpressures will be efficiently vented out of the module. For especially large modules however there is a possibility that lower confinement can lead to faster flames, with a potential for deflagration to detonation transition.
- Equipment congestion: Congestion is a critical parameter for explosion pressure. Numerous test campaigns have investigated this, illustrating how increasing pipe congestion has dramatic impact on explosion pressures.
- Fuel reactivity: Another factor that is important for explosion severity is the reactivity of the fuel. Natural gas with primarily methane tends to be somewhat less reactive than denser hydrocarbons.
- Pre-ignition turbulence caused by leak: A high pressure jet release will lead to a significant turbulence level within the flammable cloud, and if the flammable cloud gets ignited this will help accelerating the cloud initially.
- Deflagration to detonation transition (DDT) and scale: DDT cannot be ruled out for typical explosion scenarios on offshore platforms, not even for methane dominated natural gas. DDT has been observed for several natural gas explosion tests after 25m flame acceleration, and for significantly shorter distances for mixtures dominated by ethane and propane.
- Deluge: The activation of water deluge at gas detection can have a significant explosion mitigation effect due to break-up of droplets by the accelerating flame and ensuing evaporation in the flame. Turbulence due to the water deluge causes a flame speed enhancement and thereby a pressure increase. The latter effect is primarily important for low congestion or high confinement modules.

CFD-modelling is commonly used to determine explosion loads (in space and time).

When designing offshore petrochemical installations these must be designed to withstand so-called *dimensioning accidental loads* which are defined for several different types of loads, among these, explosions. Loads higher than the dimensioning accidental load that may impair defined main safety functions, shall have a return frequency lower than 1.0E-4/year[1] for each load type. The dimensioning accidental load is often provided as input to design and based on this the operator and engineering company shall select a *design accidental load* equal to or preferably higher than the dimensioning accidental load.

All the key risk drivers described above have so far been taken into account using multi-scenario-based models/approaches: a probabilistic risk assessment according to guidelines of NORSOK Z-013 with the following steps:

- Hydrocarbon leak frequencies are estimated,
- Various dispersion scenarios (several release locations, directions and rates, wind directions and speed, often different compositions) are modelled
- Frequencies for ignited cloud sizes are estimated using a transient ignition model
- Explosion simulations are performed for a range of idealized cloud sizes at various locations with varying ignition location.
- Combining the ignited cloud frequencies and the predicted explosion consequences cumulative frequency of load exceedance curves are generated for blast walls, decks and other objects of interest

The various risk consulting companies have developed their own methodologies and approaches to the proposed procedure. Various tools are used among the different consultants to estimate leak frequencies, transient release rates, or to facilitate the process of estimating the risk. To model gas explosions in congested areas the CFD tool FLACS has been the most common tool used. For dispersion also other CFD-tools are applied. To cover the required (or optimal) scenario variation as described in Z-013, various simplifications (interpolations) are done limiting the number of CFD-simulations. The consultants may also use different approaches to estimate anticipated congestion during design phases. One current challenge with the geometry import to FLACS is that explosion pressures can increase significantly when a very detailed as-built geometry is imported, even if the as-built model visually is not so different from the original model. In recent years there has been an effort by GexCon to prevent increase of explosion pressures from “invisible” objects defined inside other objects, or when e.g. a pipe is defined as a high number of smaller pipe elements. With the very detailed as-built CAD-geometries imported today, a pipe may be defined as 10s of surface plates instead of a single cylinder, which also seems to inflate flame acceleration and overpressures. GexCon is advised to investigate how to reduce this problem.

The time it takes to carry out an explosion risk study as described above may often be 2-3 months and will depend on

- Time it takes to collect the necessary information
- Interaction with other studies for instance evaluating segment sizes and leak frequencies
- 3D model preparations (import, cleaning, evaluating and adding ACM)
- Preparation of simulations
- Simulation run times
- Processing of results to estimate the risk
- Reporting explosion study and DAL

1 The RISP project has stated that current regulations shall not be used as a limitation to the development. The regulatory regime and distribution of responsibility for safe operation and liability given an accident will be important for the recommendations of method. However, since no new regulation is in place or has been indicated how it would look like current regulations have been referred to.

With reasonable CPU-capacity the CFD-simulation part of the study should not need to take more than a week (~1000 dispersion simulations and 3-400 explosion simulations).

The main uncertainties in current ERA studies during the design phase of an offshore facility are:

- Statistical foundation of determining especially the ignition probability
- Lack of geometry details during FEED phase
- Simplifications to limit the number of CFD-dispersion simulations, including frozen cloud approach
- Experience of consultants performing ERA-studies
- Accuracy of tools and assumptions used during an ERA-study

It is not possible to quantify these uncertainties but it is expected that the uncertainty in the statistical foundation for the ignition probability is the biggest uncertainty factor.

A different, simpler approach as RISP foresees needs to address the uncertainties and the key risk drivers described above.

3. Review and collection of data from explosion risk assessments

3.1 Introduction

Detailed explosion risk analysis is performed as part of the design development process of Norwegian offshore oil and gas facilities, e.g. as input to design explosion loads and ALARP assessments.

For facilities during design, one of the key objectives for the analysis has been to support defining the Design Accidental explosion Loads.

Most facilities in operation also perform or updates the explosion risk analysis throughout the lifetime of the facility. For existing facilities one of the key objectives for the analysis has been to verify that the design loads are not exceeded with a frequency higher than the acceptance criteria.

The explosion risk analysis performed both for Norwegian facilities during design, as well as facilities in operation, should be carried out in line with the procedure described in NORSOK Z-013 Appendix F (Ref. /3/).

For this reason, detailed explosion risk analysis is available for most of the facilities that are in operation at the Norwegian Continental Shelf, as well as the facilities currently in detailed design phases.

An activity has been carried out as part of the RISP project to gather data and results from existing explosion risk analyses.

Explosion analysis data and explosion design data is collected from 65 different modules or areas from a total of 18 Norwegian offshore facilities. A wide range of facility categories are covered, including

- Floating and fixed installations
- Stand alone and bridge linked facilities
- Integrated facilities including several functions such as LQ, utility, drilling, production and/or process as well as more simple platforms with only one or two of these functions included.

9 of the facilities collected are facilities that are put in operation in previous 2-3 years, or not yet put in operation (2019).

9 of the facilities collected are older facilities that are put in operation more than 15 years ago. However, since there has been development in the tools and methodologies for performing explosion risk assessments, only facilities with an updated explosion analysis performed during the last 7 years are included in the data set.

The data that is logged is described in detail in section 3.3 below, and can be summarised as follows:

- Key area characteristic parameters that have been identified as the key drivers of the calculated explosion risks that are possible to quantify for an area, including dimensions (size and shape) of the areas, factors describing confinement and ventilation areas of the modules, information about intermediate grated or partially plated decks, as well as calculated leak frequencies.
- Key results from probabilistic explosion analysis, including calculated frequency to exceed 0.3 and 0.7 bar local panel overpressure to physical area barriers, as well as overpressure exceeded for different threshold frequencies, including 1E-5, 2E-5 … 1E-4 per year.
- Design Accidental explosion Loads defined for the physical barriers of the area, either capacity defined during design, or (for some of the older facilities in the data set) explosion load capacities calculated in recent years.

3.2 Objective and possible use of collected data

There are several purposes of collecting data and results from previous explosion analyses and explosion design loads, including:

- Support basis to define standard areas / most relevant model validity envelope from an explosion analysis point of view
- Evaluate to what degree the factors that WG2 have identified as important drivers of the explosion risk traditionally have affected the calculated explosion loads.
- Evaluate to what extent it is possible to obtain simple correlations between one or a combination of parameters/factors that affect explosion risk and the calculated explosion loads.
- The data set can be used as part of verification and evaluation process of methods developed to establish explosion loads:
    - The design accidental loads valid for the existing installations may be used to document that the design or dimensioning explosion loads identified using the methodology are no lower than explosion loads for existing facilities. Based on that it can be argued that the safety level is not lower using the updated methodology.
    - The dataset may be used to verify to what degree a new or updated method produces results that correlate with conclusions from existing explosion risk analyses.
- In addition, the data set could provide other valuable input in terms of compressing experience from the past, such as evaluating how design explosion loads have developed over the years and how factors we believe influence the explosion risk have developed over the years. It is likely that data collected from 18 installations is too small a data set to provide a sufficient basis to fulfil the objectives defined above. Based on the analysis performed on the data from these 18 installations, an evaluation can be made to see if further efforts should be made to collect data from further facilities in order to perform analyses of a more complete data set.

3.3 Data collected

The following data is collected for each of the 65 modules/areas

Table 1 Overview of data collected.

Parameter	Description	Reason for including in data set
Facility name, Area/module name	Name of the facility, and name of area/module for which the data is collected. Note that in presentation of the data set, the facility name will be anonymized	Identification
Type of / function of module	i.e. Wellhead or Process, For process: oil/condensate handling, separation, gas treatment	The different categories result in different development of accident scenarios, see chapter 2 for discussion
Dimensions: -Length - Width -Height	Basis for volume and shape of the explosion area. An explosion area is defined as an area where there is congestion and where a gas cloud can freely build up. The borders are solid walls, solid decks and border between the congested area and open/uncongested area	Volume of the module is considered an important parameter for flammable cloud size, which is likely to affect ignition probability as well as explosion energy. Furthermore, many of the phenomena involved are affected by size and shape of the partly confined module/area
Number of mezzanine decks, wind walls	Not fully plated decks/partly plated/partly open decks, or grated	Affects cloud formation and explosion

	decks. Wind walls or explosion panels covering parts of the open sides of the module.	
Degree (%) of openness for natural ventilation	There are 6 outer boundaries of the explosion area, degree of openness (porosity) is defined per outer boundary of explosion area 1 = fully open, 0 = fully closed	The level of confinement affects possible ventilation of flammable clouds upon a gas leak, stagnant zones or decks/walls inhibiting fluid flow may result in gas “trapped” in the module, and explosion venting
Calculated leak frequency	Small, medium, large per year. Split on liquid releases and gas releases if available.	Proportional to explosion frequency
Results from explosions analysis (local loads)	Calculated frequency to exceed the local (i.e. 3.5 x 3.5 m^2) overpressure to physical barriers of area: -0.7 bar -0.3 bar Calculated local overpressure exceeded for the following annual frequencies: 1E-5, 3E-5, 5E-5, 7E-5, 1E-4	Key calculated explosion results
Design explosion loads	Design Explosion Load of the main area barrier, i.e -local 3 x 3m^2 panel pressure to deck or wall, including duration -global overpressure with duration if available Since criteria is 1E-4 per year per main area barrier the number of areas sharing the same main area barrier should be grouped together	Capacity of design

3.4 Evaluation of the data set

At this stage, relatively simple analysis is performed to scan the dataset and to make preliminary evaluations.
More sophisticated analysis may be preferred if the data set is to be extended and used as basis for validation of a method or model.

A summary of some key features of the 65 modules from the 18 facilities that are assessed is shown in the table below. The confinement level [m^2 / m^2] in this context is defined as the area of all the openings of the module boundaries, divided by the total surface area of the module boundaries. It should be noted that confinement 0 is fully confined, while confinement 1 is fully unconfined, thus venting degree might have been a better description. Note that a vent area parameter [Kv] is defined in section 5.1 and introduced later in this section. This definition slightly differs from the confinement level defined above, as it introduces a “penalty” to the modules with an unfavorable (elongated) shape in terms of ventilation conditions.

Table 2 Summary of key module characteristics in the collected data set

Measure	Module Volume [m^3]	Confinement [m^2 / m^2]
Minimum of all areas	1176	0.03
Maximum of all areas	105300	0.65
Average Area	10815	0.23
Median Area	6906	0.22
Number of modules	65	65

Of the 65 modules that have been assessed, Design Accidental Loads have been collected for 49 of the areas.

A summary of the local Design Accidental Blast Loads defined for the physical barriers of the 49 modules are tabulated below.

Local design accidental loads usually correspond to 3x3 or 4x4 m^2 panel overpressure. Pressure pulse durations defined for the barriers are not shown in this table.
Modules that have no loads defined are not included in the data set. It is not tracked if loads are missing because the barrier is not designed for explosions, or if the design loads are missing for other reasons.

Table 3 Summary of Design Accidental Loads in the collected data set

Measure	Local explosion load [barg] All facilities available	Local explosion load [barg] All old facilities > 15 years old	Local explosion load [barg] All new facilities < 5 years old
Minimum of all areas	0.15	0.15	0.20
Maximum of all areas	1.20	1.00	1.20
Average Area	0.65	0.54	0.79
Median Area	0.70	0.50	0.78
Number of modules	49	27	22

Note that the data presented in the two tables above can give some insight in designed capacity and offshore module characteristics but cannot be considered statistically significant to make unbiased evaluations of the design blast loads or layout of Norwegian installations in general.

When assessing separately how calculated explosion risk correlates with design parameters, some correlation may be observed, but there is no clear relationship. This can be seen from Figure 3 where the size of module volume is plotted against the calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for all of the 65 modules assessed. When examining the dataset, some of the outliers deviating most from the trends may be explained by facility specific factors.

When looking at the volume in combination with another parameter some correlation may be found. Figure 4 which shows the vent area parameter (as defined in section 5.1) plotted versus calculated frequency for exceeding 0.7 bar local panel pressure to decks/walls. The plot differentiates between areas with volume less than 12 500 m^3 plotted with blue dots, and areas larger than 12 500 m^3 in orange.

50 of the 65 areas have a volume less than 12 500 m^3. Of these 50 smaller areas, 22 have a module vent area parameter above 1.25.

Finally, the estimated leak frequency (from the explosion analysis) is plotted against frequency for exceeding 0.7 bar local panel pressure to decks/walls and presented in Figure 6. Note that this figure does not differentiate between oil and gas leaks.

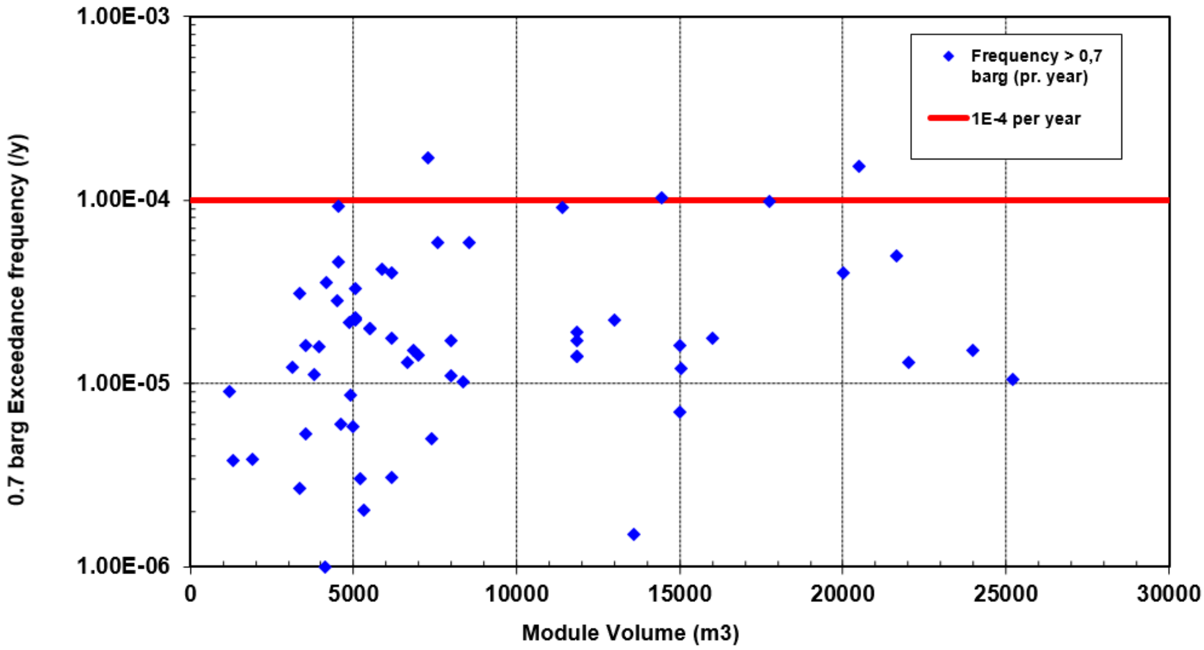


Figure 3 Size of module volume versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed

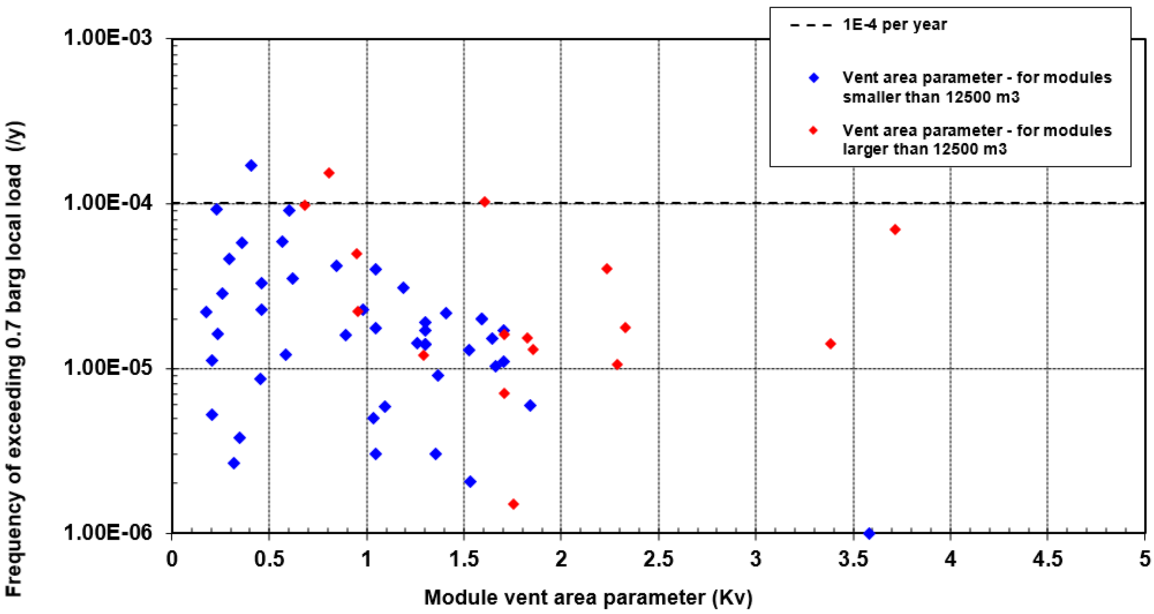


Figure 4 Module vent area parameter versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed. Scatter plot differentiates between large areas (orange dots) and smaller modules (blue dots). The split between “small” and “large” areas is set at 12 500 m^3

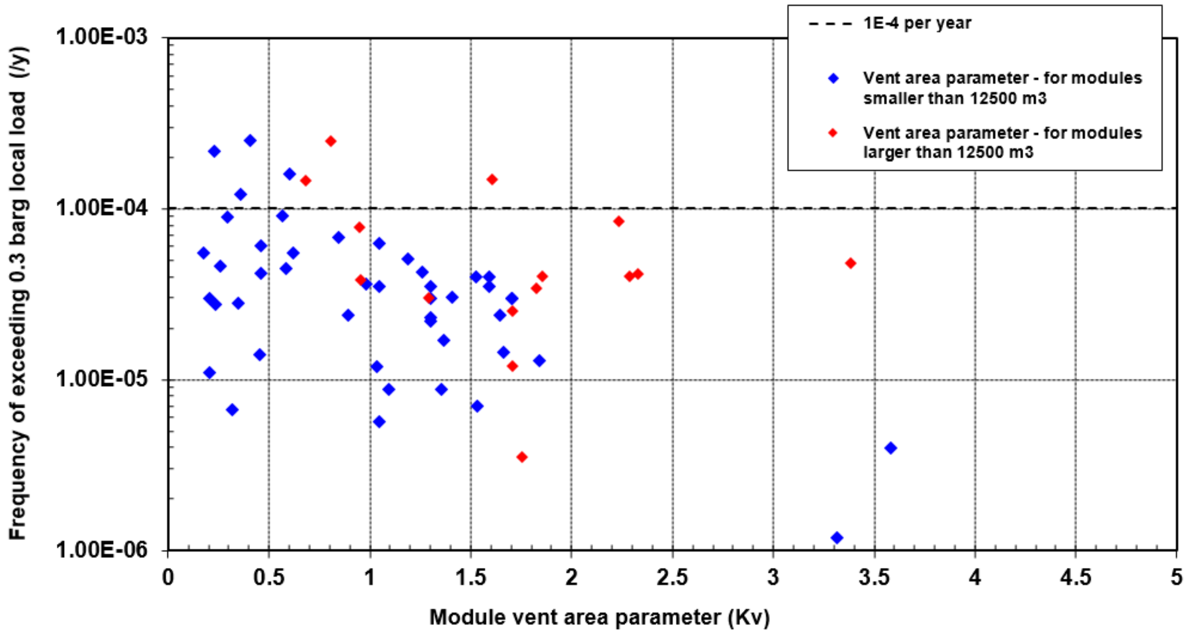


Figure 5 Module vent area parameter versus calculated frequency for exceeding 0.3 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed. Scatter plot differentiates between large areas (orange dots) and smaller modules (blue dots). The split between “small” and “large” areas is set at 12 500 m^3

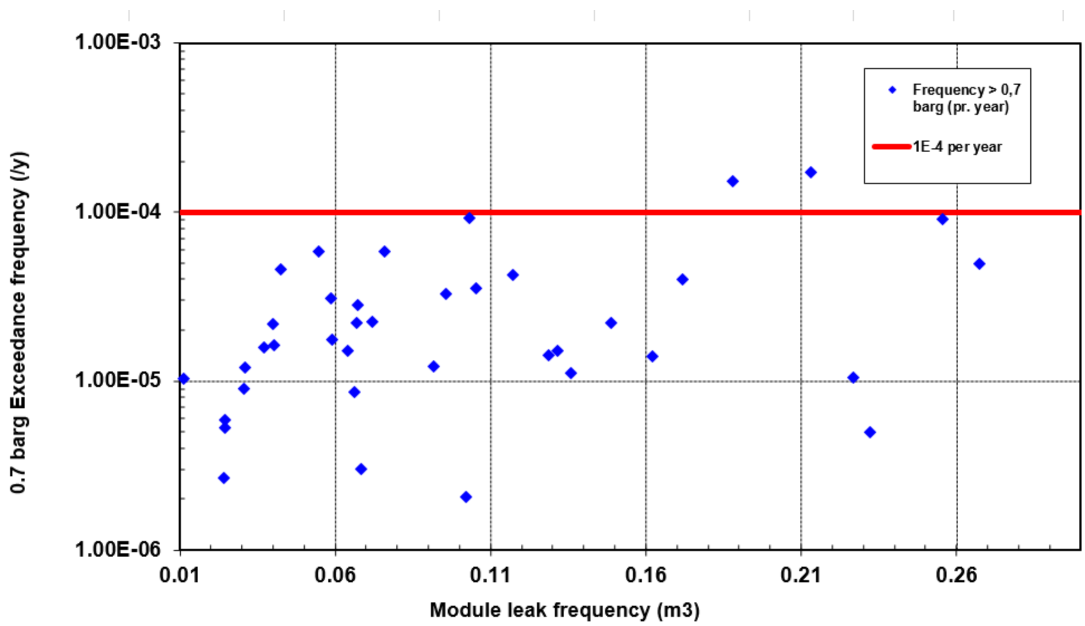


Figure 6 Calculated leak frequency versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed.

Results from performed analyses will include a variety of geometry models, different modelers, stakeholders and guidelines. Such studies can in many ways be biased. For example, conservatism in an analysis concluding with a worrying risk level will be challenged, and in many cases the frequencies for strong explosions may be reduced. In contrast, for a case with an acceptable risk level to begin with, conservatism may remain unchallenged. This must be considered when for the data set is used for demonstrating the relation between explosion risk and the chosen input parameters.

4. Methods and models for explosion risk: an overview

4.1 Probabilistic analysis of a stochastic process

There has been a discussion among RISP stakeholders to what extent a RISP explosion model or methodology should be *probabilistic*. A dictionary definition of probabilistic is included:

> *Probabilistic: Situation or model where there are multiple possible outcomes, each having varying degrees of certainty or uncertainty of its occurrence. Probabilistic is often taken to be synonymous with stochastic but, strictly speaking, stochastic conveys the idea of (actual or apparent) randomness whereas probabilistic is directly related to probabilities and therefore is only indirectly associated with randomness. Thus, it might be more accurate to describe a natural event or process as stochastic, and to describe its mathematical analysis (and that of its consequences) as probabilistic.*

It is reasonable to consider process area explosions as a stochastic phenomenon that is analysed using probabilistic methods. Using a more deterministic approach ("worst credible event scenario") is a possibility, but for gas explosions in offshore process modules this will in many cases not be feasible. When this approach is modified to a "maximum credible" load or scenario, the term "credible" is used to express the likelihood of an incident, and the approach can be categorised as probabilistic.

4.2 The system to be analysed

The system to be analysed is comprised of the following main elements. There are additional elements that are omitted (gas detection) from this list, it is meant as an overview for this note.

- Environmental conditions
    - Wind speed and direction
    - HVAC
- Geometry
    - Dimensions, congestion, confinement (incl. explosion panels, etc.)
- Leak sources
    - Process units, equipment
    - Fluid properties
- Ignition sources and mechanisms
- Explosion suppression and mitigation
    - Deluge
- Targets exposed to explosion loads
    - Partitions (walls, decks)
    - Units
    - Equipment and piping

4.3 Alternative modelling approaches

The majority of the processes involved are related to fluid dynamics and geometry. The only type of models being able to describe this well are models based on computational fluid dynamics (CFD). This is the reason why so far CFD models have been applied in spite of the lack of detailed knowledge of geometrical aspects of the installations being assessed during a design phase. This has been compensated by adding "anticipated congestion" based on "good engineering practice" and experience.

Moving away from the use of CFD for at least a number of installations implies that the models that would be used need considerable robustness since these by nature can only to a limited degree pick up effects introduced by the geometry. As such it will be difficult to use the approach/model used to perform explosion risk assessments for management of change (MoC). MoC therefore needs to be addressed in a different way as e.g. described in NORSOK standard S-001.

Generic explosion models
To catch all aspects of an ERA (explosion load and its probability) in a generic explosion model implies that the model needs to be very conservative and can only be based on historical assessments performed. The generic explosion model suggested and described in chapter 5 is conservative using the upper bound of the data gathered from 65 modules/areas as summarized in chapter 3.

Scenario-based methods
Multiple event scenario-based with CFD simulations
Scenario-based methods were generally used in combination with a CFD based tool. The main challenge with these methods is the time it takes to perform assessments together with the lack of detailed knowledge of the geometry. The methods can however be expected to be the most accurate without being too conservative.
If the number of scenarios that are to be investigated using CFD would be limited the selection of these scenarios will be a main challenge. This could potentially be determined on the basis of historical data (the database of 65 modules/areas) considering scenarios giving the 10^{-4} loads. It is however unlikely that this will be a single set of conditions, so in practice this will not be a feasible approach. Moreover, the use of CFD-tools for this kind of approach still implies that the lack of knowledge of geometry in the early phase needs to be compensated.

Multiple event scenario-based without CFD simulations
An alternative would be to develop analytical models describing the cloud build-up and explosion loads generated in congested modules. The number of scenarios that would be looked into can be considerably higher than possible when using CFD due to its character. The model would have to be validated thoroughly and would most likely have to include a lot of empirical relationships based on experiments and CFD-calculations. Depending on the complexity of such models MoC might be possible even considering changes to the geometry.

Equation-based models
Equation-based models are based on more general relations such as described in chapter 5.2. Single relationships are used to describe probability of a certain leak rate, ventilation rate, resulting dispersion processes and cloud sizes, ignition probabilities and associated explosion loads. Since these kinds of models cannot take geometrical aspects into account directly, sufficient robustness shall be included. Also here a thorough validation process is needed.

Referring to the above, it is premature to choose a modelling approach at this stage, since model formulation should build on a proper analysis, which has not been carried out. But we will show some examples just to illustrate what kind of choices developing a new model will include.

The required level of detail for the model is an important decision. This must match the purpose for the model.

4.3.1 Generic explosion model

A module comparison method is a method of finding the design loads by using a reference module. An important feature is that the frequency aspect is kept out of the method to the extent possible. The basic idea is that a “standard offshore process module” can be defined for which a standard set of design loads apply.

The module to be analysed is described with a set of parameters. Based on this the module is compared to the standard module. Model output could include that standard loads are applicable (“A”), standard loads should be modified by a factor (”B”) or that there is too much uncertainty (“C”).

This approach appears to be in line with at least some of the expectations for RISP formulated in the RISP SoW.

The frequency for leaks and ignition is kind of bounded to the module type, but in an invisible way, so that when we categorize a module to be type “A”, we also assume that the frequency for type “A” module is standardized.

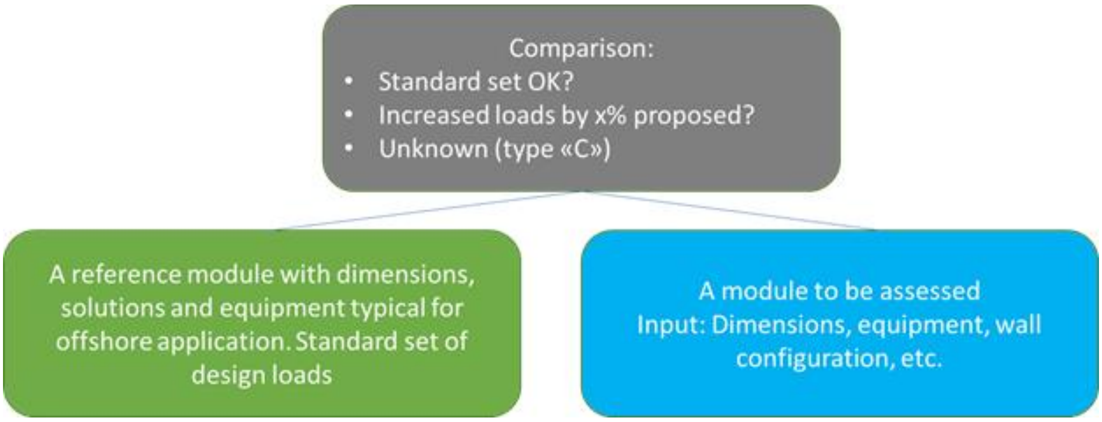


Figure 7 Module comparison methods

A slightly different generic explosion model is presented in chapter 5.1 as a look-up table using the data presented in chapter 3 based on module volume, module configuration and a vent opening parameter as main input parameters.

4.3.2 Scenario-based approaches

A scenario-based approach can be based on consequence analysis of a single credible scenario, or analysis based on a chosen limited set of scenarios with corresponding assumed frequencies.

4.3.2.1 Single event analysis - Worst credible event (WCE) approach

In the evaluation of industry incident history there have been some rules of thumb on how to define a maximum or worst credible event as basis for design.

Typically, a scenario is considered credible if it has been experienced by an operator within the geographical area and a reasonably short time frame. For example, for an operator in Texas incidents within Texas/US GoM within the past couple of decades could be credible, as well as global experience for the particular operator within a similar time span.

Worst credible event (WCE) approach was suggested by NOROG as a possible methodology to establish robust explosion design loads. Several possible worst credible events were proposed, e.g. that the platform module should withstand the consequences from:

- 2” natural gas release with delayed ignition
- 8 kg/s natural gas release with delayed ignition
- Ignition in gas cloud filling 15% of module

To help limit the spread in predicted explosion loads, a given leak location, leak direction, wind direction and strength as well as an ignited cloud location and ignition position can be proposed.

The next step is to perform a consequence analysis for the chosen scenario, possibly using CFD or similar. Explosion loads obtained by this approach are used as a basis for design loads of barriers.

4.3.2.2 Multiple events analysis

FLACS-Risk, RBM and some of the tools based on NORSOK Z-013 (e.g. ASAP) can be considered as multiple events analysis models. Each scenario starts with a leak event which is followed through multiple steps, including dispersion, ignition and explosion modelling. The modelling for each step can again be equation-based (theory-based or empirical), or numerical (CFD). The selection of scenarios is normally aimed to cover all the possibilities, and frequencies can be given to each scenario individually.

<u>ASAP as an example of model using NORSOK Z-013 methodology</u>
The idea of the NORSOK Z-013 methodology is to model individual cases detailed and transient (time development) and apply statistics and interpolation (in one way or another) to establish a detailed explosion risk picture. For example, each case (scenario) could be associated with a frequency, and then modelled relatively detailed (dispersion-ignition-explosion).

The first version of the model was presented in Ref. /5/.

The figure below shows an overview of how this is realized in the ASAP tool.

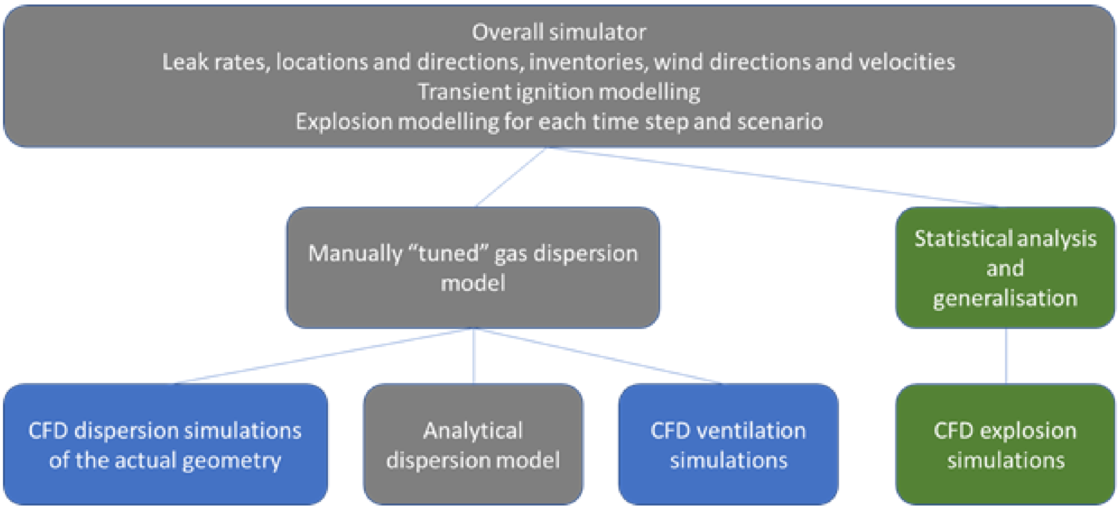


Figure 8 ASAP - NORSOK Z-013 explosion risk modelling

An alternative would be to develop analytical models describing the cloud build-up and explosion loads generated in congested modules.

4.3.3 Equation based approaches

An equation-based model can refer to a model which is represented by one or a set of equations, and can be categorized as:

- Empirical models: Empirical equations based on analysis results, using statistical methods such as regression analysis.
- Theory-based models: theoretical based generalised set of equations, typically based on known facts from physics, thermodynamics and chemistry.

The two types of models mentioned above should be treated as two different approaches, at the same time a model can of course contain characteristics from both.

Theory-based models and empirical models will be briefly discussed in the following sections.

4.3.3.1 Empirical models

It is possible to formulate one or a set of equations that can be applied for defining design loads in a one-step operation. Two examples will be presented in this section.

TNO GAME correlation

For example, if congestion is defined with the volume blockage ratio, the characteristic diameter of objects and the laminar flame speed can be found based on the fluid properties, the empirical TNO GAME correlation [Ref./6/] can be used to estimate the relation between blast loads and flame travel length (L_f) for 2D and 3D environments. For this case, the parameter L_f must be determined based on the actual geometry, to calculate the design blast load.

Models for explosion load prediction based on experimental results do exist. TNO analysed a large set of experimental results on vapor cloud explosions to develop the TNO GAME correlation [2].

$$\text{3D environment: } \Delta P_0 = 0.84 \left(\frac{VBR \cdot L_f}{D}\right)^{2.75} S^{2.7} D^{0.7}$$

$$\text{2D environment: } \Delta P_0 = 3.38 \left(\frac{VBR \cdot L_f}{D}\right)^{2.25} S^{2.7} D^{0.7}$$

L_f is the length available for flame travel. VBR is volume blockage ratio, D is the characteristic diameter of obstruction (e.g. pipe diameter) and S is the laminar flame speed. For now, these three parameters are considered constant.
The method assumes a homogeneous optimal concentration gas cloud.

This example lacks the frequency or uncertainty dimension of risk represented by leak frequency, gas cloud formation and ignition probability. For a certain category of process areas, it can be assumed that leaks, cloud formation, ignition probability and congestion could be linked to module size and confinement. In this way, it is possible to establish a model that does not explicitly address the probabilistic elements leak and ignition, while still providing reasonable results. In this approach, the frequency/uncertainty aspect is covered implicitly, for example by the relations that are linking leak frequencies to module volumes.

Challenges may include to define unambiguous input parameters, and to define the combinations of input for which the equation or set of equations is valid.

For the GAME correlation presented it is for example very challenging to define one characteristic pipe diameter representative for the actual distribution in the module. The correlations are developed based on experiments with identical, regularly repeated cylindrical pipes, and if there are pipes of varying dimensions or spacing, or other objects than pipes, no clear validation-based guidance on how to find representative pipe diameter D and volume blockage ratio VBR exist.

E.g. a platform module with 6-8m between solid decks would be a 2D case. If gas laminar flame speed (laminar burning velocity) S=0.45 m/s is assumed, and a representative pipe diameter D=0.10m is concluded, the predicted overpressures will depend strongly on assumed VBR for the non-homogeneous array of equipment.

If VBR=0.05 is assumed 0.37 bar pressure is predicted with 4m flame propagation, and 1.77 bar with 8m flame propagation. If instead VBR=0.10 is assumed 1.77 bar pressure is predicted for 4m flame propagation and 8.41 bar with 8m flame propagation. As there is no consistent way to estimate D and VBR for a realistic platform module it is obvious that there will be large uncertainties using the model. The original purpose of the GAME correlation is however not to estimate overpressures inside buildings or platform modules, but to estimate source pressure for far-field blast predictions. And since far-field blast loads are not very dependent on exact source pressure, the GAME correlations may be fit for purpose.

COSAC model

Another example is the COSAC model. The client specification for COSAC was to “use experience and results from explosion simulations to establish a tool for prediction of explosion pressures in modules/areas at an early design stage of a platform concept”.

This model is based on the result from several explosion risk studies carried out by Scandpower Risk Management, using the ExploRAM tool and methods. In this sense the COSAC model is an empirical model. The CFD-code FLACS is applied for gas dispersion and explosion simulations in the risk studies used in this analysis.

The steps in the model are as follows:

1. Estimate the frequency of significant leaks
2. Based on the leak frequency, the acceptance criterion chosen and the module geometry, find the critical cloud size (e.g. "10^{-4} cloud size")
3. Based on the critical cloud size find the dimensioning explosion load
4. Evaluate explosion load and ventilation regime and conclude with a score (1-5).

In COSAC, coarse concentration profiles (for use in a frozen cloud approach) are found using empirical models based on data from ExploRAM analyses performed.

The aim of a model like this is to predict the result that would have been obtained using a more detailed approach. Using COSAC, the aim is to predict the result from a full study using ExploRAM and an as-built geometry model.

4.3.3.2 Theory-based models

A theory-based model should involve using knowledge from physics and chemistry such as energy of combustion, thermodynamics and equations for fluid flow to establish equations for modelling gas explosion risk. As an example, a dispersion model assuming gaussian concentration distributions is described as a theory-based model.

It appears practically impossible to build a purely theory-based model for the modelling of explosion risk, including frequency of leaks or explosions. There will be a statistical or frequency part of even the most purely theory-based approach to this problem.

Example: Probabilistic theory-based model
This is an approach formulated as an alternative to simulation modelling. The focus is on establishing a framework to reflect our knowledge reasonably and explicit without being too complex or overly simplistic. Input and results (including intermediate results) are always described as full frequency distributions, reflecting possible outcomes and illustrative for the uncertainties involved.

Frequencies are included as a central part of this method because of the risk analyst's view that frequency (or uncertainty) is fundamental for decisions regarding risk mitigation and risk acceptance. An argument for this is that the value of any explosion mitigating measure is proportional to the probability for explosion scenarios that the measures could mitigate times the costs saved (value of consequence reduction) for each mitigated event. Further, frequency and probability distributions are well suited to describe the variability in possible outcomes and consequences (describe "what can happen" even if the frequency is low).

The basic idea is to first define a starting point, which could be the leak rate versus frequency relationship for the module. Next, this relation is transformed in steps using a rule-set reflecting available knowledge (accident statistics, thermodynamics and chemistry, experiments, simulation results and more.)

This approach applies mathematical models (theoretical and/or empirical) for each step. CFD simulations can be used as input to these analytical models, either for validation or improvement of such models.

The approach is illustrated below:

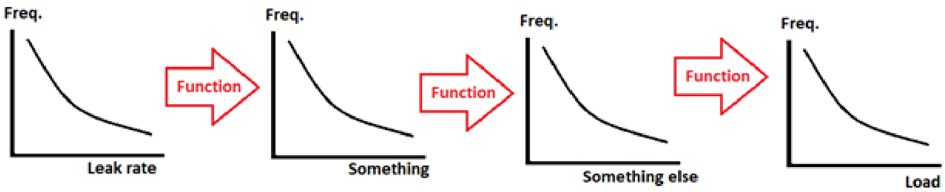


Figure 9 Frequency relationship model.

"Something" and "something else" are the intermediate results, and these should preferably provide useful insights valuable for decision support or output valuable for model validation/verification purposes. The number of steps must be as required from modelling of available knowledge and requests for intermediate results.

This model could perhaps also provide "A-B-C" categorization as additional output from the analysis[2].

2 These categories are sometimes used as input and sometimes as output in RISP work-group discussions

5. More detailed description of three different possible modelling approaches

We argue for an approach with the following steps for developing a new methodology

1. Definition stage: Defining the application range of the model: semi-confined modules, open geometries, modelling approach
2. Analysis stage – defining the purposes and describing the basis upon which we will build a model, identifying phenomena, objects and parameters.
3. Model formulation: Propose a model or method to achieve this purpose. Define input, output and describe the methodology for whatever should be in-between.
4. Model implementation
5. Model verification (which is basically QA)
6. Model validation stage (which may include tuning of parameters to obtain valid results and maintain “current industry safety level”).

This approach is meant to be sequential. Choosing model approach before completing the analysis stage may not lead to the sought simple and elegant approach.

In this chapter three different methods have been presented and discussed: a generic explosion model, a scenario based approach for a single event (Worst credible event (WCE) approach) and an equation-based approach: Risk modelling using frequency relations. The presented models are not fully developed and need to be developed fully to understand their potential.

5.1 Generic explosion model

5.1.1 Introduction

This section presents a proposed method for Generic explosion loads that can be used for standard designs.

Standard, tabulated explosion loads are proposed, with a corresponding validity envelope, i.e. criteria for when the specific explosion loads can be used.

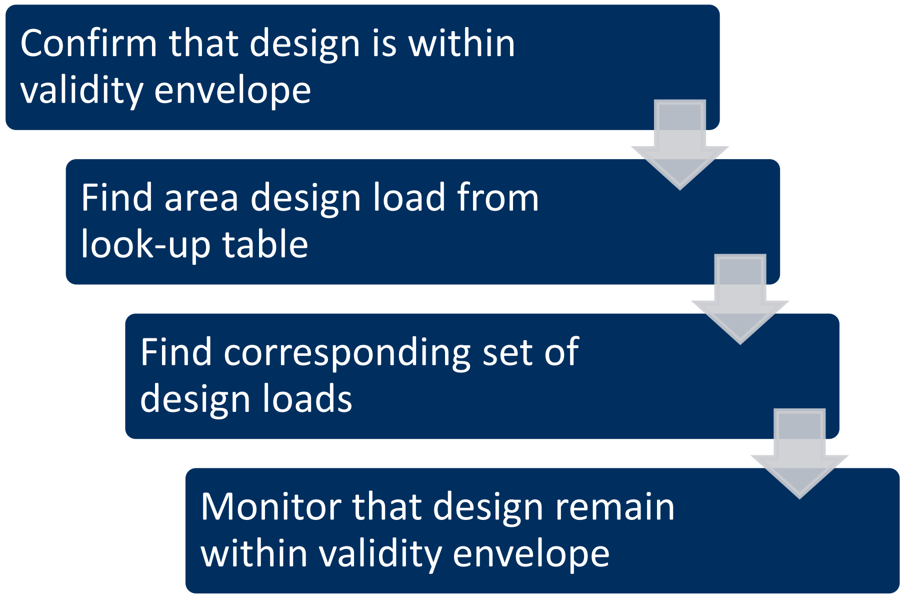
The main motivation for proposing a generic design accidental load method is to provide a consistent and efficient method to set robust design explosion loads in an early design phase, where the risk for late changes in design loads is very low. The aim is that the minimum generic design loads are set based on what is considered a non-cost driving load from a structural point of view, and also based on requirements in the PSA Facilities Regulation.

5.1.2 Principle for generic explosion model

In summary the main principle of the method is to use a checklist approach to confirm whether the actual design is within the validity envelope of the generic explosion loads method. Further, if the design is within the validity envelope, a look-up table can be used to find the corresponding area design explosion load for the given area / module. For each area design explosion load, a set of design loads are given, e.g. local and global explosion overpressure load and drag load.

Currently two different sets of generic area design loads have been included, i.e. 0.7 bar and 1 bar. It is possible to expand the method to include other sets of area design loads, e.g. a set of reduced explosion loads for wellhead platforms or for areas with less hazardous process equipment.

The main principle and process with using the generic explosion loads method, is illustrated below.



The method will be used for setting design loads in the planning phase. After the design loads have been set, there will be change management system during the execution phase, and finally verification in as-built phase, to ensure that the final design still is within the validity envelope of the generic explosion method.

This method is developed with the purpose to set design explosion loads and is not suitable for all other areas of use that a NORSOK Z-013 probabilistic explosion analysis can potentially be used for. Examples for what must be covered in other ways are:

- Sensitivity studies of explosion risk (incl. input to ALARP assessments)
- Input to design development / assess impact of changes
- Understanding of explosion risk picture

Other methods need to be used for these purposes, i.e. specific studies fit for purpose performed using probabilistic explosion analysis or a design scenario approach.

The application of the Generic explosion loads method throughout a field development project is illustrated in Figure 10.

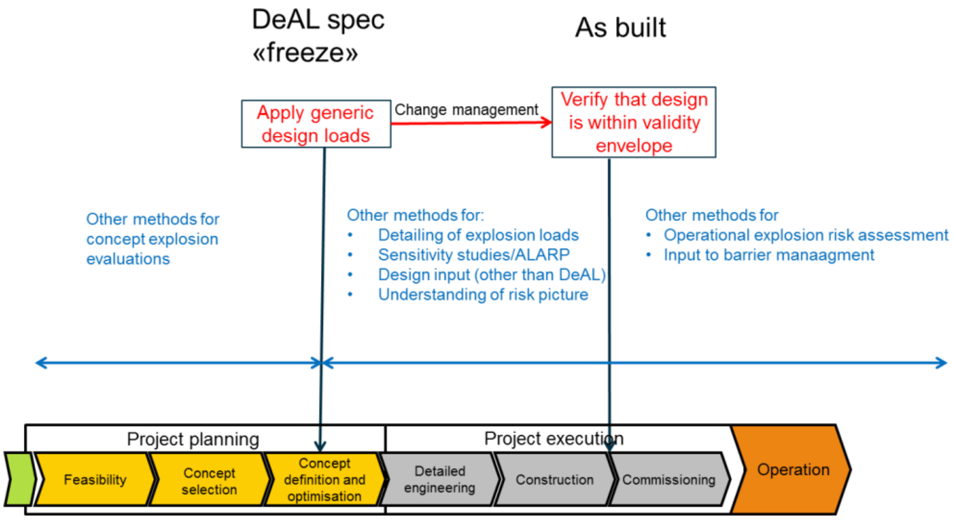


Figure 10: Application of Generic Explosion Method throughout a field development project

5.1.3 Background for chosen generic explosion loads

The chosen generic explosion loads have been based on:

- The explosion loads a standard structural design can withstand
- PSA requirements

In addition, choosing robust design loads that give a high safety level and minimize the risk for late changes, has been an objective.

5.1.3.1 Structural integrity

The main structural steel and bulkheads (walls and decks) of offshore modules or integrated constructions are designed to withstand forces induced by:

- environmental loads
- operational loads
- transport and installation loads
- accidental loads (explosion, fire, dropped object/swinging loads and ship collisions)

A general set of rules can be applied as a starting point to evaluate whether explosion loads will be dimensioning for main steel structures (see Figure 11).

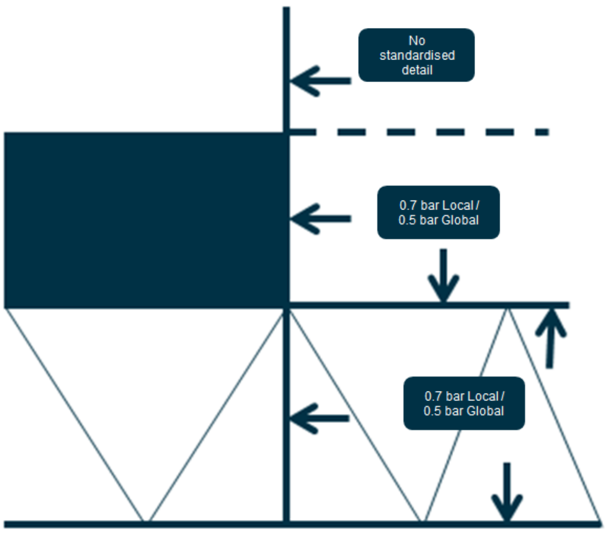


Figure 11: Standard details of main steel structures and explosion load cases in design

Explosion loads given in Figure 11 are expected to be taken by the structure without impairing the structural integrity. Hence, typical explosion loads not affecting structural design are then:

- 0.7 bar local load for approximately 200ms
- 0.5 bar global load for approximately 200ms

However, be aware of some general differences in deck and wall structures. Normally secondary steel girders in the deck need to carry higher blast loads than in the wall due to longer girder spans. Consequently, decks are typically somewhat more sensitive to blast loads compared to walls.

It should be mentioned also that the negative blast pressure (suction effect) can have a significant effect when the eigen period of the structure is close to the blast period.

Piping being exposed to blast will typically take up the energy as static deformations/deflections of the pipes and pipe supports without resulting in rupture or plastic deformations causing critical leak rates after the explosion. Typical integrity limit to be applied for single piping is found to be:

- 0.25 bar drag within a duration spread of 20-200 ms.

For blast loads acting on equipment/skids, piperacks, secondary and outfitting steel in general, no general integrity level can be specified due to the large variety of item sizes, support points, locations and equipment weights, which controls the response of the item considered.

5.1.3.2 PSA requirements

In the Guideline to the Facilities Regulation, to § 30 Fire divisions the following minimum design load is recommended:

(…) The main fire divisions in closed areas should be able to withstand an explosion load of at least 70 kPa for 0.2 seconds. (…)

Using 0.7 bar as the minimum generic load, is hence, in line with this recommendation. A lower load category (e.g. 0.3 to 0.5 bar) could however have been defined for "open areas", e.g. weather deck modules, or areas with small inventories of hydrocarbons (e.g. areas comprising produced water system or similar).

5.1.4 Categories of generic explosion loads

Generic explosion loads applicable for platforms comprising both process areas and/or wellhead and drilling areas have been presented. Generic explosion loads for wellhead platforms has not been included in this version.

Two different categories of standard definitions are presented, with a defined set of Design Accidental Explosion Loads applicable per standard design solution.

Figure 12: Categories of Generic explosion loads proposed

Category	Local overpressure load on physical area barriers (i.e. 3.5 x 3.5 m^2 panel pressure on walls, decks etc.)	Global overpressure load on physical area barriers	Drag load to piping systems and pipe supports General area loads
Moderate load	0.7 bar /200 ms	0.5 bar / 200 ms	0.25 bar / 80 ms
High load	1 bar / 150 ms	0.6 bar / 150 ms	0.33 bar / 80 ms

In upcoming sections the Design Accidental Load set suggested for "Moderate load" areas is referred to as 0.7 bar for simplicity. Similarly, the Design Accidental Load set for "High load" areas is referred to as 1 bar.

For objects for which are not walls, decks or objects with small cross-section, as well as units and structures located outside at a distance from the confined and/or congested areas, the loads defined above are not necessarily relevant. For these types of objects, the DeAL should be aligned with the loads defined in the table above. The loads may be evaluated based on explosion CFD simulations, or by a simpler approach. For instance, in a 0.7 bar area this may be applicable to

- Intermediately sized objects, for which the load can be increased linearly from 0.25 bar for objects with cross section of 0.5 m to 0.7 bar for objects with a cross section of 3 meters. For simplicity, similar linear relationship may be applied between drag duration and overpressure duration for intermediate sized objects.
- Loads into far field objects may be evaluated based on simplified far-field methods such as the multi-energy method

5.1.5 Validity envelope

A rule set has been developed to determine if the area or module is within the validity envelope of standard designs, and hence the Generic explosion loads method can be used. Three levels of rule sets have been proposed:

1. Overall requirements for use of RISP methods
2. Module /Area checklist
3. Find applicable design load from look-up table

5.1.5.1 Overall requirements for use of RISP methods

These are overall requirements for use of the RISP methods, such as design according to Norwegian Regulations and Standards (NORSOK). These overall requirements are defined in the report by Workgroup 1, Risk Management, and are not repeated herein.

5.1.5.2 Module/Area checklist

This section presents preliminary specific requirements for the area or modules considered, to evaluate if the generic explosion loads method can be used. The requirements are presented as a checklist.

The main topics in the checklist are discussed below. The proposed checklist is presented in Table 4.

If response to all questions in the check list presented in Table 4 is YES, the generic design accidental explosion loads may be applied. The Design Accidental explosion loads are typically determined based on this checklist in late concept phase or FEED phase, and the check list should be continuously monitored during the later detailed design, fabrication and commissioning phases to ensure that there are no changes that result in design outside of the validity envelope of the simplified Design Accidental Load specification.

The checklist may be expanded and adjusted after the development and validation process of the generic explosion model has been completed.

By going through the checklist given in Table 4 to confirm that the generic explosion load method can be used, it will also become clear what the explosion loads in the area should be.

In order to apply 0.7 bar Design Accidental Load, 0.7 bar must be an acceptable load both according to Table 6 and Table 7. If one or both of these tables categorize the area design load as 1 barg, 0.7 barg cannot be used based on this simplified “generic explosion load” approach.

Likewise, if one or both of these tables conclude that the module volume or vent area parameter is outside the validity envelope of 1 bar, the generic explosion loads cannot be used.

Note that the generic explosion loads defined, i.e. area design load of 0.7 bar or 1 bar, should be considered minimum design explosion loads, i.e. if there are uncertainty in the input parameters to the generic explosion loads method, additional margin should be added accordingly.

Table 4: Proposed Module/Area checklist to determine if the generic Design Accidental Explosion Loads can be applied. All the check list items need to be answered with “yes” in order for the generic explosion loads method to valid for the given design.

Checklist item #	Checklist	YES	NO	Documentation requirement
1	Have design principles from ISO 13702, (Ref. /7/) been followed?			Description of strategy to mitigate explosion risk
2	The facility is not a production facility categorized as HPHT (High Pressure – High Temperature)? Note: If the facility is HPHT the generic explosion loads method is still applicable for areas/models where the operational pressure is not classified as HP.			
3	The safety system design is according to NORSOK S-001?			
4	Is the area naturally ventilated?			Description of module ventilation
5	Has the area a rectangular shape?			Layout drawings
6	Is the area/module volume < 20,000 m^3			Layout drawings Additional module volume constraints are given in Table 6
7	Confirm that the area does not comprise any corners Note: if the area comprises corners special considerations to be made, such as doubling of the explosion load locally.			Layout drawings
8	Is the maximum flame acceleration length of the module within the acceptable limits of the generic explosion loads?			Calculating D/APOR for the specific area or module. See detailed description below Check if the obstruction adjusted flame acceleration length of the module is less than D / APOR < 25m in general, or D / APOR < 35m if the module has general area deluge coverage starting upon confirmed gas detection.
9	Is the area normally congested, i.e. not particularly congested?			Interpretation of this will be the responsibility of the

				company
10	Confirm that it is not a diesel generator without flame arrestor in combustion air intake or gas turbines present at platform? If NO, generic explosion loads are applicable if it can be documented with dispersion simulation that a steady state 200 kg/s HC leak does not expose the combustion air intake with concentration above 0.5 LFL despite unfavourable leak and wind conditions.			Safety strategy/ Performance standards Layout drawings

Ref checklist item 8, maximum flame acceleration length

With reference to checklist item 8 the definition of the maximum flame acceleration length (D/APOR) is given below, and it is the minimum of this value in the X, Y and Z direction that must fulfil the requirement listed in Table 4, i.e. for at least one direction the following criterion should be fulfilled: (see Figure 13 for illustration)

1. Xdim/(Pxn+Pxp) or Ydim/(Pyn+Pyp) or Zdim/(Pzn+Pzp) < Dmax

Often the maximum blockage (minimum porosity) corresponds to the module boundaries, in that case Pxn_min = Pxn etc. If the maximum blockage (Pxm) is not at the module boundary, but inside the module, Pxn or Pxp (same for y and z) should be replaced by the maximum blockage in the lower and upper half of the module, respectively.

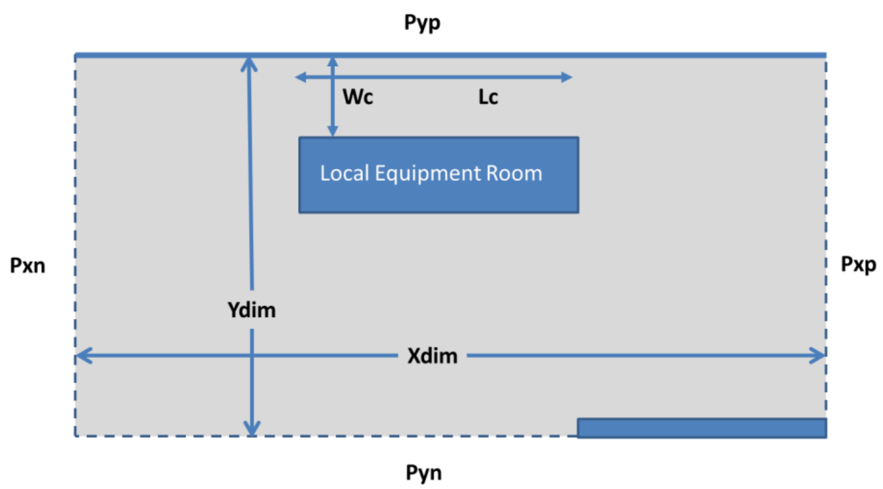


Figure 13 Illustration of horizontal cut plane through platform module, Xdim (E-W) and Ydim (N-S) are dimensions of the module, Pxn, Pxp, Pyn and Pyp are area porosities across the module openings, Wc and Lc are width and length of a “channel” between the blastwall (N) and a local equipment room, the porosity of channel into rest of module are Pcn and Pcp (not illustrated)

5.1.5.3 Find design load from look up table

If the answer to all the questions in the check list presented in Table 4 is YES, the next step is to find the generic explosion load to be used from a look up table.

The design load is found based on the following area/model specific parameters:

- Module configuration, i.e. the number of modules with border to the same explosion barrier
- Area/module volume
- Are the natural ventilation conditions of the module within the acceptable limits of the generic explosion loads? This is expressed as the function Kv

Note that certain combinations of the above parameters may also lead to a conclusion that the design is not within the validity envelope of the generic explosion loads method.

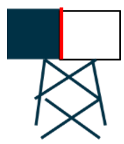
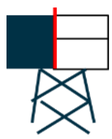
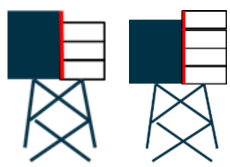
Module configuration

The risk acceptance criteria (RAC) for escalation due to explosion influence the design load.

The RAC may have been implemented in somewhat different ways for the different oil companies, but the main interpretation of the Facilities Regulation requirement, has been that the total frequency for escalation from one main area to another shall be less than 10^{-4} per year. This means that if four process modules belonging to the same main area are adjacent to the same explosion barrier to another main area, the contributions from each module to loss of explosion barrier can maximum be 25 % of 10^{-4} per year in order to fulfil the criteria, or another distribution that gives an impairment frequency less than 10^{-4} per year for the sum events in all four modules.

In order to take account for this, four different module configurations have been introduced as presented in Table 8. If the Oil Company's RAC differs from the description above, i.e. that the 10^{-4} requirement applies per area/module, Module A configuration in the table below can be used independent of the number of modules that borders to the same explosion barrier.

Table 5: Illustration of different combinations of module configurations referred to in Table 6 and Table 7.

Module configuration	Number of modules sharing the same explosion barrier	Illustration of Module configuration – number of modules sharing the same explosion barrier
A	1	
B	2	
C	3-4	
D	5-6	

Area/module volume

Preliminary volume constraints for application of generic explosion loads are proposed in Table 6.

Based on the module configuration (A-D) and the module volume, a design load is given. Note that the natural ventilation condition also needs to be checked before a conclusion on the design load can finally be chosen, ref. Table 6.

Table 6: Volume constraints for application of Generic Design Accidental Explosion Loads

Module configuration (ref. Table 8)	Module volume range [m^3]		
A	<= 12,500 m^3	12,500 – 20,000 m^3?	> 20,000 m^3
B	<= 6500 m^3	6500-9500 m^3	> 9500 m^3
C	<= 4500 m^3	4500- 6500 m^3	> 6500 m^3
D	N/A	< 4500 m^3	> 4500 m^3
RESULTING DESIGN LOAD:	**DESIGN LOAD 0.7 BAR**	**DESIGN LOAD 1 BAR**	**OUTSIDE VALIDITY ENVELOPE** **Generic explosion loads method cannot be used**

Note that the volume constraints presented are preliminarily proposed, and need to be developed further, if the generic explosion loads method is chosen for further development.

Area/module natural ventilation conditions

When the volume constraints have been checked, the next step is to check the module natural ventilation conditions. This is proposed expressed as a vent area parameter (Kv) for the specific area or module:

$$Kv = Av / (Pv*V)^{2/3}$$

where

V is the total module volume, Pv the module volume porosity and Av being the net available vent area (m^2) over all module boundaries. If Pxn, Pxp, Pyn, Pyp, Pzn and Pzp are the boundary porosities of all 6 module faces, and Xdim, Ydim and Zdim are the dimensions, see illustration in Figure 13.

$$Av = V \times [(Pxn+Pxp)/Xdim + (Pyn+Pyp)/Ydim + (Pzn+Pzp)/Zdim] \quad \text{and thus}$$

$$Kv = (V/Pv^2)^{1/3} \times [(Pxn+Pxp)/Xdim + (Pyn+Pyp)/Ydim + (Pzn+Pzp)/Zdim]$$

Porosities Pxn-Pzp should be net porosities, with any geometry blockage subtracted, normally maximum porosities in a vertical face (Pxn,Pxp,Pyn,Pyp) will seldom exceed 0.8 due to support structure etc. (0.8 is proposed as base case for fully open module faces) and if parts of one face are blocked by louvres, panels or major objects, the porosities should be reduced proportional to this blockage.

Volume porosity is Pv, this is assumed to be almost 1.00 in most cases but should be reduced if significant parts of the Xdim x Ydim x Zdim module are blocked by rooms/buildings.

The Kv criterion must also apply for any subsection of the module covering between 5% and 50% of the volume, i.e. in Figure 12 the criterion should be applicable for the channel between the local equipment room and the blast wall with dimensions Lc x Wc x H. Here internal porosities in the channel Pcn and Pcp are 0.8 (fully open). If there are local regions with significant confinement (low Kv-factor) this should be included in the assessment as follows. The **highest** value of the **minimum local Kv** and the **global module Kv** is reduced by 0.25, and thereafter **the lowest** of the two values are used as representative Kv to identify if a minimum generic DeAL are applicable.

Table 7: Requirements for vent area parameters for Generic design loads to be valid

Module configuration (ref.)	Vent area parameter (Kv) range		
A	Kv > 0.75	0.5 <Kv < 0.75	Kv<0.5
B	Kv > 1	0.75 <Kv < 1	Kv<0.75
C	Kv > 1.25	1 <Kv < 1.25	Kv<1
D	Kv > 1.5	1.25 <Kv < 1.5	Kv<1.25
RESULTING DESIGN LOAD:	**AREA DESIGN LOAD 0.7 BAR**	**AREA DESIGN LOAD 1 BAR**	**OUTSIDE VALIDITY ENVELOPE** **Generic explosion loads method cannot be used**

Note that the vent area constraints presented are preliminary and may be developed further if the generic explosion loads method is chosen for further development.

5.1.6 Basis for Module / area specific parameters and validity envelope

The preliminary module/area specific parameters have been set based on:

- Use of data from previous explosion analysis, section 3

- Use of calculations performed using existing simplified tools, including COSAC and ThorExpressLite. An example of use of the COSAC tool in this context is shown in Figure 14.
- Expert assessments in line with
  - The experience from and statistical analysis of historical observations
  - 2Knowledge of the phenomena involved including chemistry, combustion theory, thermodynamics and physical laws, and observations/knowledge gained on the phenomena from full scale experiments and CFD modelling

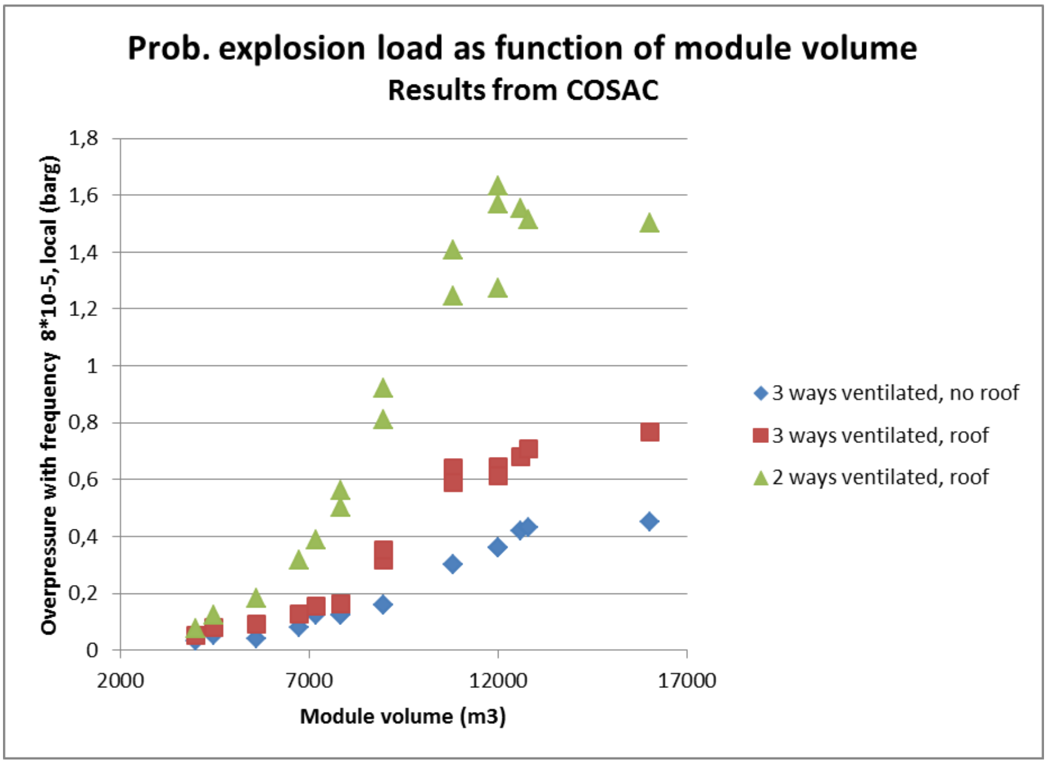


Figure 14: Example of use of COSAC for as basis or as validation of boundaries for Generic Explosion Loads method

However, note that applicability of the parameters as well as definition of the boundaries need to be further evaluated and matured. The boundary constraints presented in this section are preliminary and may need to be developed further. With the current validity envelope, the model appears to be quite conservative, and hence, a significant fraction of areas/modules may be outside the validity envelope.

In addition, there is a need for an extended verification and validation phase to define valid boundaries generally accepted in the oil and gas industry. Based on this, the description of this type of approach as well as the boundaries of the validity envelope should be considered an outline of the general principles for such a method.

Recommended further work to finalise the Generic loads method is described in section Appendix A.

5.1.7 Risk management and other decision support

The generic explosion loads method, as described above, will be used to establish DeAL level. However, a simple method will have limitations with regards to providing input to Risk management and other explosion risk-based decision support. This is also illustrated in Figure 10.

Examples of other use of the explosion risk analysis are:

- Input to ALARP assessments
- Assess impact of design changes / management of change
- Detailing of explosion loads, e.g. as input to package specifications.

It is important that the further development of the generic explosion loads method also takes into account the role in the risk management process and how other types of decision support shall be provided:

- A flexible and suitable framework of processes, methods and tools for risk management and other decision support related to explosion risk is very extensive. It is recommended that the methods for other decision support should to a large degree as possible use existing framework, rather than creating new, advanced methods and models from scratch.
- Much of the input needed may be provided by current probabilistic framework (i.e. NORSOK Z-013 annex F). Making explosion analysis fit for purpose will in many cases be achieved by adapting/improving the processes and the way the tools and methods are used, as well as making criteria fit for purpose.
- A probabilistic approach (similar to todays practice) may have advantages in FEED phase, as well as in operation of the facility, with respect to sensitivity evaluations and to get some indication of the effect of specific factors. An advantage with the probabilistic approach is that it estimates the total result of several effects. E.g. reducing the ventilation area of a module, may both increase the gas cloud size for a given leak and in addition increase the resulting explosion load for a given gas cloud size.
- When assessing robustness of the design accidental loads the probabilistic approach may give an indication. A challenge may be that if applying a detailed probabilistic analysis for different purposes than DeAL, the calculated frequency for exceeding the DeAL may in a few cases be in conflict with a DeAL established with a simplified approach. Experts, stakeholder and authorities much trust the DeAL established based on simple principles and key risk drivers.
- For specific assessments such as in detailed engineering phase when the design to a large extent is frozen, it seems advantageous to develop design events, e.g. as input to detailed equipment and structural design. Aspects of the single scenario models may be used.

5.2 Scenario based approach: single scenario/worst credible event approach

Worst credible event (WCE) approach was suggested by NOROG as a possible methodology to establish robust explosion design loads. Several possible worst credible events were proposed, e.g. that the platform module should withstand the consequences from

- 2” natural gas release with delayed ignition
- 8 kg/s natural gas release with delayed ignition
- Ignition in gas cloud filling 15% of module

To help limit the spread in predicted explosion loads a given leak location, and direction, wind direction and strength as well as an ignited cloud location and ignition position were proposed. Could this give a good basis for design explosion loads?

Scenario based approaches are used in several situations in which worst credible, maximum credible or dimensioning events are specified, e.g.

- ISO 20519 (Ref. /8/) LNG Bunkering - safety zone can be established either as the maximum LFL-distance from credible release scenarios (constant leak through instrument connection or transient leak scenario filling hose rupture after ESD-valves are closed are proposed) or from QRA risk contours.
- NFPA 59A (Ref. /9/) LNG standard – Hazard distances within property limit shall be established based on LFL-distance from credible releases in 2 m/s wind
- Worst credible process fires are used for fire studies on NCS
- Worst credible events are used extensively in risk and safety studies in the USA, e.g. in API RP 752 (Ref. /10/) for process plant safety studies.

The worst credible event (or explosion) is the worst credible combination of release (of any rate), cloud generation, ignition and explosion development that give the worst consequences at a given location. For one module there could e.g. be different WCEs for explosion loads towards the North Blastwall and for drag loads in exposing piping in the SW-corner.

The legal system is one important reason why worst credible event approaches are popular in the USA. While operators in the North Sea acknowledge the fact that there will be a residual risk (low frequency high consequence events) which cannot be designed against, and design platforms based on frequency-based risk acceptance criteria (e.g. 10^{-5}/y and 10^{-4}/y), operators in the USA would hesitate to admit the same. If an accident would happen and they would admit they were aware that a disaster scenario could develop which they had not prevented, legal claims for compensation from relatives of victims could be extremely high. In this setting it is convenient for companies operating in the US to evaluate required design based on worst credible event approach, like a worst-case explosion from a 2” release, and if a disaster would happen, this will come as a surprise, and they can claim to have done what was expected from them following best industry practice. If a similar disaster would happen in the NCS the operators would be exposed to much lower claims for compensation from relatives due to a very different legal system.

In the API RP 752 (Ref. /10/) the worst credible event is defined as the event with the maximum consequence among the major scenarios evaluated, which should all be “realistic, and have a reasonable probability of occurrence considering the chemicals, inventories, equipment and piping design, operating conditions, fuel reactivity, process unit geometry industry incident history, and other factors”

The very vague definition of credible event is one of the challenges with the concept. In the evaluation of industry incident history there have been some rules of thumb on how to do this, e.g. for an operator in Texas incidents within Texas/US GoM within the past decades or so could be credible, as well as global experience for the particular operator within a similar time span. A Macondo-type incident in the North Sea should then primarily be considered as credible for the companies involved in Deepwater Horizon.

For the mentioned scenarios where worst credible events were used (NFPA-59A, ISO 20519 and API RP 752) there is one common aspect, or at least for the LNG-hazard distances in the first two standards. The problem (LFL-based exclusion zone) increases with the size of the release. It is thus relatively easy to establish the worst consequences for a given release. For NFPA-59A this is done by specifying that the release should be modelled with 2 m/s wind, generally known to give the maximum LFL-distances. In API RP 752 dispersion, explosion and fire hazards are to be estimated for an onshore process plant. Both dispersion and fire hazards will increase with increasing leak rate. For a large outdoor process areas the same may to some extent apply for explosions, at least when the explosion risk is calculated based on explosive cloud formation using Gaussian dispersion 2D models, e.g. Phast, and from that cloud size far-field explosion loads are estimated by assuming an explosion source strength using the TNO Multi-Energy model or similar tools.

With consequences scaling with size of leak one often used approach is to consider the typical frequency distribution of significant leaks and conclude that the maximum credible leak size is the 90% or 95% percentile among these. Ref. /11/ uses a 95% argument to conclude that the common practice of using 2” leaks as the worst credible event can be justified for API RP 752 studies.

For explosion studies such an approach can be highly questionable, at least for facilities with large segments with potential for large releases of flammable gases. This is illustrated with an example in

Figure 15. The purple line illustrates a hole size distribution with the circle indicating the chosen maximum credible hole size of 2" (50mm), being the 95-percentile among leaks with hole size of 10mm or larger. For the actual facility this corresponds to a 10 kg/s release of denser than air hydrocarbons (similar to LPG). It is assumed that the risk driving segments can maintain a leak rate of 100 kg/s for long enough time to develop a large flammable cloud, for hole sizes larger than 150mm, the pressure loss in the piping will quickly reduce the leak rate to 100 kg/s. The hydrocarbon leak rate as function of hole size thus goes with the square of the hole size until being capped at 100 kg/s (>150mm), see orange curve in the plot.

For flammable cloud sizes from a high-pressure jet which can expand in three directions the explosive cloud volume tends to increase to the third power relative to the hole size. The estimated cloud volume for the various releases (relative to the maximum leak rate of 100 kg/s) is shown with a blue line, indicating that the defined worst credible event only contains 3.2% of the explosion energy compared to scenarios from leaks from hole sizes 6" or higher.

The ignition probability will also depend strongly on the leak rate. In the green curve the OGP 434-6 ignition probabilities for LPG-releases in a large onshore gas plant (Table 8) are plotted as function of leak size. For the maximum credible release the ignition probability is 2.5%, while this increases to more than 50% for the very large releases.

By combining the leak frequencies for the various hole sizes with the ignition probabilities a frequency distribution of ignited cloud sizes can be plotted. The red curve shows the fraction of explosions expected to be equal to or larger than the explosions from each hole size. So while only 5% of the significant leaks have a diameter larger than 2" (50mm) as much as 76% of the ignited clouds will be larger (and mostly significantly larger) than the worst credible event.

This example illustrates that while the risk analyst following a typical API-RP 752 Worst credible event approach like justified by Ref. /11/, the reality may be that 3 of the next 4 explosions can be expected to the stronger than what is claimed to be maximum credible and assessed in the risk assessment.

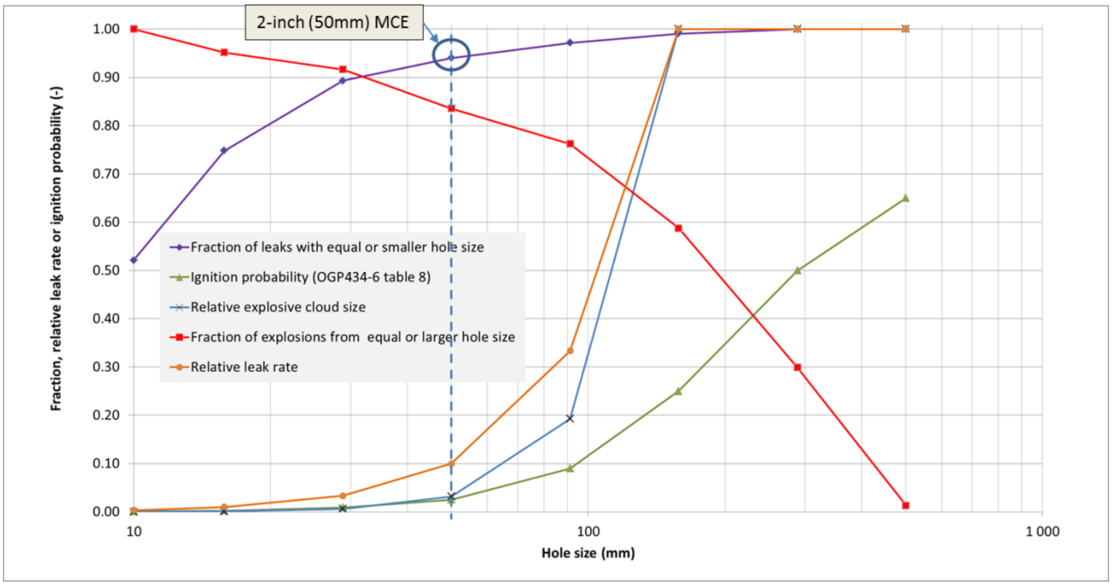


Figure 15 Illustration of possible relation between hole size distribution (purple), leak rate (orange), cloud size (blue), ignition probability (green) and probability that the next explosions will be from a given hole size or larger (red curve).

For offshore platforms the severity of an incident to a much lesser degree will increase monotonously with the leak rate. Walls, decks and confinement will accumulate gas, so that even moderate leak sizes can fill modules to dangerous concentrations, in particular on calm days, or if wind blows from a direction giving poor ventilation within the module. Gas pushed out of the platform will normally not contribute to the explosion consequences, and a larger release may even lead to a less severe explosion because much of the module has become fuel-rich with no or low gas reactivity. And while the total explosion energy is the primary parameter for explosion damage (normally far-field only considered), the oil platform study is much more focused on preventing collapse of structures. For such considerations the location of the reactive gas cloud and ignition location may be very important parameters, and there will be a large variation in consequence for different scenarios originating from the same hole size or leak rate.

Table 8 – Simplified illustration of parameters of importance for explosion risk

Risk parameter	Onshore plant	Offshore module
Most important for explosion energy	Leak rate	Leak rate, direction, location, ventilation, module confinement, size
Most important for explosion consequences	Explosion energy (far-field blast)	Reactive cloud size near structures (walls/decks/…), ignition location, etc.

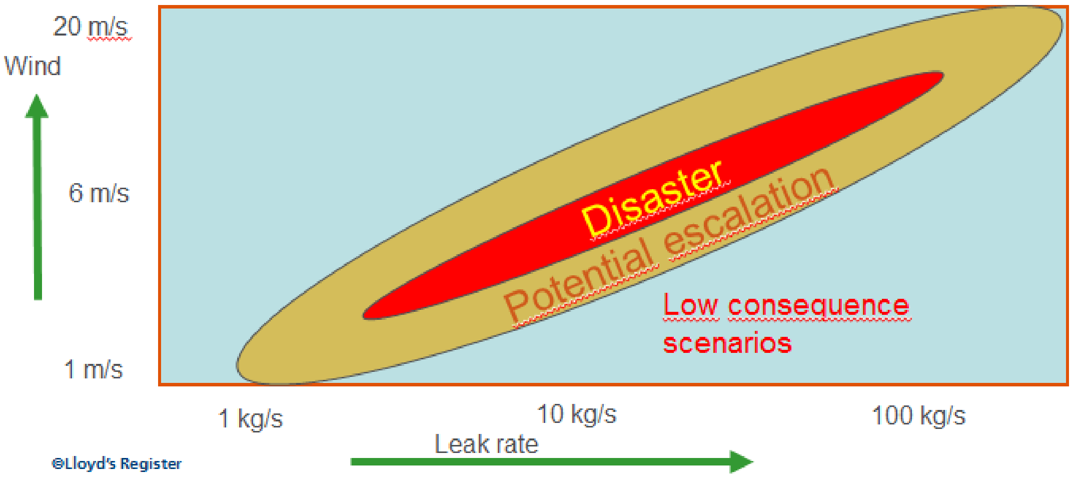


Figure 16 Simplified illustration of expected explosion severity as function of ventilation for a given platform module scenario. The worst incidents may happen for moderate leak rates in moderate wind, or with higher leak rates and more wind. A large release rate in low wind may be less severe.

The proposed worst credible events (or better "dimensioning events") suggested by NOROG for oil and gas platforms were either based on performing CFD-simulations with a given hole size (e.g. 2"), leak rate (e.g. 8 kg/s), or assuming a certain gas cloud size (e.g. 15% fill). Each of these methods will have major weaknesses for the following reasons:

a) There will be a significant spread in results depending on parameter choice (release location/direction, cloud location, ignition location). Many scenarios are required evaluated to get a proper distribution and mapping of possible outcomes. If only a specific set of parameters shall be evaluated in a WCE-assessment, the conclusions may become arbitrary.

b) With a scenario-based WCE or dimensioning approach as discussed, the more severe scenarios are not assessed, and there is therefore no insight in the possible consequences from low frequency high consequence events. No insight will then be gained regarding the robustness of the installation to handle the residual risk.

c) There may be a tendency that consultants will predict lower risk when the task is to search for worst credible event outcomes.

d) For the WCE methodology a reasonably accurate 3D geometry model is required. One of the major motivations for simplifying the approaches is the challenge to establish a proper 3D model. If a sufficiently accurate 3D model is developed, it would be much better to simulate a wider array of parameter variations to get a distribution of outcomes, than to use the model only to evaluate a limited number of arbitrary scenarios. Thus, why not systematically model a few hundred scenarios rather than 1-5 arbitrary scenarios if the 3D model is available.

To conclude scenario-based methods are not considered a good way to address performance-based requirements from authorities (e.g. frequency of impairing main safety function < 10^{-4}/year)[3].

If the general competence level in the industry is low so that the operators literally do not know what they are doing when it comes to explosion safe design, there may be a need for more prescriptive rules and to more clearly tell the operators what to do. In such situation performance-based criteria may be not be the right approach. A low competence level by the authorities may have a similar effect, as they may need simple checklists to be able to oversee the industry. Who “owns the accident” is an important aspect. If the operator/partners have the sole responsibility to take care of all sorts of problems if there should be an accident, the authorities should better define performance-based goals rather than prescriptive checklists, so that the operators can choose the optimal way to solve the safety challenges. If more prescriptive rules are required followed from the authorities, for instance based on performing a scenario-based assessment, the authorities should also take a greater responsibility for accidents.

In the current situation in Norway, with primarily performance-based requirements from the authorities, and where the operator and partners have the main responsibility for an accident, scenario-based risk assessment methodology is not considered appropriate.

5.3 Equation-based model: Risk modelling using frequency relations

The following should be considered an example, as the purpose is to describe how to proceed to establish a new methodology. The analysis stage (see above) should identify and define the phenomena and intermediate results to be reflected in the model.

It is vitally important that the method/model framework is suitable for capturing the essence of our knowledge for the different phenomena determining gas explosion risk.

The stages could be as described in the following table:

3 The RISP project has stated that current regulations shall not be used as a limitation to the development. The regulatory regime and distribution of responsibility for safe operation and liability given an accident will be important for the recommendations of method. However, since no new regulation is in place or has been indicated how it would look like current regulations have been referred to.

Table 9: Frequency relation modelling – example

Stage	Knowledge and phenomena	Model	Comments
Leak	The relations between equipment (leak sources) and leak frequency are well documented in PLOFAM2 (NCS and UKCS data). Limitations in leak duration by sectionalisation, blowdown and inventory. Data shows that leaked inventory is small in many cases.	$f = k1 \cdot ModVol \cdot rate^n$ Frequency for leak with specified rate or higher. Parameter n from PLOFAM2, parameter k1 reflects equipment in the considered module and could be simplified as follows (rate in kg/s, freq. per yr, volume in m^3): $k1 = ModVol \cdot 1.5 \cdot 10^{-6}$ $n = -0.7$	Reliable and simple. Extensive data set (strong knowledge)
Ventilation	Wind condition statistics is normally well known. Ventilation modelling can be performed with CFD.	ACH can be modelled using a lognormal distribution with two parameters: $\mu = \ln(\text{Average ACH}) - \sigma^2/2$ $\sigma = 0.78$	Ventilation can be modelled with reasonable accuracy at early stage or based on similar modules.
Dispersion distance	Location of leak sources relative to ventilation openings (outlet)	Simple probability distribution, for example uniform between 0 and module length	Uncertainty is low
Dispersion	Gas is diluted by ventilation and jet mechanisms. Dispersion limited by module size, leak rate and inventory. Flammability limits important for flammable cloud size. Buoyant/dense/neutral gas will affect dispersion (but challenging to model) Data: Simulation results, experiments	V = f (Dispersion distance, leak rate, inventory, ventilation conditions, gas properties) A conceptual model for gas cloud size has been proposed	Relations are complex, and simplifications required. Model should be evaluated considering the basis for ignition probability models (MISOF). Uncertainty (variability) should be modelled.
Ignition probability (internal)	Experience data as for leaks (NCS and UKCS since 1992) as summarised in MISOF2. There is knowledge on ignition mechanisms (energy and temperature) and equipment failure modes and data.	$\text{Ign.prob.} = k5 \cdot V_{LEL} + k6 \cdot V_{flam} \cdot t$ t is leak duration, k5 and k6 from MISOF2	Flammable gas quantity ignited, and the corresponding frequencies are sought. There is statistical uncertainty because there are very few ignitions and because gas exposure from the experienced leaks is uncertain.
Ignition probability (external)	Activities and equipment in adjacent areas, Air intake to internal combustion engines and gas turbines etc. are known to represent ignition sources.	Extension of gas cloud outside module calculated with the same dispersion model as for the internal gas cloud. Ignition sources outside module must be defined and assessed.	It is known that ignition probability is significant, but quantification is still somewhat uncertain.
Flammable gas cloud	Ignition can take place at any time, and the flammable gas cloud volume will vary between the	Simple probability distribution between the extremes.	

Stage	Knowledge and phenomena	Model	Comments
volume	maximum value applied for ignition probability quantification and virtually zero.		
Explosion energy	Based on a small set of FLACS simulations it seems that the maximum product of pressure and volume, which is a measure of mechanical explosion energy is reasonably proportional to the heat of combustion.	For hydrocarbons, energy of combustion is HHV = 55 MJ/kg. $P \cdot V = k7 \cdot HHV \cdot Mass_{Flammable}$ K7 = 0.12 (here, P is in N/m^2)	Using energy as an intermediate result will contribute to model robustness. Local and global loads, and the distance between blast walls and other targets can be assessed and modelled consistently if energy (measured as the product of pressure and volume) is introduced.
Explosion loads	Physics and thermodynamics (energy is the product of pressure and corresponding volume). Explosion simulation results	Model for global and local loads to be developed. Explosion from small clouds will have more local effect than those from larger clouds (with more energy). Far field loads similar as for multi-energy method. Something analogous to Multi-energy for modules seems promising. Sachs scaling; $\frac{E_m}{P_0^{\frac{1}{3}}}$ is an example	The explosion loads will depend on the distance between the explosion and any partition or object considered for exposure. The distance relative to the cloud dimensions matters (dimensionless).
Explosion pressure (direct alternative)	Experiments, small and full scale. CFD explosion simulation results Theory (expansion factors, adiabatic flame temperature etc.) - Deflagration and congestion - Confinement and explosion venting	In open geometries, explosion pressure is (more or less) proportional to cloud size. In closed module it is proportional to fill fraction. Pressure >= $k8 \cdot V_{flam} \cdot \Phi_3$ Pressure >= $k9 \cdot k10 \cdot$ module fill fraction Example: k8 = 0.0005 bar/m^3, k9 = 8 bar K10 is a function of module confinement (value between 0 and 1) Φ_3 is used to model variability (expectancy = 1). Lilleaker Consulting experience is that a lognormal distribution for Φ_3 is appropriate.	Apparently, congestion is similar for many process modules, but could be lower for an FPSO as compared to a smaller installation. Confinement effects to be combined with open geometry results in a somewhat more sophisticated way than above. Simple models for explosion venting exist and should be applied. The model proposed here could be modified to use energy as input.

5.3.1 Model development and improvements

5.3.1.1 General

The model framework presented above is simple and relatively easy to implement as a tool. A prototype has been developed. It is therefore considered to fulfil some of the requirements to transparency. Documentation of the basis for the proposed models and parameters is key to obtain credibility.

The main difference between this approach and the NORSOK approach is that the result is not depending on the evaluation of a set or a subset of a literally infinite set of scenarios. This model described here aims at modelling more general relations.

Each of the different calculation steps can and should be improved. It should be possible to improve one step without affecting the others. It should also be possible to insert a new step to split the modelling of one step in two.

There can be general improvements in the applied relations based on new knowledge and studies, for example new sets of simulations, new experience data or new analyses of such data. For a specific module analysed, studies (such as CFD studies) and analyses can be applied to improve the parameters for the functions applied in the calculations.

Since the use of simple relations is emphasized and applied wherever possible, the relation between input parameters and model results are in many cases obvious. Further, the sensitivity between model parameters (k_i, n and parameters such as μ and σ in the probability distributions Φ_i) and results can be obtained in seconds.

<u>Analysis of a specific module</u>

For a specific module, the default parameters could be replaced with parameters that are more accurate for the module at hand. Depending on available information, this could be obtained by simulation studies. In this case, the study is more like current (NORSOK) approach. Still, it is likely that the common framework will contribute to consistency, and in any case comparison of studies could be eased.

It may be necessary to establish working procedures for how to establish module specific parameters (k_i).

5.3.1.2 Dispersion model

The proposed method requires that a robust and reasonably accurate dispersion model can be formulated. An example dispersion model that can reflect leak rate, inventory, module dimensions and ventilation conditions is therefore presented is this chapter.

For naturally ventilated modules, air changes per hour (ACH) can be modelled with a simple probability distribution such as log-normal. Gas dilution locally in the module is dependent on the local flow velocity, Um, which is related to the ACH as follows:

$$U_{m,average} = \frac{ACH}{3600} \cdot \sqrt{\frac{V}{H}}$$

Where $\sqrt{\frac{V}{H}}$ is a characteristic length (V is module volume and H is module height)

For mechanically ventilated modules, variability in ventilation is much smaller.

k3 and “Gas quantity released”: A high fraction of experienced leaks has small inventories as compared to process segment inventories. Process segment inventories must be assessed in comparison to module size and the ventilation conditions. As a first step the largest inventory could be input to the model.

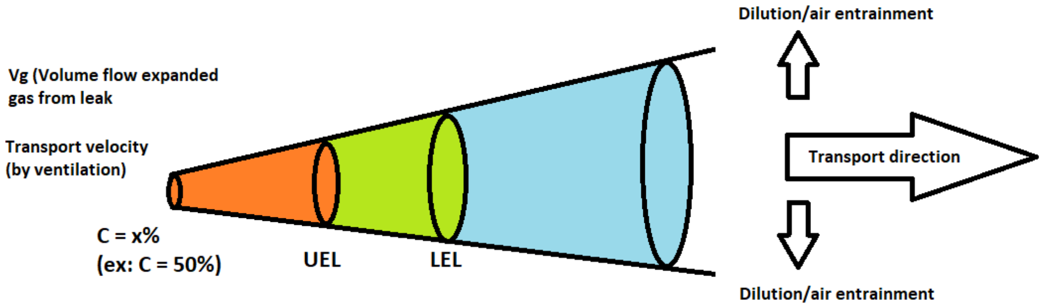


Figure 17: Conceptual model for gas dispersion

Since the transport velocity in this model is constant (and driven by ventilation), the mass of gas per unit length in the transport direction is constant. The mass and volume of gas for any range of gas concentration is identical. The actual shape of the gas cloud is of course different and could in principle be obtained from a coordinate transformation of the idealised cone model.

Example: Velocity is 1 m/s and leak 1 m^3/s. Or, rather, leak rate/velocity = 1 m^2. Density = 1kg/m^3. UEL = 0.15, LEL = 0.05.

Entrainment is modelled with $r = r_0 + a \cdot x$. a = 0.1 is used for entrainment factor in this example. Gas concentration at x=0 is set to 100%. The purpose here is just to show the simplicity of the calculations.

Area(x=0) A_0 = 1 m^3/s / 1 m/s = 1 m^2. Radius(x=0) = $r_0 = \sqrt{\frac{1m^2}{\pi}} = 0.56$m

Area(C=UEL) = $\frac{A_0}{C_{UEL}} = \frac{1}{0.15} = 6.67m^2$

Radius(C=UEL) = $r_{UEL} = \sqrt{\frac{6.67m^2}{\pi}} = 1.46$

$L_{UEL} = \frac{1.46-0.56}{2 \cdot 0.1} = 4.5m$

Volume gas with concentration > UEL: $V = L_{UEL}\frac{\pi}{3}\cdot\left(r_0^2 + r_0\ r_{UEL} + r_{UEL}^2\right) = 15.4m^3$

Area(C=LEL) = $\frac{A_0}{C_{UEL}} = \frac{1}{0.05} = 20m^2$

Radius(C=LEL) = r_{LEL} = 2.52

$L_{LEL} = \frac{2.52-0.56}{2 \cdot 0.1} = 9.79m$

Volume flammable gas: $V = (L_{LEL} - L_{UEL})\frac{\pi}{3}\cdot\left(r_{UEL}^2 + r_{UEL}r_{LEL} + r_{LEL}^2\right) = 67.4m^3$

Flammable gas mass: $mass_{flammable} = (L_{LEL} - L_{UEL})\cdot 1\frac{kg}{m} = 5.3kg$

This is a steady state consideration, and all the flammable gas may not be inside the module. The volumes estimated depend on the air entrainment factor and the transport distance to a ventilation opening. The maximum transient flammable cloud size is calculated with some additional modelling, setting the gas concentration at the outlet to LEL.

There may be objections to the model described above, but a theoretical and simplified dispersion model is required for this model approach to be useful.

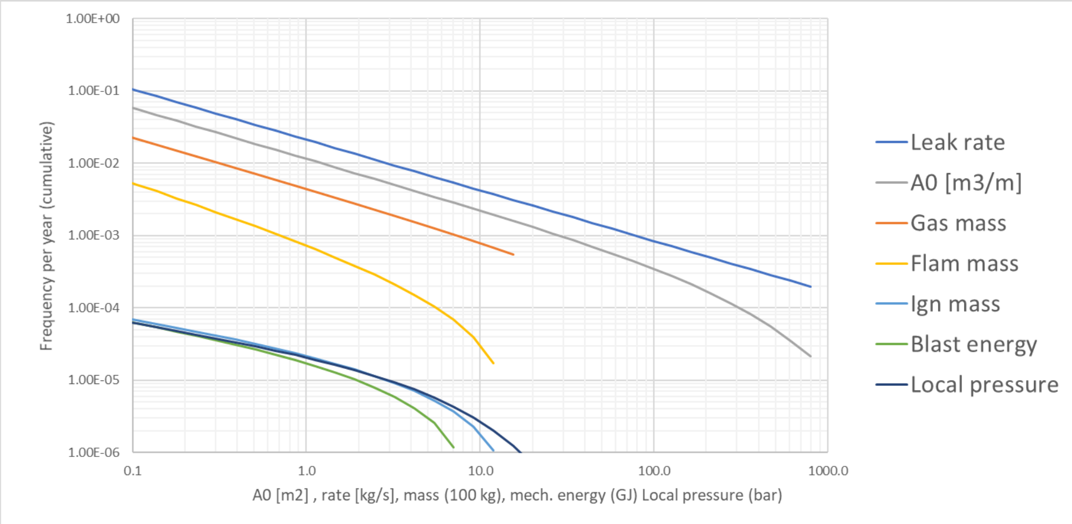


Figure 18: Prototype model results for a real case (module is 44m·40m·8m, average ACH = 261)

5.3.1.3 Use and interpretation of model results

The model proposed here presents explosion loads with corresponding frequencies. The frequency relation demonstrates uncertainty and loads that are possible although considered infrequent, which can be useful for decision support. This is the case even if the accuracy of the presented frequencies could be questioned (and the frequencies may not be interpreted literally as "true" frequencies)

With this in mind, modelling uncertainty is important. In part, this is obtained by the probability distributions Φ_i, which should be designed with care. For explosions in open geometries, it has been observed that explosion loads (near the cloud location) can be modelled using a lognormal distribution, and that the relative standard deviation (σ) is similar from project to project.

5.3.1.4 Documentation and model credibility

Documentation is as important as establishing the methods and models. Convincing arguments and references for the models applied are key to establish model credibility. WG2 recommends writing a short summary of the data and knowledge applied with appropriate references. Uncertainty (and possible lack of knowledge or relevant data) should be included.

6. Comparison and evaluation of the different methods

6.1 Introduction

The different methods described in this report have been compared and evaluated versus the predefined RISP criteria.

The following main categories of methods have been considered:

Table 10 categories of methods evaluated in the RISP project

	Method / model	Description
1	Generic explosion model	An example described in section 5.1 Conceptually described in section 4.3.1
2	Equation based model	An example described in section 5.3 Conceptually described in section 4.3.3. The method does not consider multiple incident/accident development paths upon a set of representative leak scenarios like NORSOK Z-013, but is based on more general relations such as dimensioning load expressed/determined based on mathematical functions.
3a	Scenario based method – single worst credible event scenario	An example described in section 5.2. Conceptually described in section 4.3.2.1. Method based on CFD simulations of one specific scenario, i.e. "worst credible event scenario".
3b	Scenario based method: Simplified NORSOK Z-013 approach – Multiple event scenario based without CFD simulations	Simplified models developed to perform (coarse) NORSOK Z-013 analysis without CFD simulations. May be based on simplified leak picture input. The method considerers multiple incident/accident development paths upon a set of representative leak scenarios
3c	Scenario based method: NORSOK Z-013 approach (current practice) - Multiple event scenario based with CFD simulations	Conceptually very similar to approach 3b but a key difference is whether or not some key input of the model is based on facility specific CFD simulation results.

Common for all approaches is that the output of the method could be used as basis to establish design accidental explosion loads for the facility during design development. Depending on the nature of the method/model, they may be applicable to fulfil other areas of use, for which explosion risk analysis traditionally has had/ or should have played a role in the design development project.

To what degree the method is fit for purpose in order to fulfil other areas of use discussed in section 6.2

Two other important aspects of the different method categories which may illustrate the nuances within the different categories are

- **The basis of which the method is developed upon:** i.e. The models can have a theoretical or empirical basis, and in many cases a mixture.
- **The complexity of the models**: For all practical purposes, the generic explosion model (1) and single scenario-based model (3a) considered in this context are simple methods. An equation-based method (2) may be simple (i.e. Explosion load = f(module volume)), or more complex (i.e. potentially using frequency relations such as the example described in section 5.3 which should at least be considered complex if frequency distribution parameters are determined based on a set of facility specific CFD simulations. From most practical purposes, NORSOK Z-013 methods (3b, 3c) can be considered complex. The reason that method 3b is denoted "simple" is referring to the input interface which is simplified. The model may yet be somewhat complex.

An evaluation of the method towards the RISP criteria is presented in section 6.3.

An evaluation of the methods ability to solve challenges experienced related to current practice is discussed in section 6.4. This section also briefly reflects upon potential new challenges that may be expected if this type of method is introduced.

The additional aspects related to basis and complexity are discussed in the evaluations in section 6.3 and 6.4 when relevant.

6.2 What can the different methods be used for?

As a starting point it is interesting to look into the differences in input requirements and results/outputs from the different methods. This gives a good indication of the differences in potential areas of use. As mentioned in previous section, the complexity within each category may vary, which again may again affect the input requirements.

First, the input requirements of the different method have been compared, see Table 11. The input for the most simple methods and models (1 and simple versions of 2) are limited to the module dimensions and the main characteristics important for the explosion risk picture (e.g. confinement). There is also limited input requirement to method 3b. However, note that in method 3b, there may be a lot of input parameters that are assigned default values.

More advanced equation-based explosion models (2) and simplified NORSOK Z-013 models (3b) may also require or have the possibility to give input on leak frequency, segment inventories/operation conditions and blowdown/ESD. The main difference between these models (2, 3b) and the advanced versions of the NORSOK Z-013 approach (3c) is that the latter require use of CFD.

Table 11: Input requirements of the different methods and models

Input requirements	1. Generic explosion method	2. Equation based model	3a. scenario based model	3b. Simplified NORSOK Z-013 approach	3c. NORSOK Z-013 approach (current practice)
Module dimensions and main characteristics; e.g. confinement	X	X	X	X	X
Leak frequency		(X)		(X)	X
Segment inventories, fluid properties and operating condition		(X)	(X)	(X)	X
Blowdown and ESD		(X)	(X)	(X)	X
Ignition sources / ignition model		(X)		(X)	X
Ventilation / gas dispersion simulations (CFD)		(X)	X		X
Explosion simulations (CFD)		(X)	X		X

Further, the methods have been compared principally based on what kind of output they can provide, ref. Table 12. This gives an indication of the potential areas of application of the method, but not necessarily the suitability of the method for this particular use. For example the NORSOK Z-013 approach produces output results that can be used for conceptual evaluations. However, since the input requirements are e.g. CFD simulations, which are performed on a basis not available in concept phase, NORSOK Z-013 analysis may not be very suitable for this purpose.

The main application of the simplest methods (1 and simple versions of 2) is to set design accidental loads in the project planning phase. Since these methods are based on a quite simple input (module dimensions and main characteristics), they will not be suited to e.g. perform detailed evaluations of effects of design change on the explosion risk picture. The simple equation-based model can be used for conceptual evaluations, depending on how the model is developed.

For a more complex simplified model, based on NORSOK Z-013 principles (3b), the areas of application may increase. Still it is foreseen, that with all the simple models (1-2) it will be required to have additional methods for explosion related analysis in the project planning and execution phase, if the explosion analysis shall provide the same design support to development project as it does today. The additional methods can e.g. be used of design scenarios or probabilistic explosion analysis. In case of the latter alternative, this will be NORSOK Z-013 explosion analysis with a different objective than current practice, i.e. focus on design support rather than DeALs and the quantitative risk level (versus the risk acceptance criteria).

NORSOK Z-013 analysis will in principle be possible to apply for all the different applications listed in Table 12.

Table12: Principle comparison of output from different explosion methods and models

Table legend	Description
✓	Method can be applied for this purpose, i.e. the required kind of output is available Does not necessarily mean that the method is very well suited to this purpose.
(✓)	Method may or may partly be used for this purpose, dependent on how the method will be developed /made, such as level of complexity

Output / Areas of application	1. Generic explosion method	2. Equation based model	3a. scenario based model	3b. Simplified NORSOK Z-013 approach	3c. NORSOK Z-013 approach (current practice)
Conceptual evaluations of explosion risk		(✓)		(✓)	✓
Set design explosion loads	✓	✓	✓	✓	✓
Assess effect of design changes			(✓)	✓	✓
Input to ALARP assessments			(✓)	(✓)	✓
Understanding of explosion risk picture		(✓)		(✓)	✓
Detailing of design explosion loads		(✓)	✓		✓

6.3 Evaluation vs RISP criteria

According to requirements in SoW the RISP explosion method or model:

- shall ensure **the same level of safety**
- shall be based on **best available knowledge**
- theoretical and empirical **basis shall be available for review**
- shall be **transparent**
- must be **traceable**
- shall be **openly available** to the industry

Further, the method or model shall:

- be based on input available in early phase (before DG2)

- avoid late design changes
- give decision support at the right time
- focus on individual decisions
- be based on principles in ISO 17776 (Ref. /4/)
- utilize knowledge and experience in the industry
- give consistent results independent of individual / Company

6.3.1 The same level of safety

The term same level of safety is subject to interpretation.

Evaluations of safety from an explosion analysis point of view depend on perspective. There may be different barrier elements and performance requirements relevant for mitigating catastrophic events than what are relevant with respect to loss of physical barriers. Hence interpretation of level of safety depends for instance on whether the concern is total loss events or if the main concern is loss of barriers.

Arguably, focus traditionally in explosion analyses has tended to be loss of physical barriers / blast walls, since the regulatory requirements have criteria relating to unacceptable frequency for loss of barriers.

When comparing the level of safety in design of future facilities to level of safety for facilities designed in the past, it is also necessary to clarify if the intension is to compare the calculated frequency of escalation or if the intension is to compare what loads the facility is designed to withstand.

Whether a new method will be able to maintain the same level of safety in future design will to a large degree depend on what level of conservatism is incorporated in the method. For all of the methods evaluated, it should to some degree be possible to develop the method either using an optimistic approach or using a conservative approach.

6.3.2 The best available knowledge

Similar to the term "same level of safety" best available knowledge is subject to interpretation.

All categories listed in the introduction to this section may be developed to be based on the best available knowledge. There is another type of categorization that is relevant in this context

- One category is models that are purely empirical equations based on previous explosion analysis results and are using statistical methods such as regression analysis. The knowledge reflected in this type of model will never be better than the limitation in the previous analyses representing the basis for the knowledge.
- A second category is models and methods that are not purely based on analysis results from previous analyses. For these types of methods and models, there will be no limitation to how good or bad knowledge the method may be based upon.

For this reason, the analysis results logged in section 3 should be used during verification and validation of the model developed, but if the basis of the model is limited to this type of database alone it can be argued that the model is not developed based on the best available knowledge.

6.3.3 Theoretical and empirical basis shall be available for review

In principle all the different approaches, including implementations of methods interpreting NORSOK Z-013 analysis, can make the theoretical and empirical basis available for review. The difference is that for the models developed and owned by a Risk Consultant Company, the detailed basis for the model will normally only be available internally in the relevant Company. This is in principle not different from the status of CFD-tools extensively used for risk assessments, none of the consultants or operators performing studies with these CFD-models will have a full insight in the models.

6.3.4 Transparency and traceability

The less complex methods and models can quite easily be made both traceable and transparent.

Generic explosion loads methods (1) which only perform very simple calculations are both transparent and traceable regarding which input parameters result in what design loads.

The same applies for most equation-based models (2). Equations are (mainly) used to calculate the final output such as explosion overpressure vs frequency relation, and the traceability and transparency is potentially good.

A scenario-based method (3a) can fulfil the requirements to traceability and transparency, in particular if there is focus on intermediate reporting of results like ventilation conditions, ignited cloud size distributions and explosion load distributions.

When the complexity increases for the NORSOK Z-013 type models (3b – 3c) which are based on large branch trees or utilize Monte Carlo simulations to reflect the large number of combinations of factors that may affect the consequences of an accidental event, this may reduce the traceability and transparency of the model.

6.3.5 Openly available to industry

A method or model can be openly available to the industry in different ways:

1. Detailed and unambiguous description of the method in a standard e.g. NORSOK Z-013. All users can implement their own spreadsheet / model as required. Because the model is described in an unambiguous way, the results will be consistent independent of Company/person.
2. Free model/software that can be used by the industry. The program is maintained/owned by one Company, e.g. one of the large Risk Consulting companies in Norway.
3. A third alternative could be an open source code, free for download and possible editing. This is not considered very realistic and has obvious weaknesses with regards to securing the quality of the model/software as well as taking care of improvements / maintenance. This alternative is therefore not discussed further.

Both alternative 1 and 2 can be realistic. However, 2 may have some obvious challenges in ensuring that all Risk Consulting Companies will use this model. In addition, financing of the development and maintenance of the model may be a challenge. For alternative 1 it may be a challenge that further development and maintenance may not happen at all, e.g. if a severe error or weakness in the model is identified there may be no obvious mechanisms to sort out the problem so the industry can continue using the model with confidence.

Both the generic explosion model (1) and less complex types of equation-based model (2) can easily be made open available to the industry, e.g. by including the method description in NORSOK Z-013.

6.3.6 Summary of evaluation versus criteria

As seen from the discussion in sections 6.3.1 to 6.3.5 it will to some extent be possible to develop models within all the 5 method categories that will fulfil the criteria relating to available basis for review, transparency, traceability and availability (open to industry).

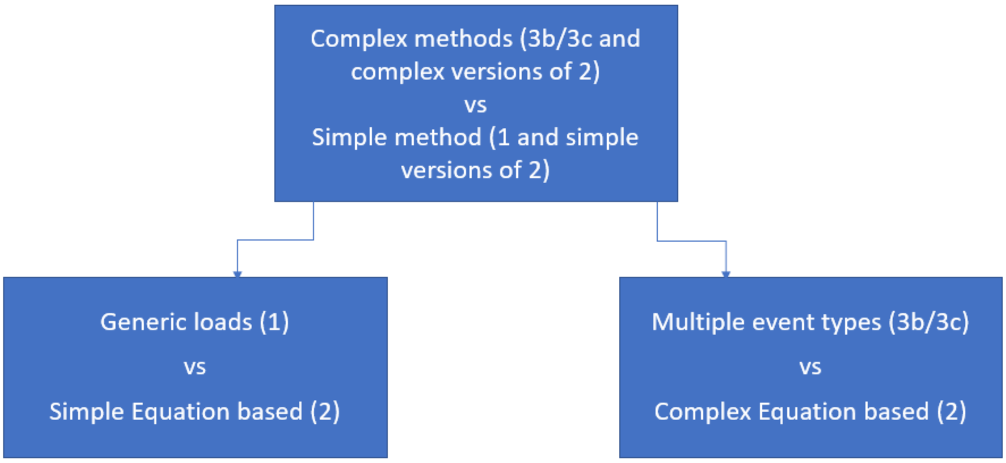
The key features that should be focused on in order to fulfil the criteria are

- Basis: If the model is based on interpolations and regression analysis of output from existing explosion analyses based on to what degree the input corresponds/overlaps with input from previously performed explosion analyses there may be a limitation in order to fulfil criteria relating to **"best available knowledge".** If the model is based upon a combination of theoretical basis from physical laws, thermodynamics, chemistry etc., supported by statistical analysis of historic accident events, and empirically based on laboratory/full scale tests there are no such limitations with respect to "best available knowledge".

- Complexity: With a relatively simple model it will be easier to fulfil the requirement related to transparency and traceability. There is likely to be practical challenges with respect to fulfilling criteria relating to **transparency and traceability** for more complex model types. This is in particular relevant for a detailed NORSOK Z-013 model (3c), but most likely also for simplified NORSOK Z-013 type model (3b) which may also be complex despite a simplified input interface. This may be the case if the model in reality is computationally expensive since it supports much more detailed input than what is available in the standard user interface, but the extra input parameters are assigned default/typical values.
- A key challenge may prove to be how to make the model **open to the industry.** This may also prove more challenging for more complex models.

6.4 Summary: The methods ability to solve current challenges with explosion analyses

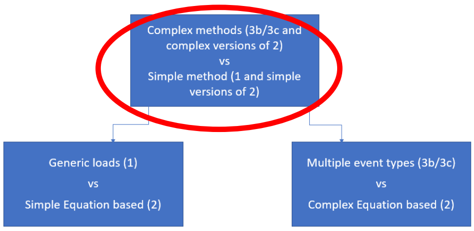
This section compares the different types of methods to give a summary on the differences with respect to fulfilling the requirements to the method. It is also focused on ability to solve challenges with current practice with explosion analysis (as well as generate new challenges). All methods listed in Table 10 are included in the assessment, with one exception. As discussed in the summary in section 7.2, the single scenario based method is not recommended for establishing explosion DeAL. For this reason, the single scenario based method (3a, single worst credible event) is not included in the evaluation presented in this section.



In the following context, a simplified method is defined as a model with a limited set of unambiguous input.

Based on this definition the following methods can be considered simplified:

- Generic loads (1)
- Simple Equation based models (2), which do not include input parameters determined based on subjective evaluations or require interface with other tools/methods, such as CFD tools to fit the parameters



When comparing a simplified method to a more complex method, the following advantages and disadvantages are identified in terms of solving challenges with respect to current practice:

Advantages for simplified methods (versus complex):

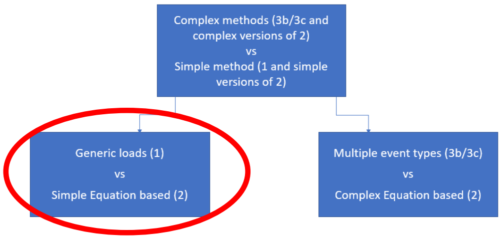
- There will be less subjective interpretations needed to perform modelling, which will ensure that inconsistent results for different companies/persons are avoided, which will reduce the risk of late changes (lower risk of change)
- The input will be available when needed, which will also reduce the risk of late changes
- A leaner process of establishing Design Accidental Explosion loads

In summary, a simplified method may be tailor made in order to be fit for purpose of establishing Design Accidental Explosion loads.

Disadvantages and new challenges that need to be solved for simplified methods (versus complex):

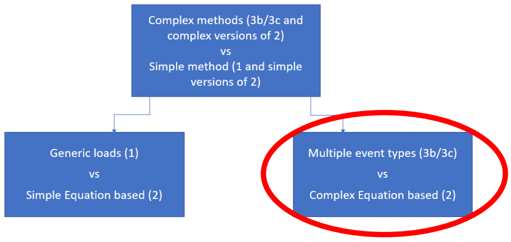
- The chain of events leading to and determining the outcome of an explosion is very complex and sensitive to small details. A simple method will not have the ability to reflect details that may be important in the context of an explosion event.
- A simplified method needs to be **conservative** as well as rely on good practice in design to ensure robust barriers. A simple method may solve challenges related to consistency in use of the explosion model, but it may impact the challenges related to consistency in design practice in other ways.
- The purpose of the simplified method is limited to establishing Design Accidental Loads, and it is not fit for purpose for the other areas that explosion risk analyses are used/ or should be used for. We have a good understanding and can document ability to predict many of the phenomena and relations involved in an explosion risk analysis. Hence, **with a simplified method, we need other methods to be able to provide high quality recommendations regarding optimal design in terms of mitigating explosions and providing input to ensure safe design and operation of oil and gas facilities.** In a more complex model we are to a larger degree able to incorporate this knowledge into the model.
- For the purpose of providing explosion risk based input to ALARP processes, risk management in operation etc. additional methods, tools and/or processes will be required. It is likely that there will be a need for more detailed models to fulfil these needs, such as current Z-013 practice. Design explosion loads defined and followed up based on a simplified method, may in rare cases be lower than dimensioning loads calculated through detailed explosion risk analysis performed in as-built phase or during operation. This potential conflict must be addressed if a simplified method for establishing DeAL is to be further developed.

Next, the two types of simplified methods are compared, generic loads versus simplified equation-based. Generic loads will provide minimum values for Design Accidental Loads. An equation-based model will provide dimensioning accidental loads as input to defining Design Accidental Loads.



Differences between generic loads versus simplified equation-based methods:

- The equation-based model may provide information regarding the robustness of the design in terms of the margin between design accidental loads and dimensioning accidental loads. But this also requires that clear recommendations are developed for the method in terms of determining acceptable margin. If the dimensioning accidental loads provided by the method could be considered conservative, less margin may be accepted. The method development should in any case give clear description of the evaluation of uncertainties.
- If an equation-based method is based on some of the same fundamental assumptions as the PLOFAM/MISOF model, it is likely that the model will provide estimates for smaller areas indicating that there are no dimensioning loads for these areas. This may allow for low or no design accidental loads for these areas. In any case, a simplified equation-based method will be sensitive to the limited set of input parameters reflected by the method. Some combination of input parameters will result in no dimensioning loads, these cases need to be treated with care, since there is likely there will always be some uncertainties related to the fundamental assumptions of the model.



Differences between NORSOK Z-013 approach and a complex equation-based model (includes input parameters determined based on subjective evaluations or requires interface with other tools/methods, such as CFD tools to fit the parameters):

- A complex equation-based model could be developed more transparently, traceable and arguably more robust. An equation-based model may be less suitable for ALARP purposes etc. than a multiple event analysis. The reason for this is that it is possible to extract contributions for a subset of scenarios from a multiple event analysis, and use this to quantify the effect of certain factors, such as wind from a certain direction, failure of an isolation valve etc. In an equation-based model, much of these factors are implicitly reflected in the probability distributions applied in the method. Hence, a somewhat more extensive analysis must be performed to quantify the effect of certain factors. The results should in any case be handled with care due to the uncertainty related to reflecting reliable predictions when quantifying effect of specific changes.

6.5 Overview of main differences

The evaluation of the different methods and models as described in the section 6.2 to 6.4 are aimed summarized in table 13. Further Appendix D is mentioned presenting an Evaluation Protocol for NOROG/RISP Models developed.

Table 13: Overview of main differences

Models compared	Advantages of simple models	Disadvantages of simple models
Simple models (1 and simple version of 2) vs complex models (3b, 3c and complex version of 2)	• Less subjective input/interpretation => reduces risk of inconsistent results & late changes • Input available when needed => reduces risk for late changes • Efficient process to establish DeAL and monitor DeAL • Easier to fulfil the requirement for transparency and traceability • Can easily be made openly available to the industry with method description in NORSOK Z-013	• Areas of application of the model is limited to establishing DeALs (additional methods will be required in addition) • Needs to be conservative • The method will most likely not be applicable to novel / non-standard designs • Due to its simple nature, the model may not be able to reflect details that may be important in the context of an explosion event
Generic loads method (1) vs. simple equation-based model (simple version of 2)	Advantages of Generic loads method	Disadvantages of Generic loads method
	• Provides minimum DeAL directly • The generic loads method will for most cases provide more robust loads than an equation-based model (minimum load of 0.7 bar specified in example in this report) • Will ensure a robust design independently of estimated leak frequency in a module (which might be uncertain at DG2) • May be easier to define the validity envelope of the model and how "as-built" verification shall be performed (to reduce risk for late changes)	• Does not provide dimensioning load, i.e. margin between DiAL and DeAL is default/generic and not specific for the given module. • Does not provide any specific information for the given module • Not currently based on new knowledge such as latest leak frequency and ignition model (PLOFAM and MISOF), but could be adjusted to be • Loads may be too conservative since they do not reflect leak frequency in the module or latest leak frequency / ignition model • Because the loads have to be conservative, the model cannot be used for all designs (some will fall outside the validity envelope)

<table>
<tr><td rowspan="2">Complex equation-based models (complex version of 2) vs NORSOK Z-013 approaches (3b,3c)</td><td>Advantages of Complex equation-based models</td><td>Disadvantages of Complex equation-based models</td></tr>
<tr><td>• More transparent and traceable
• More robust since it is based on general relations instead of scenarios</td><td>• Less suitable for ALARP assessments and assessing design changes</td></tr>
</table>

7. Summary

7.1 Summary by Chapter

Chapter 2 summarizes our knowledge on gas explosion modelling, and key drivers of explosion risk at offshore installations. A more extensive overview can be found in Appendices B and C.

Chapter 3 presents a collection of data from historical explosion risk analyses and designs. The explosion analysis data and explosion design data are collected from 65 different modules or areas from a total of 18 Norwegian offshore facilities.

Chapter 4 has described alternative approaches to explosion risk modelling. These have been categorized according to the type of knowledge and data applied. Another difference will be the level of detail in input, output and the models. These differences will determine the potential areas of use of such models.

Chapter 5 describes some modelling examples to demonstrate how the different modelling approaches in chapter 3 can be materialized in an explosion risk model.

Chapter 6 compares and evaluates the different modelling approaches. The alternative approaches considered are:

1. Generic explosion loads (prescriptive loads per design category)

2. Equation based model (based on more general relations, not multiple events analysis)

3a. Scenario based method (single worst credible event)

3b. Simplified NORSOK Z-013 approach (multiple event analysis, without CFD simulations)

3c. NORSOK Z-013 approach (current practice; multiple events analysis, with CFD simulations)

At this stage no specific approach is recommended. However, the views from different participants in the group are presented in Appendix A.

7.2 Establish DeAL

All the different approaches described in the report could in principle be used to establish design accidental explosion loads.

However, WG2 does not recommend the single scenario based method (3a, single worst credible event) used for this purpose. This is mainly because CFD explosion simulations are required as input with this approach, and the basis for the CFD simulations (i.e. 3D model) is not mature at the time the design loads need to be frozen.

In addition the following arguments support not to use the single scenario based method to establish DeAL:

- There will be a significant spread in results depending on parameter choice (release location/direction, cloud location, ignition location). Many scenarios are required evaluated to get a proper distribution and mapping of possible outcomes. If only a specific set of parameters shall be evaluated in a WCE-assessment, the conclusions may become arbitrary.
- With a scenario-based WCE or dimensioning approach as discussed, the more severe scenarios are not assessed, and there is therefore no insight in the possible consequences from low frequency high consequence events. No insight will then be gained regarding the robustness of the installation to handle the residual risk.

Note that the above only applies for specifying DeAL, the use of design scenarios as decision support, in particular in the detail engineering phase, can be useful if done properly, see section 7.3. It is also considered useful, and required, to transform a DeAL load into typical physical scenarios (examples), in order understand which scenarios the installation is designed to withstand and not (leak size, gas cloud size etc).

7.3 Risk management and other decision support

A simple method should be sufficient to establish DeAL level. However, a simple method will have limitations with regard to providing input to risk management and other explosion risk based decision support.

For a more complex model, based on NORSOK Z-013 principles (3b), the areas of use may increase. Still it is foreseen, that with all the simple models it will be required to have additional methods for explosion related decision support, if the explosion analysis shall provide the same design support to a development project as it does today. The additional methods can e.g. be use of design scenarios or probabilistic explosion analysis, or most likely a combination. In case of the latter alternative, this will be NORSOK Z-013 explosion analysis with a different objective than current practice, i.e. focus on design support rather than DeALs and the quantitative risk level (versus the risk acceptance criteria).

A probabilistic approach (similar to todays practice) may have advantages in FEED phase, as well as in operation of the facility, with respect to sensitivity evaluations and to get some indication of the effect of specific factors. For specific assessments such as in detailed engineering phase when the design to a large extent is frozen, it seems advantageous to develop design events.

It is important that the further development of a RISP explosion risk method/model also takes into account the role in the risk management process and how other type of decision support shall be provided.

8. Way forward

One of the objectives of the work to be carried out by Workgroup 2 was to make recommendations for further work, i.e. a recommended way forward. Workgroup 2 however did not manage to make a single unified recommendation. Recommendations suggested by members of the Workgroup 2 have however been presented in Appendix A of this report.

9. References

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Appendix A

Recommendations regarding further work

Recommendations suggested by members of the Workgroup 2 are presented below.

Lloyd's Register

Memo

JIP: Risk informed decision support in development projects (RISP)			
To:	Aker Solutions	**Cc:**	
From:	Linda Fløttum (AkerSolutions), Jens Johansson Garstad (DNVGL), Olav Roald Hansen (Lloyd's Register Consulting), Jo Wiklund (Lilleaker Consulting) and Kees van Wingerden (Gexcon)	**Date:**	10 March 2019
Project no:	**Error! Unknown document property name.**		

1 Way forward

It has been a wish from the RISP project that WG2 should develop tools that RISP partners could use for early explosion assessments to establish minimum recommended design accidental explosion loads for future platform modules.

The expectations among the RISP partners have been very high, there has been spread/variation in expectation among them. It has been very clear that not all expectations have been realistic.

Due to the challenging task, and different experience backgrounds, opinions have not been fully aligned within the WG2 explosion expert group.

As a consequence of the above the RISP steering committee has asked the various WG2 members for their opinions regarding the way forward, in this memo some opinions of Olav Roald Hansen, Lloyd's Register, are presented.

1.1 Generic model

For the most basic category of models, Generic Explosion Models, this has been feasible to develop and a draft prototype model has been described in WG2 report. Rather than categorizing the modules by several parameters like volume, aspect ratio and open sides, which would likely lead to significant variation in required minimum design load within each category, a simple approach based on dimensionless vent coefficient Kv and dimension restrictions has been proposed.

By quick hand calculations or the use of a simple spreadsheet, see layout of draft version in Figure 1, a recommended local minimum design pressure is estimated primarily based on module dimensions and confinement. It could also be possible to estimate further parameters like drag loads and global pressure loads. The model has been preliminary checked against the design loads for the 65 platform modules collected as part of the WG2 work, and seems to nicely bound this population, see Figure 2. This is a wanted behaviour of the model, if such a simple model shall recommend robust design loads for all possible module concepts for which it is defined valid, higher design loads than necessary will be recommended for a significant fraction of possible modules. If a more accurate design load prediction is required for such platform modules an explosion model with more input parameters and phenomena modelling will be required.

The proposed way forward for the Generic Explosion Model will be that the model is tested by RISP partners and also undergoes a proposed validation/evaluation exercise as described in the appendices of the RISP WG2 report. Thereafter the model can be finalized, possibly with some adjustments based on feedback and validation. Due to the generic and simple nature of the model it can be distributed and published without limitations.

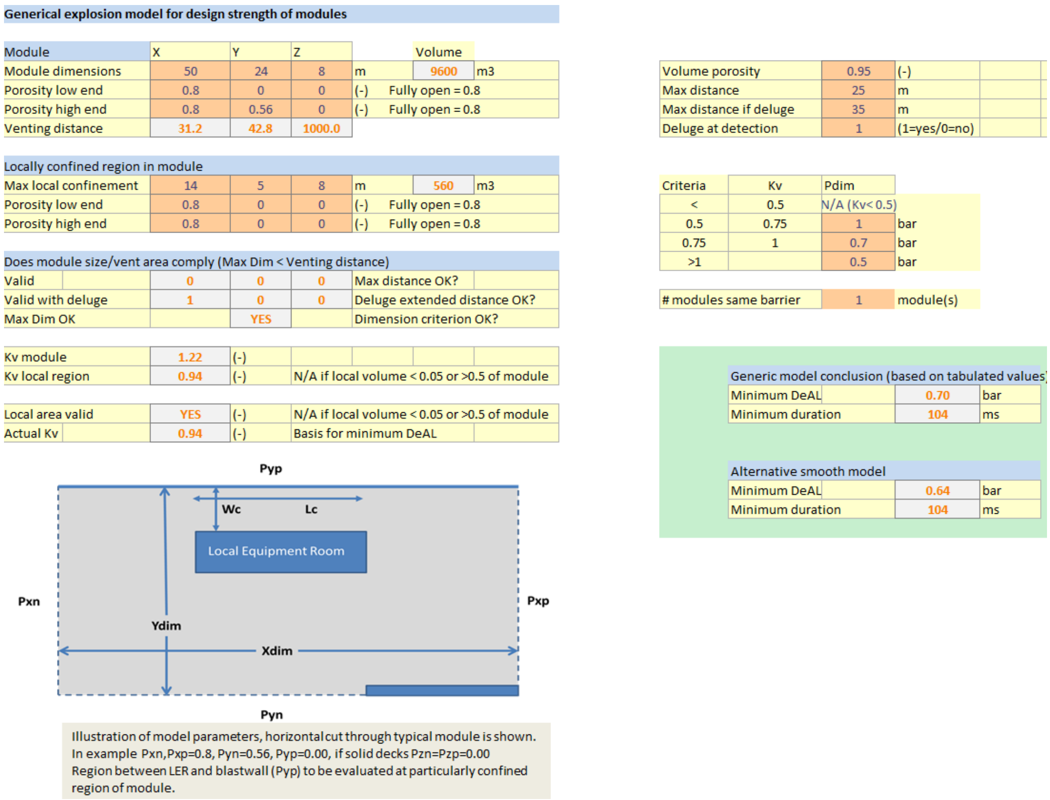

Figure 1 Draft worksheet for Generic Explosion Model Prototype. Input cells are in orange. Results are found in the green area, the upper result lines give either "Not Applicable", 0.5 bar, 0.7 bar or 1.0 bar, while the lower output gives an estimated design load above 0.5 bar according to a smooth model. In all cases pressure duration is given. In the WG2 report only "N/A", 0.7 and 1.0 bar output categories were provided and no duration.

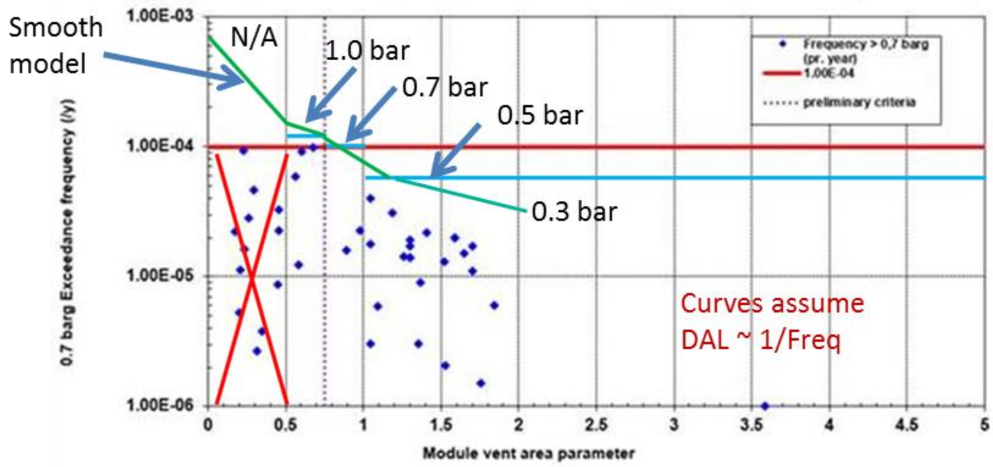

Figure 2 Generic Model is compared example platform design loads (blue dots). Plot shows frequency for exceeding 0.7 bar as function of vent parameter. Smooth model version is shown in the green line, while stepped version (0.5, 0.7, 1.0 bar) is shown with light blue horizontal lines. The goal of the generic model is to envelope (be above) the dataset.

1.2 Simplified NORSOK Z-013 models (and equation based models)

The model category I have personally concluded to be most promising as a RISP early design models is the Simplified NORSOK Z-013 models. Equation based models, like discussed and illustrated in the RISP WG2 report, which follow the chain of event from a release through gas cloud formation, ignition and explosion is considered to below to the same category.

This category of models generally predicts explosion load frequency of exceedance curves after estimating consequences of numerous release scenarios, each with a frequency, predicting flammable cloud developments, ignition probabilities and explosion loads. Compared to traditional best practice NORSOK Z-013 studies these models estimate ventilation, dispersion and explosion consequences without the use of CFD-models, and will thus provide answers (and intermediate answers) within moments. The various submodels for a given model are generally developed with inspiration from analytical phenomena models, best practice models (e.g. leak/ignition models), experimental knowledge and experience from previous detailed risk assessments. The input parameters and degree of details modelled can vary among the models. The models of this category are therefore highly non-homogeneous and a significant scatter in predicted minimum design loads can be expected.

In Figure 3 some example validation plots from a LR simplified NORSOK-model under development is shown. The validation against CFD-studies shows that quite decent results can be achieved both for ventilation, dispersion and explosion. Pressure exceedance curves for local deck pressure, global deck pressure and local drag, are also promising. Before it could become a RISP model candidate the MISOF ignition model should be implemented, as well as more automatic way to evaluate multiple scenarios, each with a frequency. Currently the tool is used inside a risk based inspection software, and the looping-function in the stand-alone tool has not been required.

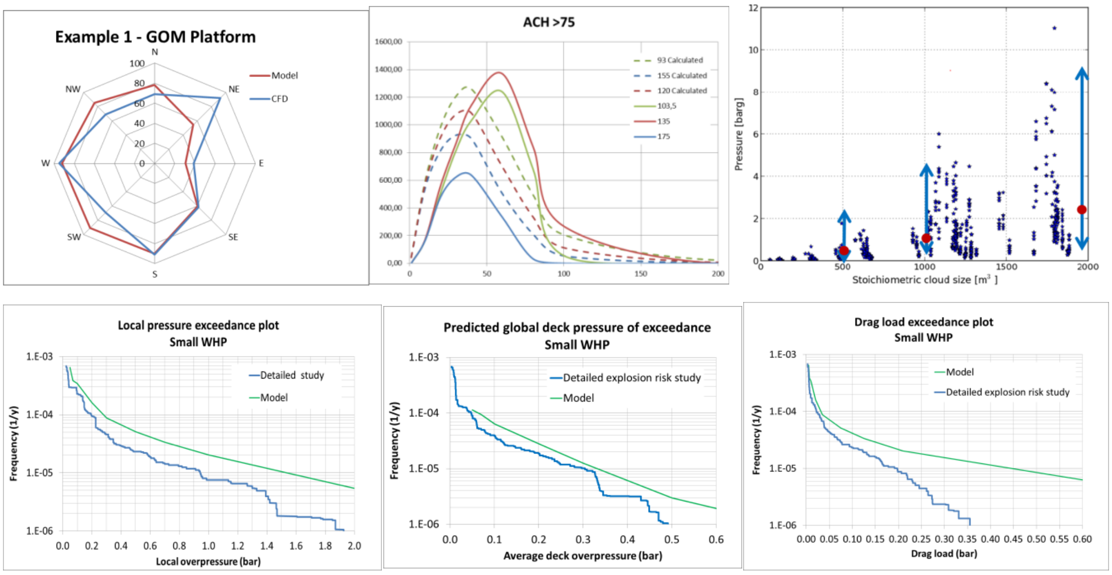

Figure 3 Example validation CFD versus Simplified NORSOK model LR, ventilation pattern (upper left), transient gas cloud sizes (upper centre), predicted explosion pressures (upper right), pressure exceedance curve for local panel, global panel and drag (lower left, centre and right).

A quite significant effort has been, and still is, invested in the current models of this category, and investments will be required to maintain and improve the models in the years to come. To develop such rather complex models numerous decisions and model optimizations must be done and it is likely not feasible to develop or maintain such a tool within a consortium of experts from different organizations like WG2. Instead the following approach is proposed to establish one or more explosion prediction tools for RISP.

1 RISP project should invite anybody to nominate potential early explosion tools for evaluation. The tools shall be stand-alone tools that could be made available to NOROG members through annual licensing. In the nomination process a simple model description (maximum 5-10 pages) should be submitted, describing model inputs, modelling approach/basis for models, validation status, compliance with RISP-requirements, suitability as RISP tool, and considerations about model licensing concept (tool distribution and license fee concept). The proposed Model Nomination Template is described in WG2-report appendix and shows expected content of the Model Nomination Report.

2 The nominated tool description goes through a screening evaluation by RISP and/or experts appointed by RISP, and some of the proposed models are invited for further evaluation by RISP. The model owner must then make the tool, with sufficiently detailed user guidance, temporarily available to selected persons within RISP (or appointed by RISP) for evaluation.

3 The model owner must thereafter perform the validation and evaluation tests specified in the RISP Model Evaluation Protocol, see proposed content in WG2-report Appendix, and submit a validation report to RISP-project. The use of potential input parameters beyond what is clearly defined in model user guidance must be justified.

4 An evaluation committee appointed by RISP-project, with temporary access to the tool and the validation report, will thereafter evaluate the nominated tool description and validation performance. Based on this it is concluded to what extent the tool fulfils RISP-tool requirements and is considered to give reasonable and robust design advice. This evaluation shall both consider the input provided by the model owner, but also independently assess user dependency of the tool and to what extent input parameter variations are considered to give expected trends. The evaluation committee shall issue a formal evaluation with recommendations regarding suitability. This evaluation shall also as clearly as feasible indicate main shortcomings/weaknesses of a model preventing it from being concluded suitable as a RISP tool. If these aspects will be clearly improved, RISP-project may at a later stage consider to re-evaluate the model.

It is foreseen that the preparation and nomination of the various models will be done at the cost of the model owners. RISP project may decide to compensate model owners for participating in Step 2 and 3, and should compensate potential experts outside RISP to contribute to Step 4.

The explosion models with a positive evaluation after Step 4 may be candidates to become a RISP model endorsed by the project and the RISP WG2. The owner of any candidate model should be prepared under confidentiality to describe model details to RISP partners or appointed experts that wish to understand the underlying algorithms of the modelling.

If several tools receive a favourable evaluation, RISP project will have to conclude whether to endorse one model as a preferred RISP-model or to do so for more than one model. RISP project must also consider whether to negotiate joint terms and conditions for its partners for annual lease agreements for one or more models. If a model is endorsed, but functionality could be strongly enhanced by some further model refinement/development then RISP-project and the model owner should discuss how this development may be funded.

1.3 Final words

Personally I believe that very good early design studies could be performed efficiently by competent consultants using CFD. But this would require that the industry did an effort to stimulate to knowledge development and awarding competence and skills. When projects with few exceptions are won by the bidder with the lowest price, not by the most competent groups, it is difficult to achieve a situation with very skilled CFD-teams which can deliver good results in time for FEED-decisions.

One other aspect that has been missing since 2001 is benchmarking of consultants. Since the Holen (2001) study little has been done from the industry. As a result of this, lots of methods have not been improved enough over the past decades, and we are in the situation we are with possible increasing scatter among the results from various consultants. If the industry wants a better control of competence and continuous improvements, they need to invest in benchmarking exercises and guide the consultants to become more competent.

DNV GL and Aker Solutions

TECHNICAL NOTE					
			Pages :1 of 7		
Classification:					
Project: **Risk Informed Decision Support to development Projects (RISP)** Title: **RISP Explosion WG2: Concluding remarks and proposed way forward**					
Issued for information	01	05.02.2019	Jens Garstad (DNV GL) Linda Fløttum (Aker Solutions)	NA	NA

1. Introduction

This technical note describes the suggested way forward for development of a framework for explosion risk based support to development projects, based on the views of the WG2 participants from DNV GL and Aker Solutions.
The background for the suggested way forward is that:

- We believe that challenges related to today's explosion analysis are related to the limitation in our ability to accurately and consistently predict explosion loads with a low frequency of occurrence for a particular facility. In particular, when the Design Accidental Load (DeAL) are to be established many years before the facility is put in operation, lack of consistency and confidence of calculating a load with a frequency less than 1E-4 per year result in significant project risk.
- There are extensive knowledge and capacity within the industry related to understanding many of the phenomena and relations that influence the explosion risk picture. It is critical to utilize this to provide decision support and input to the risk management process of upcoming projects, to enhance low risk design development and ensure safe facilities.

2. Main requirements to the new method/model

In our opinion, the quite "openly" defined scope for a RISP explosion model in SOW has been one of the reasons why the work group has not been able to find a common conclusion for a way forward. Examples of some main questions that should be agreed before starting the further work are:

1. Are consistent results between the different Companies/persons a requirement?
2. Is it considered feasible to develop one software which is common for the whole industry? Ownership and commercial aspects?
3. Or is it a more realistic approach to provide an unambiguous description in a standard/guideline?
4. Shall the design loads be based on a probabilistic approach, i.e. involving frequency (directly or indirectly)?
5. What does the same level of safety mean?
    a. Shall the method or model provide design loads in line with practice in historical designs? (and historical explosion analysis)
    b. Or shall the method or model provide design loads according to the latest leak frequency and ignition model?

Some type of models may be ruled out depending on the answers. E.g. if the answer to question 3 is yes, this may rule out the more complex models such as simplified NORSOK Z-013 approach.
Our proposed way forward is based on the following:

- The method/model shall provide consistent results for different persons/Companies
- The model shall be possible to unambiguously describe in a standard/guideline
- The design loads shall be based on a probabilistic approach
- The method and model shall provide design loads in line with historical designs (but risk model can be based on latest leak frequency & ignition model)

3. Recommended method and way forward

It is recommended to develop a new / alternative stand-alone approach with purpose of develop basis for establish and monitor explosion DeAL level, as discussed in section 3.1 below.

In addition, it is recommended to either develop stand-alone methods or/and adapt and improve existing framework to be more fit for purpose of providing explosion risk-based input to the design development project (Risk management and other decision support). This is discussed further in 3.2 below.

3.1 Establish DeAL

In order to improve the process of establishing explosion DeAL in design development compared to todays practice, it is considered crucial to have one common model or method which is used by all relevant parties in the Norwegian oil and gas industry.

It is recommended one of the following methods to establish explosion DeAL:

1. **Generic explosion loads** (different types of conventional design categories are defined, and prescriptive loads applied per type). DeAL (or minimum DeAL) is defined directly.
2. **Simple equation based explosion model** where input can be uniquely and unambiguously described. Output is an explosion load vs exceedance frequency curve. Clear guide lines must be in place to suggest DeAL based on the frequency vs load curve.

Conceptually, the methods are very similar, and can be further developed in combination. The best version of a simplified model for DeAL is likely to be achieved in a combination of the two methods. In this case, an explosion load–frequency relation is calculated from the simple model, and in addition minimum DeAL is recommended (based on the principle of the generic explosion load method).

The following should be taken into account when developing the method /model further:

- The method /model needs to be simple and unambiguously defined in order to be consistently implemented to all relevant consultant companies /parties.
- The method / model shall be based on few input parameters, such as module dimensions, confinement, presence of strong ignition sources and potentially leak frequency, typical segment inventories and congestion level.
- The method/model shall not include user influenced parameters (tuning of results etc.)
- The method/model shall not depend on CFD simulations as input.
- If leak frequency shall be included in the model this is recommended to be an input parameter, not an integrated part of the model. Guidance on typical leak frequency per square meter or volume could be included.
- The DeAL proposed with the method should be conservative. The equation based model will be based on a limited set of key parameters. As explosion risk may also sensitive to small details related to the design that is not possible to reflect with a simple model, conservative DeAL levels is recommended.
- Recommended minimum DeALs should be provided as part of the method /model. Alternatively, a detailed guideline on how to establish DeAL based on the frequency vs load curve must be provided.
- A multidisciplinary evaluation should be carried out to define what DeAL level is cost driving from a structural perspective, per type of area and type of equipment/structure. This should be used as input to defining minimum DeAL or as input to generic loads method (DeAL levels).
- The method/model could have a theoretical or an empirical basis, but most likely a combination.
- Independent of whether model 1 or 2 is chosen or a combination of the two, the validity envelope need to be further developed, including the method to monitor that the design is within the validity envelope during all design phases and finally to verify design at as built stage.
- Further, also independent of method chosen, a guideline on how to establish DeAL for areas/modules outside the validity envelope needs to be established.
- Independent of model chosen, the model need to be validated. The basis for validation (e.g. existing designs) need to be established.
- The further development of the method/model is recommended by involvement of oil companies, engineering companies and all the different main risk consultant companies. Involvement in all the stages of development is recommended (not only to validate a model).
- The simple method will only provide general area DeAL, such as global and local load for walls and decks in general per area, and general drag loads to pipe systems per area. Additional guidelines must be in place in order to refine DeALs to specific packages, systems or units; reflecting the shapes/sizes of the respective units, criticality/damage criteria and possibly reflect locations where general area DeAL is not covering or relevant. The need to develop these guidelines illustrate the bridge towards next section 3.2 related to need for other explosion risk related decision support apart from establish DeAL.

3.2 Risk management and other decision support

As discussed above, a simple method should be sufficient to establish DeAL level. However, a simple method will have limitations with regards to providing input to Risk management and other explosion risk based decision support. This is illustrated in Figure 1.

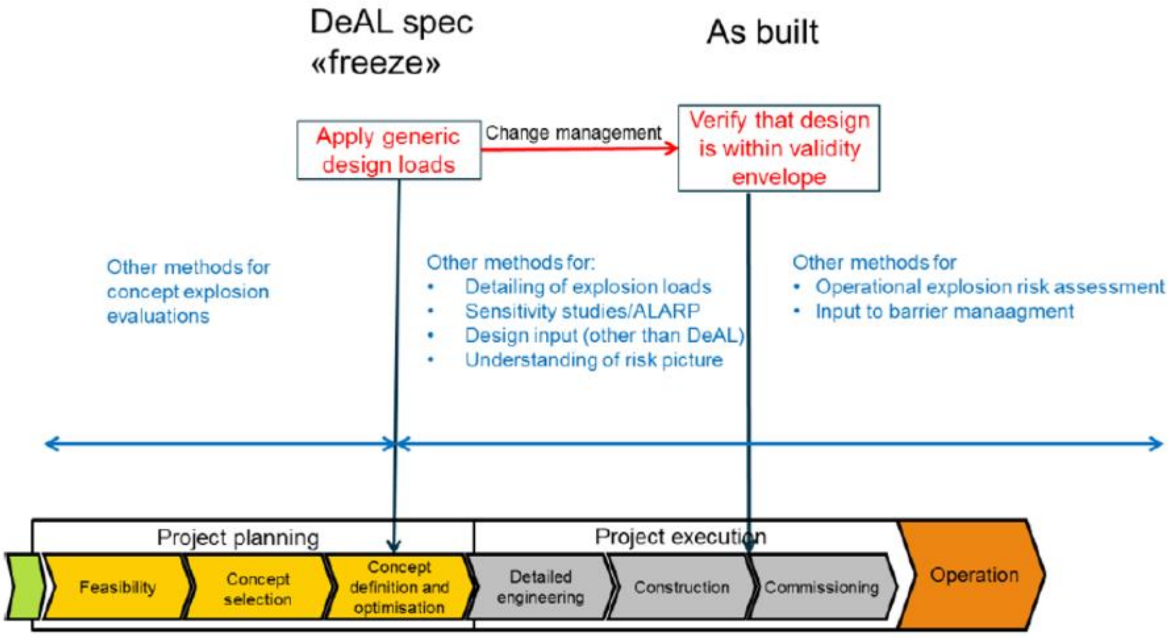

Figure 1 Ideal role and purpose of explosion risk analysis during development project sorted on a frame work suggested for RISP "generic explosion load" method

It is crucial that the way forward takes into account the role in the risk management process and how other decision support shall be provided:

- A flexible and suitable frame work of processes, methods and tools for risk management and other decision support related to explosion risk is very extensive. It is recommended that the methods for other decision support should to a large degree as possible use existing frame work, rather than create new advanced methods and models from scratch.
- Much of the input needed may be provided by current probabilistic frame work (i.e. NORSOK Z-013 annex G). Making explosion analysis fit for purpose will in many cases be achieved by adapt/improve the process and the way the tools and methods are used, as well as criteria fit for purpose.
- A probabilistic approach (similar to todays practice) may have advantages in FEED phase, as well as in operation of the facility, with respect to sensitivity evaluations and get some indication of the effect of specific factors. An advantage with the probabilistic approach is that it estimates the total result of several effects. E.g. reducing the ventilation area of a module, may both increase the gas cloud size for a given leak and in addition increase the resulting explosion load for a given gas cloud size.
- When assessing robustness of the design accidental loads the probabilistic approach may give an indication. A challenge may be that if applying a detailed probabilistic analysis for different purposes than DeAL, the calculated frequency for exceeding the DeAL may in a few cases be in conflict with a DeAL established with a simplified approach. Experts, stakeholder and authorities much trust the DeAL established based on simple principles and key drivers.
- For specific assessments such as in detailed engineering phase when the design to a large extent is frozen, it seems advantageous to develop design events fit for purpose of tuning the design parameters still not fixed. Aspects of the single scenario models may be used.

Lilleaker Consulting

Technical Note

To:	**Kees van Wingerden**				
Copy:					
From:	**Tien-Yun Lee-Johannessen, Jo Wiklund**				
Doc. No.:	**LaC-P0605-N-0009**		**01**		**17.01.2019**
Subject:	RISP discussion and way forward				

1. RISP discussion and way forward

1.1 Summary

This document summarises Lilleaker Consulting's views on explosion risk analysis (ERA) as part of RISP (Risk informed decision support in development projects). This note is a supplement to the main report WG2 - explosion and should be read in conjunction with that report.

In this note we briefly share our views on NORSOK and CFD based ERAs. We argue that a simpler (and more transparent) model could in many ways be preferable for establishing design explosion loads. Further, we explain why a model for risk quantification and a method for setting design loads should be kept separate.

It is important that an unambiguous scope without conflicting requirements is applied as a basis for the specification of an ERA tool to be used in a RISP context. This document describes Lilleaker Consulting's proposed way forward, including:

- Proposed specification and possible modelling approach
- Evaluation of alternative modelling approaches

The proposed model is not mature, but a solid framework as a starting point of further development. Such a model is not expected to replace CFD simulations, but rather allowing more resources for CFD to be better used in decision support.

1.2Confidence in "state of the art" ERA

Currently, probabilistic explosion modelling in line with the guidelines in NORSOK Z-013 is used to quantify explosion risk. These models are practically always used to establish as-built documentation. In early phase assessments, these probabilistic analyses are sometimes used as a basis for selecting design accidental loads.

The NORSOK approach is laborious and lots of geometry modelling and CFD simulations are carried out. Resources spent on this are significant (manhours and computing time). The resulting ERA is voluminous and includes modelling assumptions, input data, intermediate results and result presentation. Still, by experience, we know these analyses are hardly verifiable.

There are several sources to uncertainty in these results. Opinions on the main drivers to uncertainty may differ, but analysts agree that results are very sensitive to several aspects of inputs and calculation steps involved. Part models commonly mentions as important contributors to uncertainty[4] in explosion risk quantification include the following three steps:

- Gas dispersion modelling
- Ignition modelling
- Gas explosion modelling

Standardization of the modelling steps ("PLOFAM" for loss of containment, "MISOF" for ignition modelling, targets for congestion in geometry models, standard gas cloud shapes, etc.) has been introduced to improve consistency. Still, it is our impression that the NORSOK based explosion tools have trouble to accurately measure and quantify gas explosion risk. Analysts consider a simulation results as stochastic and therefore simulate many scenarios to reduce stochastic uncertainty. Our experience is that only some aspects of uncertainty are reduced through numerous simulations and that overall uncertainty is essentially preserved.

Despite extensive efforts invested in modelling and CFD simulations, it is our opinion that the risk level is not really known with satisfactory accuracy. It is interesting to note that the confidence in ERA results varies among analysts as well as among other stakeholders. We will consider alternative ways forward assuming confidence in the detailed and complex analyses is unsatisfactory even when CFD simulations are applied extensively.

One option could be replacing risk quantification (and probabilistic methods) with prescriptive rules and methods. However, any such methods or ruleset must be based on either analysis, experience or guesswork. With limited experience available (or at least few gas explosions), analysis is preferred choice. After all, knowledge of explosion risk is the only rational basis for assessing the value of alternative explosion risk mitigating measures.

Could a simple model be feasible as basis for setting design explosion loads?
An emerging question is, considering the limitations and costs involved in a detailed ERA, could simple probabilistic analyses replace the complex NORSOK models for explosion risk quantification? The spontaneous answer to this question from the other analysts in WG2 has been "no, it can't be done". We would like to challenge this view.

1.3 Proposed specification and a possible way forward

Before a simple model can be formulated it is important to agree on the purpose and requirements to such a model, and to make sure these are unambiguous and not conflicting. In the following we discuss a way forward based on a proposed set of requirements.

The calculation model is limited to the analysis of physical explosion effects and frequencies. This is considered input to another process to define design explosion loads. These two processes are of different nature and should therefore be kept separate, see illustration. (See also WG1 report App A with ref to NORSOK Ch 5.6))

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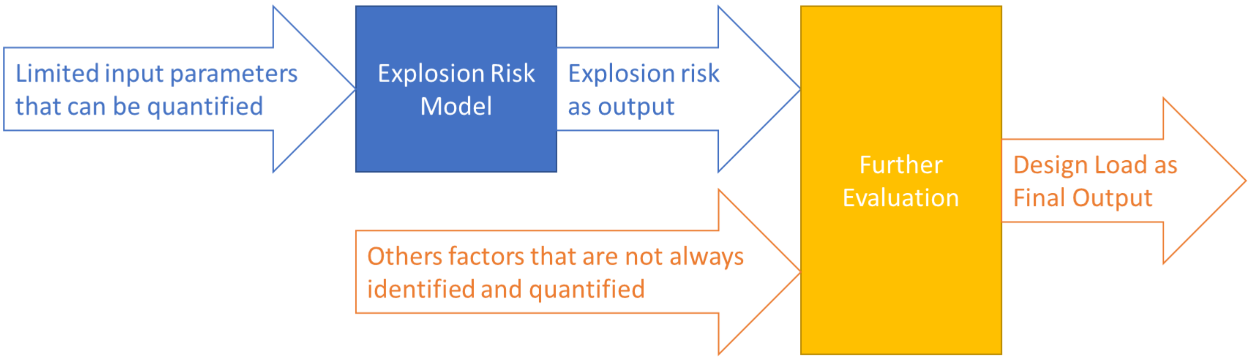
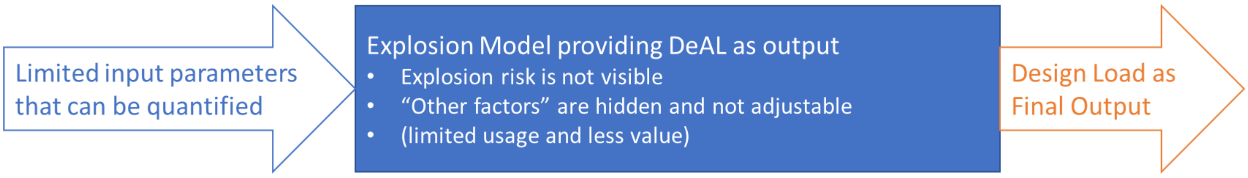
4 The term «uncertainty» is here used to describe variability or lack of consistency, and not as in "new" definition of risk as a function of uncertainty and related consequences





A proposed (example) set of further requirements are listed in the following.

1) The model should be transparent and not unnecessarily complex (i.e. a verifiable model that also can be shared as a free download)
2) Physical phenomena are reflected such that some sensitivities (ref. WG1 App A with reference to Ch 6 in NORSOK: *Describe key design parameters influencing explosion risk*) can be performed and the result explained/understood. Parameters include
    a. Module dimensions
    b. Confinement
    c. Congestion
    d. Gas properties
    e. Inventory (See WG1 report Appendix A)
3) The best available knowledge on generic leak picture and ignition probability should be reflected (PLOFAM and MISOF). WG1, App A: *Support decision on compact flanges and installation flanges.*
4) CFD simulation is not part of the model. However, it should be possible to apply CFD to improve modelling steps (as basis for parameters)
5) The output of the model shall be explosion consequences or loads with corresponding frequencies (an explosion risk picture).
6) Calculation time should be short (seconds) to facilitate sensitivity studies.
7) (Debatable): Model should be possible to tune (more or less conservative). This to be more consistent with existing analysis results (previous studies) to ensure "same level of safety"

1.4 Analysis and conclusion

For the sake of this discussion, an explosion risk analysis can be simplified to consider one specific outcome: Will a strong explosion (defined as a blast exceeding the design loads) occur during the lifetime of the installation.

The probability for a strong explosion to occur is a function of several parameters, including the chosen design explosion loads. The quantified frequency for blast load as a function of design explosion loads is therefore a very useful result. This relation is superior to just a frequency since sensitivities are readily available (the expected effect on frequency from increased design loads, or the effect on the loads if a different frequency is considered). In addition, the sensitivity to other key governing parameters should also be available, and the model should be suitable as a basis for understanding and communicating explosion risk.

With the proposed set of requirements and the brief analysis above, it seems to us a phenomenological (theory based and analytical) model would be the preferred choice for ERA in a RISP context. The model is coarse, and results will be reasonably robust to design development. Also important, results will be more repeatable than is the case for a NORSOK Z-013 type ERA. We therefore think a well formulated coarse model will have better precision (and repeatability) without compromising accuracy as compared to a more detailed model.

Lilleaker Consulting does not expect such a model to replace CFD simulations at large, since there will be many issues where CFD will be the most suitable tool for analysis. This will include changes and modification of layout and arrangement, verification of gas detection system, potential for exposure of (external) ignition sources and more. CFD has a great strength in the mentioned types of study, however, we often don't have enough resources for these in the projects. Simplified ERA could save time and ease this problem, and this is a side-effect that is wanted as part of the RISP initiative. Provided we are confident in using the simpler model for explosion risk analysis, we do not find it valuable to perform an ERA in line with NORSOK as a validation of as-built verification of design loads. CFD simulations and equipment counts can however be applied during project development and as part of as-built verification to check (or improve) some of the relations applied in the model.

1.5 Evaluation of alternative model formulations

1.5.1 Worst Credible Design Events (WCDE)

WG1: *Can [explosion risk] follow up using defined WCDE combined with recognized CFD tools be more effectively applied?*

A model can be formulated that provides a WCDE or a set of WCDEs as output. The difficulties with a CFD model is that the results are very sensitive to geometry modelling. Even for an as-built geometry, it is hard to make a perfect representation. Results will therefore vary, even if CFD analysts simulate many scenarios to control the randomness in results. So, this approach will have many of the same challenges as a NORSOK Z-013 ERA.

1.5.2 Generic load model based on performed analyses

Results from a set of performed analyses were collected as part of the WG2 work. The results showed huge variation and there were weak relations between for example module volume and explosion risk, or between module ventilation and explosion risk. Other factors may have been more important, but the study did not identify these. We see limited use of these data as a basis for ERA. It has been proposed to use the cases at the tail of the distribution (worst credible?) as basis for a rule of thumb model for establishing design accidental loads. This may be a convenient way to set these loads (and obtain same level of safety), but the model will to a large extent be a black box, and the basis for the loads will not be the best available knowledge.

1.5.3 CFD simulation for systematic variation of parameters as basis for a simple model

This alternative is a suggestion from the NOROG workgroup. We find this alternative more appealing than using performed studies, since the variations can be better controlled. For example, the effect of changed natural ventilation can be more reliably reflected and modelled. This approach will better facilitate use of the best available knowledge, and it can be much more transparent than a model based on performed analyses.

The approach has the disadvantages inherent to CFD analyses (i.e. dependence of geometry modelling and randomness in result for individual cases). The geometry model and performed simulations can be open and available for review. The effect of for example new versions of the CFD tools can be investigated and documented.

This approach can also be combined with (or support the validity of) a model that is more theory based analytical model.

Gexcon

TECHNICAL NOTE

Way Forward

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1. Introduction

In the report three main modelling approaches have been defined:

- Equation-based methods
  - Empirical
  - Theoretical
- Scenario-based methods
  - Single event
  - Multiple event
- Generic explosion methods
  - Single reference module
  - Catalogue of standard modules

2. Explosion events

Explosion loads are the result of a sequence of events where each of these are influenced by many factors. The event starts with a release following by a dispersion process where the flammable material mixes with air resulting in a flammable cloud. Next ignition of this flammable cloud occurs resulting in a combustion event, often an explosion.

A release is probably best described by a rate with which gas, vapour or mist is being released into the atmosphere and the associated fluid dynamic disturbance of the atmosphere. Additional but not less important is the development of this release in time.
Important factors influencing the release are therefore the pressure of the releasing substance inside the reservoir, its temperature, its aggregation state and the hole size. Additional factors include the shape of the point of release (flange seal, hole in pipe, etc.), its direct environment (in case of pressurized release; impinging jet) and its direction (in case of a pressurized release). The direct environment can be a wall or deck or congestion (equipment) resulting in jets from pressurized releases impinging and losing momentum. Flammable liquids may cause a mist in case of a pressurized release or a vapour in case of evaporation (diffusive release). The inventory and any mitigation actions upon a release (activated by gas detectors) determines how the release develops in time.
The probability of a release of a certain size depends on the design of the installation, its age, its maintenance and its operation (human factor).

The dispersion process is closely related to the momentum due to the release (in case of pressurized releases) causing mixing with air and the ventilation. The turbulence caused by the release itself causes this mixing which makes it also dependent on the hole size. In case of an impinging jet the mixing/dilution of air is strongly reduced affecting therefore the dispersion process. The ventilation dilutes the gas/vapour/mist cloud, I,e, reducing the concentration. This can cause parts of the cloud which have a concentration higher than the upper explosion limit to become flammable and parts that are flammable drop below the lower explosion limit. In case of natural ventilation the wind speed and the wind direction (in combination with the geometrical aspects of the installation: walls, decks, equipment/congestion density)) and its variation will determine the ventilation in time and in space.

The probability of a certain cloud (size, shape) arising depends on probability aspects related to the release including its direction, its location and possibility of impinging. The wind (direction and speed) is the second factor affecting the probabilistic aspects of the dispersion process.

The ignition source will affect explosions because of its location and moment of becoming effective. The probability of ignition depends on its being present, the incendivity of the ignition source itself and the local concentration of the gas/vapour/mist cloud. Ignition sources can be hot surfaces, electric sparks, electrostatic sparks and discharges, mechanical sparks, open flames etc. Choice of equipment, hot work operations, maintenance and ignition control measures (again depending on gas detection) are contributing factors determining the ignition probability.

The strength of the explosion is directly related to geometrical aspects: congestion density, dimensions of the congested area, degree of confinement and in addition to that the size of the cloud within the congested area (at the moment of ignition), the location of the ignition source, the combustion properties of the fuel and the turbulence generated by the release (initial turbulence).

3. Modeling

The majority of the processes involved are related to fluid dynamics and geometry. The only type of models being able to describe this well are models based on computational fluid dynamics (CFD). This is the reason why so far CFD models have been applied in spite of the lack of detailed knowledge of geometrical aspects of the installations being assessed during a design phase. This was compensated by adding “anticipated congestion” based on “good engineering practice” and experience.

Moving away from the use of CFD for at least a number of installations implies that the models that would be used need considerable robustness/conservatism since these by their nature do not or hardly pick up any effect introduced by the geometry. As such it will be difficult to use the approach/model used to perform explosion risk assessments for management of change (MoC). MoC therefore needs to be addressed in a different way.

Generic explosion models

To catch all aspects of an ERA (explosion load and its probability) in a generic explosion model implies that the model needs to be very conservative and can only be based on historical assessments performed. The generic explosion model suggested and described in chapter 5 is conservative using the upper bound of the data gathered from 65 modules/areas as summarized in chapter 3. It should however be mentioned that in most studies initial turbulence was not taken into account which as recent large-scale tests show (AIRRE) cause a considerable increase of explosion pressures.

Scenario-based methods

Scenario-based methods were generally used in combination with a CFD based tool. The main challenge with these methods is the time it takes to perform assessments together with the lack of detailed knowledge of the geometry. The methods can however be expected to be the most accurate without being too conservative.

If the number of scenarios that are to be investigated would be limited the choice of these scenarios will be the main challenge. This could potentially be determined on the basis of historical data (the data base of 65 modules/areas) considering scenarios giving the 10^{-4} loads according to the historical data. It is however unlikely that this will be a single set of conditions. Moreover the use of CFD-tools for this kind of approach still implies that the lack of knowledge of geometry needs to be compensated.

An alternative would be to develop analytical models describing the cloud build-up and explosion loads generated in congested modules. The number of scenarios that would be looked into can be considerably higher than possible when using CFD due to its character. The model would have to be validated thoroughly and would most likely have to include a lot of empirical relationships based on experiments and CFD-calculations. Depending on the complexity of such models MoC might be possible using such models even considering changes to the geometry.

Equation-based models
Equation based models are based on more general relations such as described in chapter 5.2. Single relationships are used to describe probability of a certain leak rate, ventilation rate, resulting dispersion processes resulting in cloud sizes, ignition probabilities and associated explosion loads. Since these kind of models cannot take geometrical aspects into account directly sufficient robustness shall be included. Also here a thorough validation process is needed.

4. Way forward

A generic explosion models has already been developed and can be used directly. If more CFD-studies would become available validation of the robustness of the generic explosion model shall be performed.

No choice for the development of a scenario-based method using analytical models or an equation-based model has been made within the current project. It is therefore proposed that both approaches should be developed further. This would be possible through a process where the current sponsors of RISP invite individual parties to prepare proposals for developing one of the two models. Those two parties that are chosen by the sponsors of RISP develop a validated methodology (an equation-based model or an analytical multi-scenario model) which are presented. Depending on the outcome one or both models are accepted as a RISP methodology.

Appendix B

Gas explosion risks at offshore installations

Introduction

This text is limited to address gas explosion risks at offshore installations following a process leak. The chain of events considered is loss of containment – gas cloud formation and ignition. BLEVE and other process vessel failures that could generate blast loads are not considered. Also, blowouts have been left out of this discussion.

Types of knowledge

Knowledge as described above can be categorized as follows:

- Physics and chemistry including properties like combustion energy, expansion ratios for gases and thermodynamics.
- Experimental results (gas dispersion, explosion loads)
- Simulation modelling results using models that reflect physics, chemistry and thermodynamics, but also models that include empirical models such as for the sub-grid modelling applied in FLACS and Kameleon FireEx KFX/EXSIM.
- Observations of facilities in operations: Process leaks, gas exposure (detection), ignitions, explosions casualties and damage.

In the industry, there is also another form of knowledge that has been accumulated over the years. This is our experience of how installations are normally designed, including the explosion design loads. This reflects the results from quantitative risk analyses, but we assume there is a feedback loop between what is feasible to design for and explosion risk quantification. We may know that 0.7 bar design load is a reasonable design load for a blast load reflecting what is commonly concluded in risk analyses. This evaluation will never be better than the limitation in the previous analyses representing the basis for the knowledge.

Obviously, this can lead to overconfidence in the realism and quality of decisions. Uncertainties in data and strength (or lack of such) in knowledge have been addressed above. In addition, we should have a brief assessment of uncertainties and limitations in NORSOK type explosion risk modelling.

Experience from North Sea offshore operations

From experience we know that gas explosions in offshore process modules are infrequent. Only very few gas explosions have occurred in the North Sea since 1988:

- A gas explosion contributed to the Piper Alpha disaster at the UKCS in 1988. Following a condensate leak during a maintenance operation, there was a high-level gas alarm and then an explosion causing the failure of a fire wall (that was not rated for explosion loads). Debris from the explosion ruptured a condensate pipe resulting in an escalated process fire. The lack of MoC principles after changing from producing oil to producing gas played an important role.
- A ruptured high-pressure pipe from a gas compressor sparked an explosion at Gorm C in the Danish North Sea in 2001. There were significant material damages, but the installation was repaired.

- Failure of a gas cooler at Rough B in 2006 caused impact and rupture to an adjacent cooler and about 7000 kg gas was released within seconds. The gas cloud was ignited, but the blast loads appeared to be modest, likely due to low confinement and very fuel rich plume.

It is interesting to note that the two latest (and largest) ignited gas leaks occurred spontaneously due to equipment burst and were probably both ignited as gas was sucked into a gas turbine air intake. The leak rate for these two incidents were much higher than the 96kg/s commonly applied as a maximum rate in explosion risk modelling. The Piper Alpha disaster is the only incident where a firewall has been impaired from a gas explosion.

Note that blowouts are outside the scope of work for this study. The West Vanguard shallow gas blowout (1985) is the most severe explosion and fire incident in Norwegian offshore history. Ignition took place in the engine room. According to Ref. /1/, *It appears quite safe to assume that the maximum blast load exceeded at least 2 bar*. This was a confined explosion. There was also an explosion in a gas blowout scenario at Ocean Odyssey in the Fulmar area (UKCS) in 1988.

North Sea experience for the period 1973-1997 is examined to establish a generic relation between blast loads and frequency Ref./1/. Findings from this report is summarised in the following, since this is the only data set of experienced explosions from offshore installations available. These results should be used with care for several reasons, such as the relevance of old data and the categorisation of events, including the blast loads and how these are defined.

The population of “relevant installation years” was estimated to 5363. There is a total of 34 incidents included in the data set, three of these were fatal accidents. The overall explosion frequency is $34/5363 = 6 \cdot 10^{-3}$ per year. Based on description of the event and damages, blast loads were assessed as follows (all events included, Table 4.2 in Ref./1/):

- > 0.2 bar: $1.1 \cdot 10^{-3}$ per explosion area and year
- > 1 bar: $2.2 \cdot 10^{-4}$ per explosion area and year

The generic frequency for explosion barrier failure was estimated to $2.2 \cdot 10^{-4}$ per year, but the report includes alternative figures as well. Note that most of these incidents are not relevant for process accident risk quantification (PLOFAM (Ref. /2/), MISOF (Ref./3/)).

Ref./1/ further quantified the frequency for explosion barrier failure to $4.3 \cdot 10^{-4}$ per explosion area year based on 4 incidents, all at the UKCS during the period 1983-1988. The barriers referred were not in all cases rated barriers and should rather be considered area divisions.

The report indicates that new installations (installed after 1980) have a better track record than older installations, and that for the old platforms, explosion frequency is reduced over time. Newer data (Ref. 2/ and Ref./3/) confirm this trend.

When considering the whole history since 1973, hot work is a dominant cause for ignition, and statistics shows this risk has been controlled over time. The last process leak > 0.1 kg/s ignited at the NCS was in 1992.

Based on the available data from PLOFAM2 and MISOF2, it is possible to set an upper limit for the generic gas explosion frequency per platform or process module per year. But due to the complexity of the phenomena involved in terms of the coupling to a specific design (both the properties affecting probability for the outcome and design attributes affecting consequences), data are way too scarce to be used as a basis for defining generic design blast loads or arguing that for example designing for 0.7 bar is a good compromise between cost and safety.

Loss of containment – leak picture

A gas leak is the first link in the chain of events leading to blast loading of structures and equipment. Explosion frequency is modelled as proportional to gas leak frequency. The industry has systematically collected data for hydrocarbon leaks at North Sea offshore installations since 1992 (See Table B.1). The PLOFAM project has scrutinized the available data, and the main conclusions are the following:

- Equipment counts are commonly used to model leak frequencies. This model was found valid, as a linear relationship was observed between the observed leak frequency and predicted leak frequencies using equipment count and fluid properties.
- A high fraction of the leaks is caused by or related to maintenance work or other activities
- The format and data available makes comparison between UK and NCS leak frequency hard. The PLOFAM project concludes that process leak frequency is similar for the NCS and the UKCS.
- In a high fraction of the observed leaks, duration was short, and the quantity of hydrocarbons released was small – too small to represent a risk for explosions and/or fires with severe consequences.
- Current explosion modelling assumes there is a transient leak rate determined by gas inventory in the process segment and blowdown. Such incidents occur but are not typical for the observed leaks.
- The number of leaks is sufficiently high to establish very reliable frequencies for small and medium leaks (0.1 kg/s to, say, 10 kg/s), and a quite accurate estimate of the frequency for larger leaks (uncertainty interval less than a factor of two).
- There are few large leaks where large quantities of gas are released. Modelling large leaks will include statistical uncertainty.

The PLOFAM project defined leaks where less than 10 kg gas was released as *marginal leaks*. A release of 10 kg hydrocarbon gas will not lead to any severe explosion in typical offshore modules.

Table B.1: Process leaks (UKCS 1992-2015)

Average rate (kg/s)	Quantity released (kg)					
	<10	10-100	100-1000	1000-10000	>10000	Total
>100	-	-	1	1	-	2
10-100	-	-	4	9	10	23
1-10	3	19	75	28	1	126
0.1-1	48	192	224	28	10	502
<0.1	1464	608	117	12	1	2202
Total	**1515**	**819**	**421**	**78**	**22**	**2855**

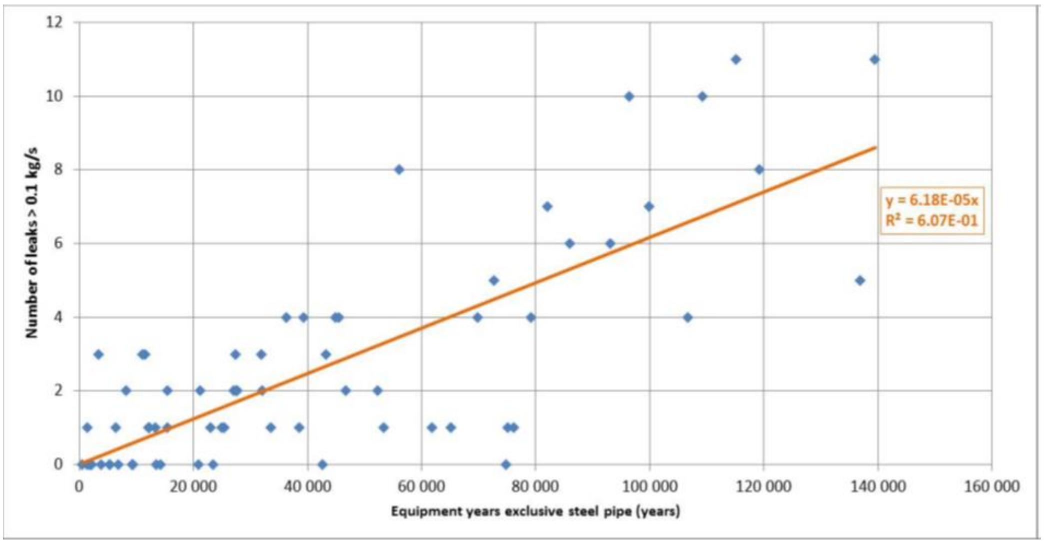

Figure B.1: Equipment years and observed number of process leaks > 0.1 kg/s [PLOFAM]

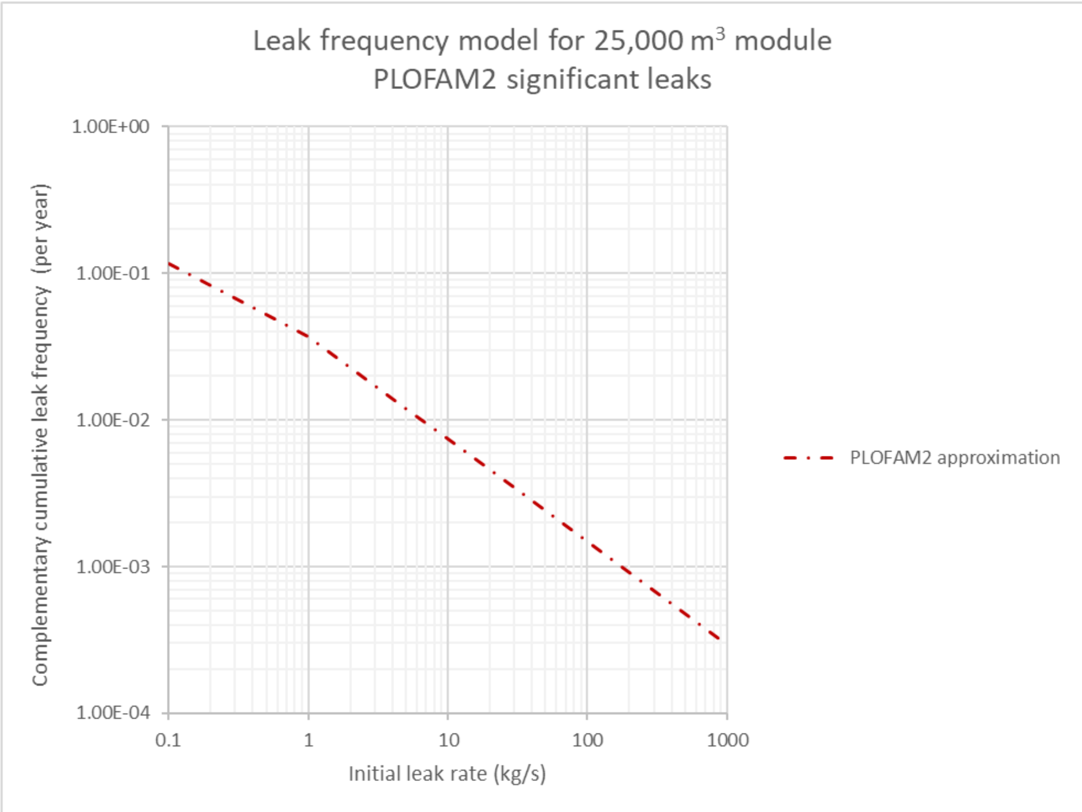

Figure B.2: Leak frequency for a 25000 m^3 process module [PLOFAM]

For a 25000 m^3 process module, the generic leak frequency as reported in (new) PLOFAM is as shown in the figure above (Figure B.2). Leaks with rate less than 0.5 kg/s can normally be neglected in explosion risk modelling for offshore installations. For leak rates exceeding 0.5 kg/s, the following relation can be applied:

$$f\,(\text{leak with rate} > r) = 1.5{\cdot}10^{-6} \cdot V \cdot r^{-0.7}$$

where r is leak rate in kg/s, and V is module volume in m^3

The model accuracy can be improved by replacing volume by equipment count, and even more so if the PLOFAM model is applied, reflecting both equipment counts and fluid properties (pressure and density).

Uncertainty using the PLOFAM data set

Different data periods were considered, and this result in different generic frequencies. For small leaks, the uncertainty is mostly related to whether or to what extent a falling trend should be reflected. For larger leaks, there is uncertainty because the data set is scarce. For leaks exceeding 100 kg/s the uncertainty is significant. If the leak frequency is to be based on module area or volume instead of equipment count, uncertainty will increase.

Natural ventilation

Natural ventilation is primarily wind-driven, but there are also thermal contributions from hot surfaces of piping and equipment which become important during calm conditions and in very confined modules. Natural ventilation is determined by the location specific wind conditions, confinement (walls, wind walls and decks), congestion and geometry (module size).

Natural ventilation is often simulated using CFD for 8-12 wind directions and one wind speed. Then wind statistics is used, assuming ventilation scales with wind speed. With 12 wind directions and 16 wind velocities, there are almost 200 wind conditions to consider, each with a certain frequency. A statistical analysis can be useful. Figure B.3 shows examples from four deck levels for a jacket being designed. (The basis for the wind statistics is actual observations over several years.)

For improved precision some study approaches also simulate lower wind speeds with thermal effects included to quantify ventilations by convection during low wind conditions.

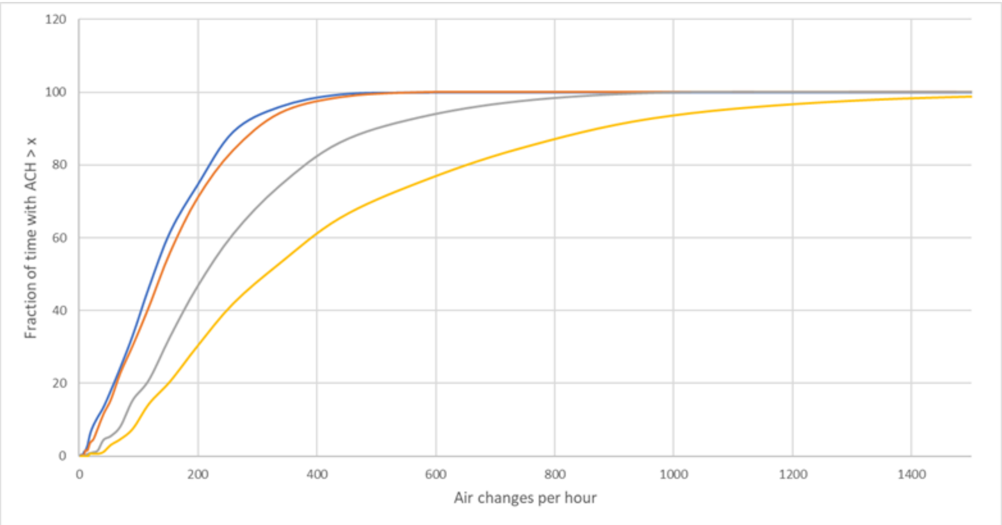

Figure B.3: Statistical analysis of natural ventilation expressed as ACH (examples)

Ventilation flow patterns inside a module may deviate significantly from external wind conditions, both in strength and direction. Due to reversed wake flow behind a platform a module can see significant ventilation even with external wind from the opposite direction (dead angle). Strong vertical flows (chimney effects) through grated deck areas can also be seen. When modelling ventilation one should therefore ensure that the domain is extended and properly resolved sufficiently far outside the platform to capture wake effects, and to consider modelling thermal effects when appropriate.

Gas dispersion and gas cloud formation

Blast energy results from combustion of a flammable cloud of hydrocarbon gas and aerosols. The flammable cloud within a semi-enclosed, congested process area (often module) is normally of primary interest, for deflagrations, which is the combustion mode expected for dimensioning cloud sizes on offshore platforms, parts of the flammable clouds in the unconfined/uncongested area outside the module will have much less impact on the loads. The flammable cloud size and reactivity/energy inside the module is consequently an important parameter for explosion risk.

For pure gas releases the flammable gas quantity is the fraction of the gas in the module with a concentration between the upper and lower flammability limits. One should however be aware that parts of the gas plume with rich concentrations (>UFL) may be diluted to reactive gas concentrations during an explosion increasing the combustion energy. Condensate and two-phase releases can further complicate the simplified assessment of explosion energy as the liquid particles may add to the combustion energy in a flame, and for significant explosions even expand the flammable zone beyond the gas LFL-concentration. The detailed dynamics of two-phase dispersion and explosion are generally too complicated to address properly in quantitative explosion analyses, a good compromise is to represent the hydrocarbon spray/aerosol mass fraction by dense hydrocarbon gas.

The transient release rate and density of the released flammable cloud are very important for the gas dispersion and cloud development. This is governed by the composition and pressure, and too some extent the temperature, inside the segment. Gas detection, isolation (large releases) and blow-down (smaller releases) will usually also be important for explosion risk. Natural gas releases dominated by methane will normally be buoyant when released into ambient air, but may become neutral or dense relative to ambient air with increasing fractions of denser components and cooling due to expansion during release. Such releases will normally be from high pressure and sonic, for significant release rates the release momentum can dominate the local wind fields inside the module.

For condensate and multiphase releases a lower release velocity and a significant amount of aerosols are expected. This will give a denser than air plume and a different cloud development than for pure natural gas releases. If the release originates in a separator a measure like blowdown may have less effect than for gas segments as lighter oil fractions will boil at pressure reduction and delay pressure reductions inside the separator.

In an explosion study it is important to estimate proper transient release rates, with proper density relative to ambient air. The fraction of aerosols generated, which may contribute to explosions, should be estimated, here the vapour fraction and pressure in the segment are important parameters.

The most important mechanisms for dispersion in a semiconfined offshore platform include release momentum, gravity and natural ventilation. For open modules of limited size there may be a significant possibility that releases may leave the module due to release momentum, and natural ventilation will be significant and may push flammable gas efficiently out of the module. For more enclosed modules both these venting mechanisms will be weaker and significant gas clouds can be expected for smaller release rates compared to more open designs.

To predict transient gas clouds it is common to apply CFD-calculations. Due to Cartesian grids applied by most applicable CFD-models simulations of high pressure releases are more efficient and of higher precision when releasing gas along axis directions. Since the location and direction of accidental releases will vary a simulation study will usually perform a representative selection of release scenarios for each leak rate, often modelling a few different release locations and up to 6 different release directions. In different QRA-approaches it will vary how many wind speeds, directions and leak rates and directions that are modelled with CFD, while some approaches extensively extrapolate simulation results from one or a few leak rates and wind speeds to all other combinations of leak rate and wind, others will simulate a range of different leak rates and wind speed/direction combinations and interpolate/extrapolate to nearby.

The ability of the CFD software to predict a given gas dispersion scenario is considered reasonably good. The FLACS software has been extensively validated against atmospheric dispersion experiments [Ref./4/], the LNG Model Evaluation Protocol [Ref. /5/] against various hydrogen dispersion experiments [Ref. /6/]. For realistic large scale dispersion tests inside offshore modules the number of experiments are limited. The most important series of realistic experiments are the BFETS Phase 3B realistic release experiments [Ref. /7/]. 20 large scale high pressure natural gas release experiments into a 2600m^3 offshore module replica were performed, with transient gas concentrations reported at 45 sensor locations. The clouds were ignited after reaching steady state and explosion pressures reported. In [Ref. /8/] FLACS simulations are compared to experimental results. Despite challenges in the experiments both with strongly varying wind and gas sensors influenced by jet-induced changes in flow-field the flammable clouds are fairly well predicted. In Figure B.4 the estimated flammable volumes (upper plot) and Q9 equivalent cloud volumes (lower plot) based on observations (blue) and simulations (red) are shown for all 20 experiments. Q9 is the most frequently used equivalent stoichiometric cloud approach for explosion studies in which the actual dispersed flammable cloud volume is scaled by relative reactivity and volume expansion down to a smaller maximum reactivity cloud with volume Q9. Another equivalent cloud volume, Q8, based on relative expansion scaling only, gives the available explosion energy in a flammable cloud. For flames burning faster than pressures can be vented, like large explosions in enclosed modules or detonation flames, Q8 is the appropriate equivalent cloud approach, see [Ref. /8/] for description and discussions.

For most experiments the comparison of flammable volumes is fairly good, for the Q9 equivalent volumes deviation is slightly higher. In Figure B.5 sensor by sensor comparison for test 9 and test 16 are shown. Among the 20 experiments test 16 has the largest deviation between simulated and observed Q9 equivalent stoichiometric cloud (factor 3 overprediction), still the gas concentration distribution inside the module is fairly well predicted with FLACS.

A competent modeller following the user guidelines for scenario setup and gridding should be able to predict gas dispersion with good accuracy. Potentially even better results could be achieved for high pressure releases by improving the pseudo-source term (increase velocity and reduce temperature). Incompressible solvers often applied also introduce some inaccuracies.

Dispersion simulations can be important not only to estimate the possible explosion energy (flammable volume, Q8 or Q9) but also to extract typical pre-ignition turbulence levels inside the flammable cloud to be used in the explosion simulations.

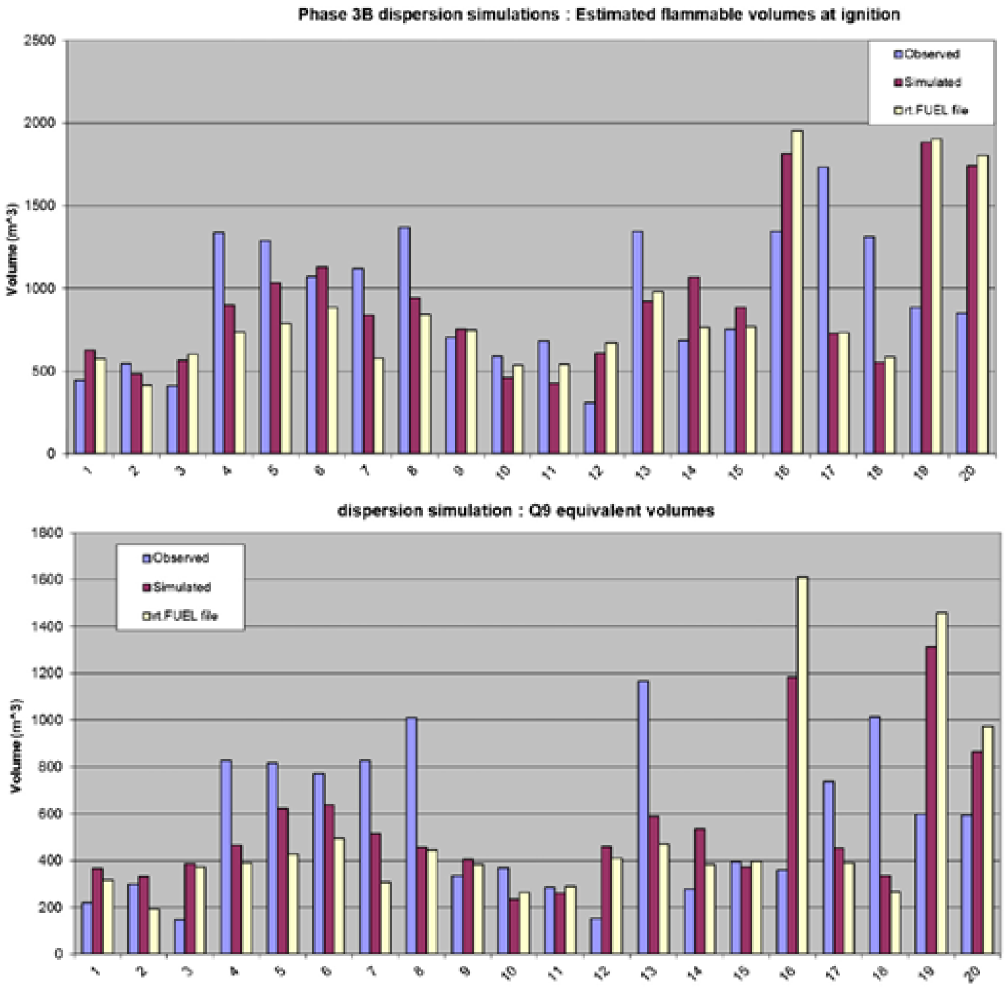

Figure B.4: Estimated flammable (top) and equivalent stoichiometric Q9 volumes at time of ignition from observed gas concentrations at sensors (blue), predicted gas concentrations at same sensors (red) and exact estimates from simulation (yellow) for the 20 ignited dispersion tests.

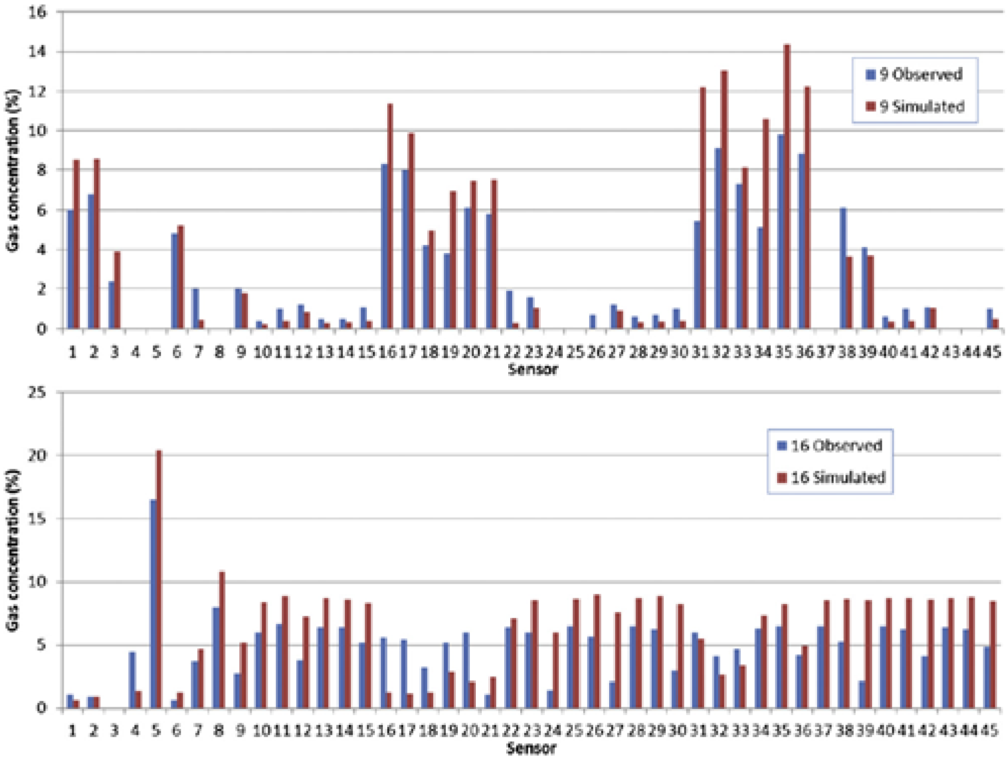

Figure B.5: Examples of sensor by sensor comparison of gas concentrations at ignition for Test 9 (top) and Test 16 (bottom). For Test 9 the simulated flammable volumes are very good, whereas for Test 16 there is a factor of three difference in estimated equivalent stoichiometric cloud.

Ignition probability and ignition modelling

Ignition in the present context can be described as the process of starting the combustion of fuel after an accidental release. This ignition can be immediately: the fuel does not or hardly gets the chance to mix with air, and delayed: ignition occurs in a premixed mixture of fuel and air, a gas cloud.

The European standard EN 1127-1 (Ref. /9/) distinguishes 13 different ignition sources. The most common ignition sources offshore are electric equipment, open flames, hot surfaces, electrostatic sparks, mechanical sparks but also electromagnetic radiation, stray currents and lightning are possible. The incendivity of these ignition sources depends on the ignition source but also on the ignition properties of the gas: often described by the minimum ignition energy and auto-ignition temperature.

The minimum ignition energy of alkanes is typically about 0.25 mJ. The auto-ignition temperature (AIT) however varies considerably. Considering alkanes the AIT can vary from 630 ^oC for methane to 205 ^oC for n-nonane. The former parameter can be used to describe the affinity to be ignited by electric and electrostatic sparks whereas the latter describes that for hot surfaces.

For each of the ignition sources measures have been taken to avoid their presence. The measures are taken based on the likelihood an explosive atmosphere can arise (hazardous area classification).

Electric sparks can in principle be very strong and can easily ignite alkane-air mixtures. Measures can be taken to reduce the likelihood of electric equipment becoming an ignition source using principles such as flame proof equipment (clouds ignited inside equipment cannot ignite the cloud surrounding equipment), intrinsically safe equipment (electric sparks in the equipment do not have sufficient energy to ignite; surface temperatures are limited), pressurised equipment (flammable gas cannot enter the equipment). The application of the different principles depends on the likelihood an explosive atmosphere can arise, i.e. the hazardous area classification.

Open flames are very strong ignition sources and their presence are normally prevented by procedures (hot work permits). Reciprocating engines and turbines on offshore platforms may become ignition sources on offshore platforms. Reciprocating engines can be protected by flame arresters on the air intake preventing a flashback. These equipment items may also have hot surfaces both internally and externally.

Hot surfaces can arise due to hot work operations, malfunctioning rotating equipment (friction), at electrical equipment, at reciprocating engines, at turbines etc. If the surface temperature exceeds the auto-ignition temperature ignition is theoretically possible. In practice temperatures have to be considerably higher due to the geometry of the hot surface (surface area, orientation) and associated buoyancy of the gas causing it to move away from the hot surface. All equipment (electrical and mechanical) used in potentially explosive areas shall be approved bearing in mind the classification and the maximum allowed surface temperature of the flammable gases that may arise in these areas (temperature class).

Electrostatic sparks and discharges arise due to electrostatic charging by contact and breaking of contact between two objects made of different materials (tribo-electric effect). An example is crude flowing through a pipe. Both the crude and the pipe will get charged. Accumulation of charge on the pipe and crude depends on the rates of charge generation and the rate of loss of charge. The pipe can be grounded (high rate of charge loss) preventing charge build-up whereas the properties of the crude (conductivity) determines the charging of the crude. Grounding, choice of equipment and procedures (e.g. use of anti-static footwear) prevent electrostatic sparks and discharges.

Mechanical sparks are directly related to equipment (rotating equipment) used and hot work (e.g. grinding) and can be prevented by choice of this equipment (e,g, prevention of use of light metals), its maintenance and procedures regarding hot work. The choice of equipment is again related to the hazardous area classification.

Also the presence of other ignition sources (electromagnetic radiation, stray currents and lightning) can mainly be avoided by applying and following related international standards.

In addition to hazardous area classification and the associated choice of equipment ignition control is effected: when a leak is detected (using gas detection) ignition sources are isolated. This action is also aiming at reducing the probability for igniting releases.

Risk analysis commonly distinguish between event or immediate ignition and delayed ignition. To simplify matters, gas explosions is only considered for delayed ignition. Delayed ignition is when a pre-mixed gas cloud is ignited.

Delayed ignition of a pre-mixed gas cloud from a process leak in an offshore module is a very infrequent event. In a JIP, available data from the NCS and UKCS for the period since 1992 has been analysed. A transient ignition probability model (MISOF, Ref./3/) has been developed based on this analysis.

The data analysis concluded that, in addition to Gorm C at the Danish continental shelf, the following incidents are ignitions of process leaks > 0.1 kg/s that are relevant in a QRA context. (UKCS and NCS since 1992).

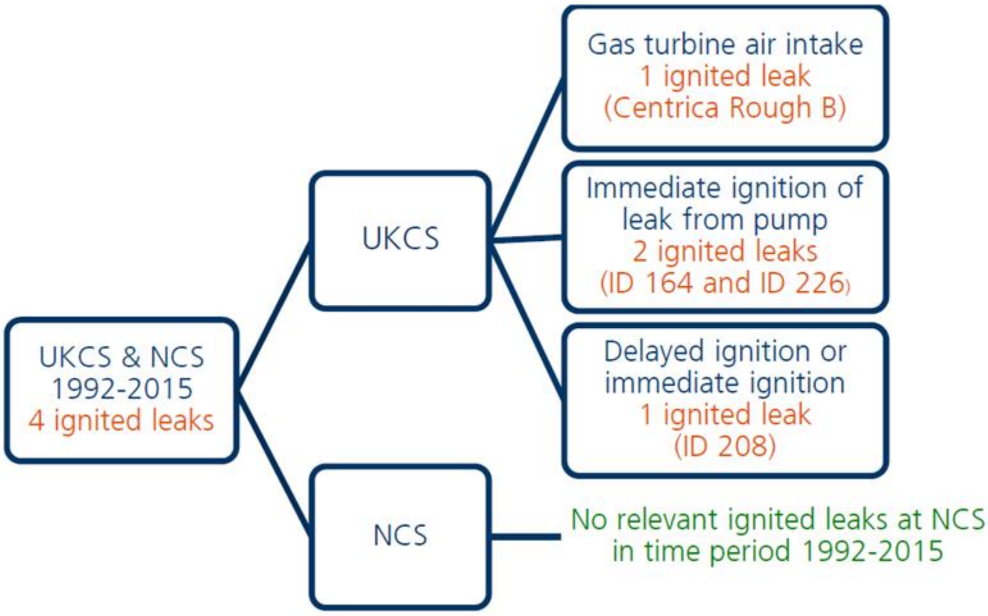

Figure B.6: Ignition of process leaks UKCS and NCS 1992-2015 [MISOF, Ref./3/]

The project establishes the relation between ignition probability and the extent (volume) and duration of flammable gas exposure. On a high level, it is concluded that ignition probability is low, since there are very few delayed ignition incidents, while there are hundreds of gas leaks.

Looking more closely at the data, the majority of leaks, even leaks with initial leak rate exceeding 0.1kg/s, the volumes exposed to flammable gas are very small. There are a handful leaks with very large gas clouds that dominate the total gas exposure volume.

Quantifying the exposed volume of the experienced leaks is very uncertain. For the HCR leak records, information on gas exposure was made available to the JIP. This information is sometimes qualitative and sometimes quantitative, but always hard to interpret for our purpose. For the NCS incidents, investigation reports were made available. Many of these describe the gas exposure in detail, sometimes from simulations performed trying to model the incident. Still the figures are considered very uncertain, and again, there are a few leaks that dominates and contribute to the total. For smaller leaks, the JIP applied simple relation for leak rate and gas fraction and the quantity released to quantify flammable gas exposure. Observe that ignition following flammable gas exposure of the air intake to turbines or engines may be the dominating cause of ignition for large (rupture) gas leak incidents[5].

Modelling gas dispersion and flammable gas exposure as part of explosion modelling should be considering how gas exposure data from experienced incidents are interpreted and modelled. To obtain valid results, these two aspects must provide consistent results.

Because of the more limited data and challenges to quantify gas exposure even for well documented incidents, the basis for ignition probability modelling is way more uncertain than the basis for leak frequency modelling. Uncertainties are introduced when the statistics is used as basis for ignition

5 In the original JIP on ignition modelling, gas exposure was quantified based on the number of gas detectors exposed and their reading. Such information has typically not been utilised in the most recent studies, where the estimation of exposed volumes for the most significant leaks has been based on CFD studies

modelling in a QRA context. From the data we know with certainty that the probability for ignition of small gas leak is small, and the data proves that ignition probability in classified areas is low. Large gas leaks with extensive gas cloud volumes are rare events, and quantification of ignition probability for gas clouds exposing equipment in process areas will necessarily be uncertain.

This is a main challenge in modelling of fire and explosion frequency. Using the PLOFAM2 and MISOF2 models, massive leaks (> 50 kg/s) drives the explosion risk in naturally ventilated areas. This is in accordance with our evaluation of the underlying risk, i.e. that the uncertainty related to massive leaks and that the volume of the exposure is important for the ignition probability. However, there is little experience from such incidents, and we are extrapolating the models into a part of the sample space where knowledge from historical events are scarce. This means that it is important that any QRA carefully addresses the risk for massive leaks, considering the uncertainty in the models predicting the associated risk. A QRA should therefore include quantification of risk from leaks considerably larger than 50 kg/s.

Gas explosions

Explosion energy

The main concern related to explosions on offshore platforms is potentially high explosion loads within a module that may threaten the integrity of firewalls, decks, hydrocarbon carrying piping or equipment or even the entire platform. In contrast to explosions on petrochemical facilities onshore, where far-field blast overpressures onto control rooms and neighbours of the plant, there are often more than a hundred people living within 50m from the process areas, which will be at severe risk if there is a major incident at the platform.

The damage potential of a gas explosion depends on a number of parameters. One very important parameter is the potential combustion energy that may contribute to an explosion. For a deflagration, which is the most likely flame propagation mechanism on an offshore platform, flames will accelerate with the help of turbulence in the flame front. In this case the combustion energy contributing to the explosion loads is in most cases limited to the hydrocarbons at flammable concentrations inside the module.

Confinement

One of the most important parameters for explosion severity is confinement. It has already been discussed how high natural ventilation will help limit the expected flammable cloud sizes. Also for explosion consequences within offshore modules low confinement can be a major advantage. With significant vent areas, preferably well distributed across the module, overpressures will be efficiently vented out of the module, and often flammable gases are pushed out as well, and larger clouds and longer flame propagation will be required to generate damaging overpressures. Another important consequence of larger vent areas is that once a pressure is generated inside the module, the pressure pulse duration, and thus impulse, will be significantly lower with a large vent area. Shorter pressure durations are normally less damaging to a structure.

Possibly negative effects of low confinement are that for large explosive clouds there is a possibility that lower confinement can lead to faster flames, with a potential for deflagration to detonation transition, see discussions below, or that far-field explosion loads may be more severe. Such a trend was possibly seen in the BFETS Phase 2 experiments (Ref. /10/) carried out in the years after Piper-Alpha accident. Here Test 14 with 33% added vent area seemed to give faster flame propagation than Test 7, and locally very high pressures (of short duration). Despite the higher local pressures, more damage to the test rig was observed in the more confined Test 7. Despite higher reported pressures locally, this observation may support the expected trend that more confinement leads to more damaging explosions, higher risk for DDT and worse far-field blast consequences.

Gas concentration and reactivity

Another factor that is important for explosion severity is the reactivity of the cloud. Natural gas with primarily methane tends to be somewhat less reactive than denser hydrocarbons, one important reason is the higher stoichiometric concentration of methane which allows less air and oxygen in he mixture, other reasons are the chemistry and higher reactivity of fuels with a higher fraction carbon and chains of carbon-atoms.

Natural gas with methane as the main component has a relatively narrow flammable range, from about 5 to 15% in air, with high reactivity in a narrower range from 7-8% to 12% in air. For concentrations outside this range the reactivity is significantly lower. With increasing amounts of ethane, propane and heavier hydrocarbons a somewhat higher reactivity, over a slightly wider concentration range (mass based g/m^3) is expected.

Oil mist and condensate

For multiphase or condensate releases, or other releases involving liquids the flammable cloud may consist of significant fractions of droplets. Released at high pressure and/or high temperature particles may be sufficiently small to remain airborne (aerosols). Aerosols and sprays may significantly contribute to explosions, in particular once initial explosion starts to accelerate and break droplets into finer mist. Tests at GexCon [Ref. /11/] found that for hexane sprays (flashpoint -26˚C) explosion pressures were equally high as for stoichiometric propane, while for limited volatility Oseberg stabilized crude oil sprays explosion pressures were about half of what was seen for propane and hexane. The tests indicated that for spray and aerosol mixtures a significantly wider concentration range with high reactivity was observed, as aerosols would make lean flames more reactive while rich flames would be less influenced. For an actual leak scenario one could therefore fear that presence of aerosols could lead to increased explosion consequences.

Pre-ignition turbulence caused by leak

A high pressure jet release will lead to a significant turbulence level within the flammable cloud, and if the flammable cloud gets ignited this will help accelerating the cloud initially. As a part of the EMERGE project [Ref. /12, Ref. /13/] British Gas (DNV GL) and CMR (GexCon) performed experiments looking into the effect of pre-ignition turbulence on explosion pressures. The tests showed that in a very congested geometry (dense array of pipes) the pre-ignition turbulence had only a limited effect, while it was very important with pressure increase of 100-200% in the low congestion 1:5 scale $50m^3$ offshore module experiments performed at CMR. CMR also performed ignited dispersion tests in the 1:5 scale $50m^3$ offshore module [Ref. /14/], in 5 ignited dispersion scenarios, one experiment gave 30% higher overpressures than the 100% stoichiometric reference test (despite only 50% of module filled with gas), another resulted in same pressure level as the full stoichiometric reference test. The remaining 3 tests gave significantly lower pressures than a 100% reference cloud, primarily because clouds were only filling a small fraction of the module. Within the Phase 3B project [Ref. /7/] similar tests were performed in the DNV GL $2688m^3$ full scale test module at Spadeadam, UK. 20 dispersion experiments were ignited, in addition 3 base case experiments with 100% stoichiometric quiescent cloud size were performed, and 6 partial fill experiments with 10-40% (one 100%) quiescent cloud size were performed. [Ref. /15/] analysed the experiments and compared to FLACS simulations, in Figure B.7 a comparison between reported equivalent cloud size Q9 (estimated based on gas concentration measurements from 45 sensors in the experiments) and maximum explosion overpressure (after 1.5ms averaging) is presented for the two different geometry configurations with gross vent areas of 3 x 12m x 8m (Confinement 1, vent ratio Kv ~1.49) and 28m x 8m (Confinement 2, vent ratio Kv~1.16). From this plot there are several interesting observations to draw.

For Confinement 1 it can be seen that the majority of ignited dispersed clouds (red circles) gives significantly higher pressures than the idealized clouds of comparable size (red triangles), the main reason for this is likely the pre-ignition turbulence for the ignited dispersed clouds (red circles) while the idealized clouds are quiescent at ignition. For the Confinement 2 the largest dispersed reactive cloud (Q9: 48% module fill) gives 25% higher pressure than the quiescent 100% base case cloud. This also highlights the importance of including pre-ignition turbulence when predicting explosion pressures in explosion studies. In the latest revision of NORSOK Z-013 (Ref. /16/)) it is mentioned that pre-ignition turbulence should be modelled, but this has not been done consistently among consultants in recent years.

Another interesting observation is that the pressures in the Phase 3B experiments correlate reasonably will with the relation P = Q9(m3) mbar, i.e. that pressures scale with size of cloud. The module is small and open (Kv = 1.1-1.5) compared to many actual platform modules, one may therefore fear higher pressures for the same cloud sizes if the module dimensions were larger, i.e. that excess gas cloud is pushed into other parts of the module rather than out of the module.

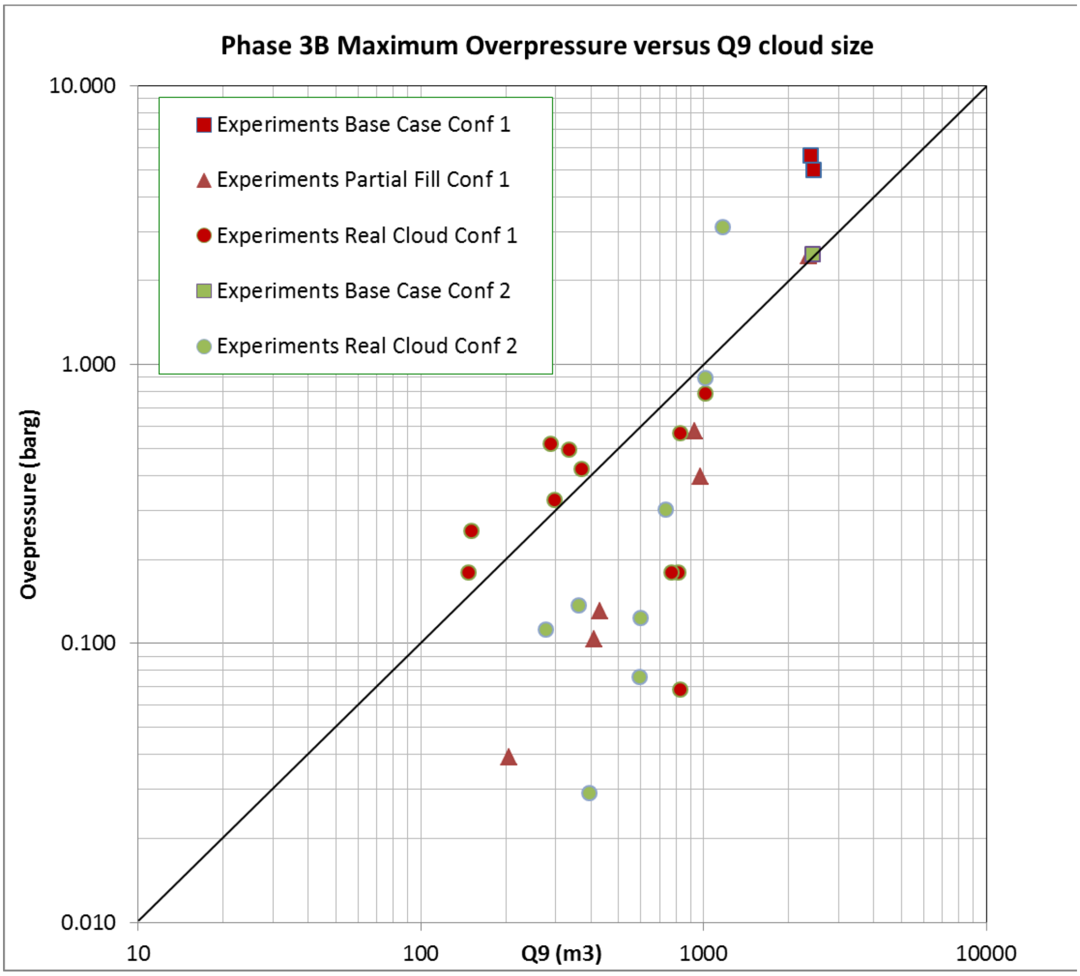

Figure B.7: Overview of BFETS Phase 3B experiments, overpressures plotted versus estimated Q9 equivalent stoichiometric cloud size [Ref./8/] for experiments in Confinement 1 (Red colour, 12m x 8m vent area on 3 sides) and Confinement 2 (Green colour, full venting 28m x 8m on one side wall). 100% worst-case quiescent clouds are shown in squares, partially filled quiescent stoichiometric clouds are shown in triangles (only Confinement 1) and ignited dispersion tests are shown in circles.

Equipment congestion

Congestion is a critical parameter for explosion pressure. Numerous test campaigns have investigated this, in the 1980s and 1990s experiments like CMR 3D corner tests, MERGE/EMERGE tests [Ref./12/] and British Gas Bang-box tests [Ref. /17/] illustrated how increasing pipe congestion would have dramatic impact on explosion pressures. In the 3D corner tests it was demonstrated how pressure for the same volume blockage ratio could increase by a factor 10 to 100 by replacing 9 large diameter pipes by 36 or 225 smaller pipes. During the BFETS large scale project [Ref. /10/] experiments were performed with varying obstruction density, in the 25.6m x 8m x 8m base case test rig with 8m x 8m openings at both ends, the worst-case explosion pressures in a 1500m^3 natural gas cloud increased from 0.5 bar (low congestion test module) to 2-3 bar and >4.4 bar (high congestion test module) for central ignition and end ignition, respectively. Even in the high congestion rig the congestion density was considered moderate compared to what can often be seen on real offshore platforms.

Deflagration to detonation transition (DDT) and scale

With increasing flame speeds there is a risk that a gas deflagration will transition to detonation (DDT). This can typically happen when the flames accelerate to velocities above the speed of sound in the cold air ahead of the flame, so that the flame front captures and merges with the pressure wave from the explosion. This can lead to strong shockwave generation in the flame front with autoignition of unburnt gas where shockwaves meat ahead of the flame. The propensity of different gases to undergo DDT varies significantly, for hydrogen a direct detonation may be initiated by 1g TNT explosive charge, while for ethylene about 10g TNT, propane around 100g TNT and for methane 1000g TNT is required. When a gas detonates there will be a characteristic (fish shell like) shockwave pattern established with nodes where shockwaves meet and autoignite gas. The distance between nodes is called detonation cell size, λ. For a deflagration flame front to transition to detonation the initiation energy must be distributed over a certain flame front area, typically 10λ -13λ in two directions, i.e. an area ~100-$200\lambda^2$. If an unconfined initiation flame front area is smaller than this, there will be too much loss at the edges of the initiation region to sustain the detonation, and the "hot spot" will not successfully initiate a detonation. With some confinement smaller dimensions may be required to for DDT, in the most extreme, a circular pipe, a pipe diameter of 1λ can be sufficient, see e.g. [Ref. /18/]. Equipment congestion in the initiation region will disturb the regular shock wave pattern needed for DDT and further increase the requirement for the size of the initiation zone.

If the detonation initiation energy (Ei) is translated into a spherical combustion volume, the surface area of this volume corresponds to ~$400\lambda^2$ (a spherical detonation needs higher initiation energy than a plane front due to the high curvature). The detonation cell size λ for hydrogen is found experimentally to be around 1cm (1.09cm according to Ref. /18/), for ethylene ~3cm, propane ~10cm and methane ~30cm, all following the relation $\lambda \sim Ei^{2/3}$.

The implication of this is that while hydrogen flames may initiate detonation in fast deflagrations within an unconfined flame front area of D=10-15cm, less reactive gases will need significantly larger flame front areas for a detonation to initiate. For this reason it has in the industry for decades been widely accepted that hydrogen could detonate in an accident, as this had been clearly demonstrated in experiments, while DDT for less reactive gases like propane and methane during accidents were not considered credible, and not even possible when it comes to methane.

This understanding has changed over the past decades. After Buncefield and Jaipur explosion accidents the general acceptance that LPG-vapours can undergo DDT has increased. Post-Buncefield DDT experiments with propane inside arrays of trees and gas cloud detonation tests demonstrated not only that DDT in LPG-vapour is highly credible in an accident, but also that developed detonations can propagate through shallow layers of propane with depth < 0.5m (< 5λ).

There are several experiments with gases like ethylene (BG MERGE, Bakerrisk-rig), ethane (Shell flame acceleration tests) and propane (BG BEX-tests) in which DDT is observed within 5-10m when flames are leaving a high-congestion region.

Severe mine explosions in the USA increased the focus on detonation hazards in methane rich natural gas and NIOSH performed experiments investigating DDT in D=1.05m pipes filled with natural gas (97.5% methane), see [Ref. /19/]. During the Phase 3A experiments [Ref. /7/] natural gas experiments in the 28m x 12m x 8m low confinement module resulted in very high overpressures, often with local pressures well above 10 bar. Repeat experiments also demonstrated a very high variation among nearly identical tests with maximum pressures varying from 7.6 bar to 35 bar (beta-series). FLACS validation studies reported major challenges modelling the Phase 3A experiments (Ref. /20/), with significant underprediction both inside the module and for far-field blast [Ref. /21/]. [Ref. /22/] repeated the simulations including prediction of DDT and thereafter switching combustion mode to detonation, and this way the FLACS CFD simulations reproduced the far-field blast patterns around the module with very good precision, see Figure B.8. The calculation with DDT modelled reproduced the experimental blast pressures well, and were convincing evidence that this experiment, and a handful of others from the Phase 3A test series, involved DDT and detonations. All these experiments were with a typical natural gas mixture (91% methane, 7% ethane and some propane), all four module walls were fully open, the tests were ignited in the west end of the module, and the DDT took place when flames approached the far end (after 25m flame propagation).

The implication of the above for offshore explosion safety is that DDT cannot be ruled out for typical explosion scenarios on offshore platforms, not even for methane dominated natural gas. DDT has been observed for several natural gas explosion tests after 25m flame acceleration, and for significantly shorter distances for mixtures dominated by ethane and propane. DDT risk may be significant once local overpressures in flame front approach 2 bar or more, and flame speeds reach 600 m/s. In recent RPSEA propane explosion experiments by GexCon [Ref. /23/] video recordings indicated DDT initiation at even lower flame velocities. If DDT would happen the remaining flammable gas cloud would detonate within ~10-20ms with overpressures of 15-20 bar, leading to major damage inside the module and vicinity. DDT risk can be assumed to increase with gas reactivity, with congestion level in the module, and with the size or maximum possible flame path of the module.

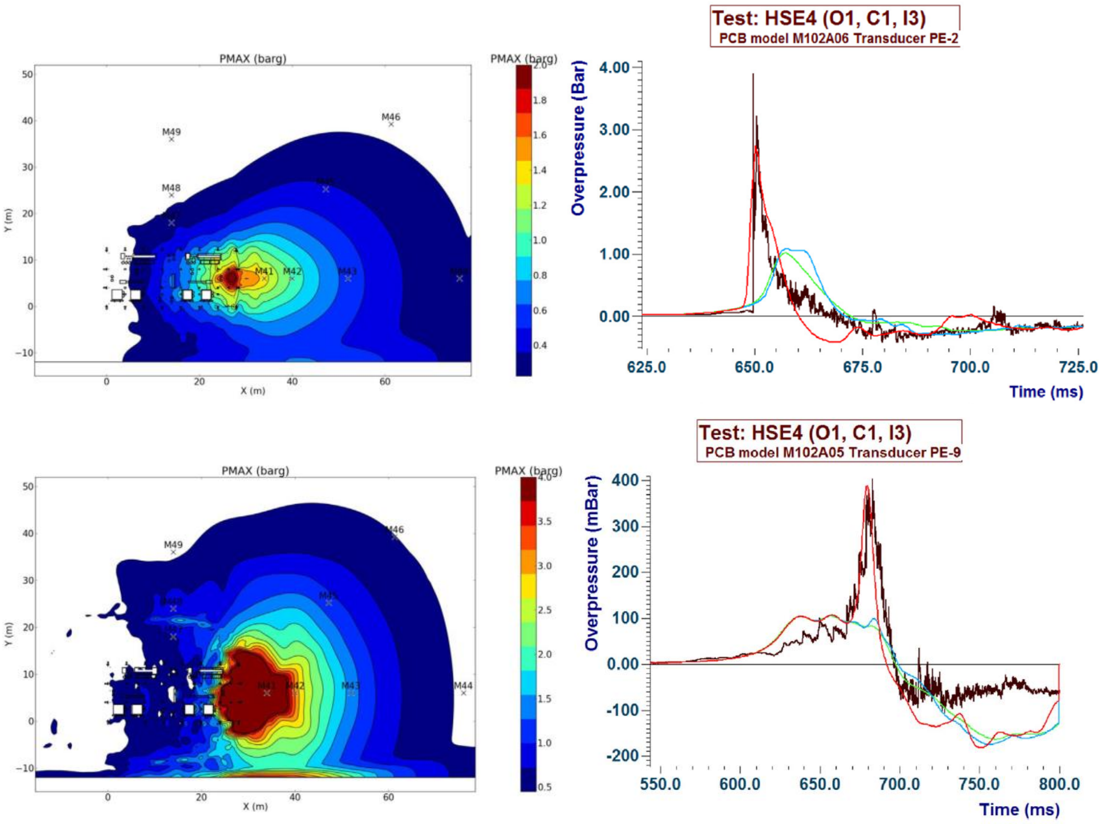

Figure B.8: Comparison blast patterns in Phase 3A Test 4 predicted as a deflagration (upper left-legend 0.25 bar – 2 bar) and a DDT towards end of module (lower left, legend is 0.5-4.0 bar), module with no walls extending from X=0-28m, Y=0-12m. In the plots to the right experimental pressures (black) are compared to pressures predicted in deflagration simulation (blue/green) and in DDT simulation (red) for pressure transducer PE-2 12m East of the module along flame path (upper right, coordinate 40m,6m) and PE-9 24m North of module (lower right, coordinate 14m,36m. For more details see [Ref./22/].

Deluge

The activation of water deluge at gas detection can have a significant explosion mitigation effect. Tests at British Gas [Ref. /17/] and CMR [Ref. /24/ and Ref. /25/], and later the BFETS Phase 2 [Ref./10/] and Phase 3A [Ref./20/] full scale tests gave good insight into the main effects of water sprays on gas explosions including:

- The spray momentum from the deluge nozzles will contribute to a significant mixing of gas within the module, in most cases this will help dilute the clouds to less reactive concentrations, while in some cases with a fuel-rich part of the cloud significant reactive explosive clouds may result.
- If a gas cloud would ignite after deluge is initiated the turbulence from the deluge sprays will initially enhance flame propagation and give faster pressure increase. This effect seems to increase with the flow momentum of water (i.e. injected water volume x velocity).

- With increasing flame speeds and pressures air ahead of the flame will be accelerated, and once the air velocity relative to droplets reaches the droplet break-up criterion (We-number based) the water droplets will scatter and become very fine mist. This mist will be absorbed and cool the flame slowing down or stopping the flame propagation.

For the initial medium scale experiments explosion pressures both increased and decreased as a result of water deluge. The following trends were seen:

- The break-up of droplets required a certain flame run-up distance, thus the positive effect of deluge is much better on large (real) scale than observed from the early medium scale experiments.
- Larger droplets break more easily than smaller droplets, normal sprinkler droplets (500-800 micron) generally have a good mitigating effect after break-up, while fog droplets (50-80 micron) have barely any mitigating effect on flames due limited break-up. Finer mist from release of superheated water (10 bar, 180˚C) with a significant fraction of droplets of the order 20 micron or less, again had a positive explosion mitigation effect, but less than for the larger droplets after break-up.
- The mitigation effect of water increased with amount of water, but so did the turbulence effect. At large scale the mitigation effect became dominating.
- With low confinement the mitigation effect is significantly better than for high confinement, this is both because pressure builds up more easily with high confinement, and because low confinement give consistently higher flow velocities ahead of the flame at lower pressure levels than with high confinement.

For BFETS Phase 2 experiments with 26 and 16 l/sqm/min of water injected prior to ignition gave maximum pressure reductions from 2-3 bar to 1 and 1.3 bar for centrally ignited experiments with 13m maximum flame propagation distance, and from around 5 bar to 0.5 and 0.8 bar for end ignition with 25m flame distance [Ref./10/]. For Phase 3A experiments the effect was even better, here explosion pressures were reduced from >10 bar (DDT-scenario) for end ignition without water deluge to 0.3 bar with 10 l/sqm/min deluge [Ref./20/]. Tests were also performed with 2-3 water curtains with ~10m separation distance, for these tests flame speeds and pressures were temporarily reduced strongly, but flame speeds would quickly pick up again giving local pressure levels of 2 bar. General area deluge thus seemed more efficient to limit explosion pressures.

Deluge activation may typically require 20-30s from gas detection, and there will be a risk for explosions prior to deluge activation. The likelihood to obtain very large, near stoichiometric clouds within 20-30s will likely be limited. Thus with the understanding that DDT can be a real risk for offshore installations, in particular with increasing size (and potentially openness) of modules, deluge activation at gas detection in a relatively large, open module will likely be a very efficient way to mitigate the residual DDT risk.

CFD modelling of explosions

Since the commercialization of FLACS in 1997 it has been the globally most applied CFD tool for offshore oil and gas explosion calculations. Extensive validation studies during the 1990s, including the numerous large scale experiments BFETS Phase 2 [Ref./10/, Phase 3A [Ref. 20/] and Phase 3B [Ref. /7/] have indicated that provided the 3D geometry and scenario are properly described and represented, a majority of large scale explosion scenarios can be predicted with a reasonable precision, not only the pressure level but also pressure distribution and transients.

For tests with water mitigation a particularly good prediction capability was seen [Ref. /26/], with good trends and an average underprediction of pressure of 10% (total of 500 pressure detectors compared in 20 large-scale experiments). For the tests without deluge the average underestimation was 30%. A somewhat closer study of the deviations did however reveal that for the deviation was particularly high for the highest pressure levels seen in low confinement tests with end ignition. Like [Ref. /22/] demonstrated the deviation for several of these tests was likely related to DDT and detonation flames during the tests, which is not predicted in a standard FLACS simulation. Standard FLACS does however have a capability to predict the potential for DDT, but not the consequences, thus a competent modeller could predict that some of the tests with most significant underprediction of pressure might undergo DDT.

In addition to DDT-prediction there are some further modelling challenges with FLACS:

- Explosion results depend strongly on congestion, and for an early phase module the detailed congestion density is unclear. The explosion results may therefore depend strongly on the modeller's ability to estimate the actual anticipated congestion level. Due to changes A challenge is also that the geometry import models will sometimes interpret structural beams to be hollow with small openings, which can lead to strong explosions inside the beams if not discovered by the modeller. Current as-built models are sometimes extremely detailed, which can give challenges since the FLACS turbulence/flame-folding models may exaggerate the flame acceleration. Experienced modellers may limit this problem to some extent by tedious cleaning of imported 3D geometry model, for more reliable predictions GexCon should improve the flame acceleration sensitivity to congestion.

Concluding remarks on the strength of knowledge

The term "strength of knowledge" is applied by the PSA (and in for example [Knowledge in Risk Assessment and Management]) to say something about the quality of the assessments performed. With limited knowledge, the analysis approach could be close to guessing, and this will obviously result in poor quality of the assessment. It follows that conclusions will be uncertain, and decisions made on this basis may be off the mark.

Gas explosion risk assessment involves several steps of which some are hard to model with desired accuracy. Ignition modelling is uncertain because the lack of relevant incidents as basis for establishing models and frequencies. Also, it seems modelling explosion loads in open geometries is still a topic that is hard to model with precision.

CFD modelling of the turbulent combustion mechanisms in a complex geometry apply porosities and distributed resistances (PDR). Modelling vapor cloud explosions is extremely complex, and the use of CFD tools for modelling explosions in open process modules have, at least historically, been imprecise. This is not only related to the CFD model as such, it also involves the CAD modelling and the import (and cleaning) of the CAD geometry to the simulator and its sub-grid models. It is interesting to note that [Ref. /27/] stresses that users of CFD codes for vapor cloud explosion (VCE) should have a strong background in of VCE phenomena and evaluate results bearing in mind relevant experimental VCE data.

Still, the knowledge acquired must be the basis for decisions. The challenge is to apply the knowledge in a sound and rational way in the decision-making process.

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Appendix C

Explosion modelling results – its use and limitation during the various design phases

Regulatory requirements

Offshore petrochemical installations must be designed to withstand so-called *dimensioning accidental loads* which are defined for several different types of loads, among these, explosions. Loads higher than the dimensioning accidental load that may impair defined main safety functions, shall have a return frequency lower than 1.0E-4/year for each load type. The dimensioning accidental load is often provided as input to design and based on this the operator and engineering company shall select a *design accidental load* equal to or preferably higher than the dimensioning accidental load, so that the impairment frequency for each main safety function and load category becomes less than the risk acceptance criterium of 1.0E-4/year.

It should here be noted that for a situation with more than one barrier between two main areas, there can be many combinations of dimensioning loads on these barriers that can fulfil the criterion, thus, the design accidental load for one given part of the barrier would not necessarily need to be higher than the proposed dimensioning load on this part of the barrier to fulfil the risk acceptance criterion for the combination of barriers. If e.g. the risk assessment is performed with the assumption that the strength of both parts of the barrier shall be the same, and a dimensioning load on e.g. 0.7 bar is estimated to fulfill the 1.0E-4/year criterion, the engineering company could choose to use a higher design load for the most exposed part of the barrier (e.g. 1.0 bar) and a lower load on the less exposed part (e.g. 0.5 bar), as long as the total impairment frequency is lower than 1.0E-4/year.

Guidance on these rules and regulations can be found in the PSA Facilities regulation, guidance and interpretations, NORSOK S-001 [Ref. /1/] and Z-013 [Ref./ 2/.] As the responsibility for doing a proper job, and the losses in case of an accident, in the end rests on the owner of the facility, the way the study is carried out will also depend on company internal standards and guidelines and the way the actual operator interpret the regulations.

For each installation a number of main areas must be defined, as a minimum hazardous area with fire and explosion risks, and non-hazardous area. Each main area could be split into one or more fire areas and sub-areas.

The PSA regulations (Facilities regulations), NORSOK Z-013 and company internal guidance documents describe how the Main Safety Functions shall be defined and the criteria to be applied for each Main Safety Function.

Examples of Main Safety Functions and relevance for the explosion study could be as follows:

- MSF A - Preventing escalation of accident situations so that personnel outside the immediate accident area are not injured.

  Usually there are one or more physical blast walls or decks which separate two main areas, and to fulfil this MSF it must be demonstrated that the frequency for parts of this barrier to fail due to an explosion in one main area is less than 1.0E-4/y. If the barrier between two main areas consists of several parts with interface to several fire or sub-areas within the same main area the combined frequency (=sum of frequencies) for escalation from all these should fulfil the criteria. This is usually the main focus of an explosion study.
- MSF B - Maintaining the main load carrying capacity of the platforms and integrity of wells.

  In an explosion study it must be demonstrated that the integrity of the installation is maintained, and that the frequency for explosions which may lead to partial or full collapse is below the required criteria. The exact interpretation of this MSF is difficult, the definition of when the load carrying structure is impaired is unclear, and the exact load required to give the given damage is challenging to quantify. For this reason there are many interpretations with varying degree of conservatism. Usually the impairment is coupled to strong explosions in the lower part of a platform structure.

- MSF C - Protecting rooms of significance and functions to combating accidents so that they remain operative until the facility has been evacuated

  In an explosion study it should be demonstrated that the sum of frequencies for explosion loads from any area that may threaten the integrity of the rooms of significance or e.g. deluge systems shall be less than 1.0E-4/year. In an explosion study this criterion will usually either be covered by MSF A evaluations if the rooms are protected by a barrier between main areas, or by far-field blast evaluations if the room is located further away from the hazardous areas. In the latter case buildings with normally robust offshore design will normally have no problem maintaining their integrity exposed to far-field blast, and this MSF is rarely a challenge for an explosion study.
- MSF D - Protecting the facility's safe areas so that they remain intact until the facility has been evacuated

  An explosion study will normally demonstrate that TR, LQ and muster areas will not be vulnerable to explosion loads. For larger installations this criterion is seldom a challenge.
- MSF E - Maintaining availability of escape ways until all personnel have escaped to safe area

  This study will evaluate to what extent explosions, fires and escalated fires e.g. from explosions rupturing HC-piping/equipment, will impair evacuation from other main areas, including the evaluation of available escape routes, life boat integrity or mustering area, or bridge access. This criterion has in the past often been a challenge due to estimated impairment of escape due to smoke, with part of the contribution coming from escalated explosions. Due to a lower estimated significant fire frequency with PLOFAM, and possibly a new understanding regarding robustness of piping exposed to explosions, it would be expected that the challenge with MSF E impairment may be somewhat less in future analyses.

In addition to the impairment criteria for main safety functions the individual fatality risk must be estimated for various group of employees and compared against acceptance criteria.

Current practice

The current practice for explosion studies on the NCS by most consultants is to perform a probabilistic risk assessment according to guidelines of NORSOK Z-013 appendix F. This is a probabilistic explosion risk assessment approach with the following steps:

- Hydrocarbon leak frequencies are estimated, traditionally using SHLFM, may be replaced by PLOFAM
- Various dispersion scenarios (several release locations, directions and rates, wind directions and speed, often different compositions) are modelled, either by CFD or through analytical models with some level of calibration based on CFD
- Frequencies for ignited cloud sizes are estimated using a transient ignition model, in recent years the OLF (Ref. /3/) or TDIIM (Ref. /4/) model has been used, this may be replaced by the MISOF-model
- Explosion simulations are performed for a range of idealized cloud sizes at various locations with varying ignition location. From these explosion loads at various targets, e.g. overpressure at blast walls or decks, drag loads within the module or forces onto particular equipment are reported.
- Combining the ignited cloud frequencies and the predicted explosion consequences cumulative frequency of load exceedance curves are generated for blast walls, decks and other objects of interest

The various risk consulting companies have developed their own methodologies and approaches to the proposed procedure. Not all the recommendations are followed by all consultants. One mechanism which is often ignored is to include jet-induced turbulence in the explosion calculations (Section F4.3 of Z-013 (Ref. /2/)).

The scope and precision of studies will vary with the phase. In concept selection phase few parameters are decided, and the main purpose may be to compare various design solutions to identify if one design has significant advantages or disadvantages to the others. As the input parameters will be very coarse, the precision in estimated design loads will be limited.

In FEED phase tentative design loads should be estimated for blast walls, decks and equipment packages to be ordered from subcontractors. At this stage the design details are few, and it is a challenge to define explosion loads in detail. Where there is uncertainty in design choice, moderately conservative assumptions are recommended. Dimensioning loads are usually proposed based on the explosion assessment, on this basis the engineer/operator will choose design loads. Explosion assessment results are also used as input to frequencies for the fire assessment to estimate a best possible frequency for impairment of escape (MSF-E). Usually the design loads are set higher than the dimensioning loads predicted so that the design shall be robust against changes in predicted loads caused by design modifications or smaller weaknesses in the calculation methods.

In Detailed engineering/design phase more details of the design are available, and some of the assumptions made during FEED may have been changed. The explosion assessment performed during FEED will usually be repeated using the design details now available, and the predicted dimensioning loads are hopefully not too different from those estimated during FEED, and still lower than the planned design loads by some margin. If not, there may be a need to consider possibilities for risk reduction or strengthening of the structures.

In the as-built phase the risk assessment is again repeated using the as-built geometry model and actual system design parameters. For the as-built study the exceedance frequency of actual design loads, which is hopefully sufficiently low to avoid impairment of main safety functions criteria, should be calculated to document compliance with the regulations.

Tools

For the risk assessment various tools are used among the different consultants, some are in-house tools to estimate leak frequencies, transient release rates, or to facilitate the process of estimating the risk. Examples of the explosion risk tools used in recent years include ASAP (Lilleaker Consulting), ExploRAM (Lloyd's Register) and Express (DNV GL). Other tools used are commercial. Validated CFD-tools required used to estimate gas dispersion and explosion loads according to NORSOK Z-013 Appendix-F guidelines.

FLACS (www.gexcon.com) has been used for explosion simulations for practically all explosion assessments on the NCS. FLACS was developed with support from several major oil and gas companies, and explosion validation against medium and large scale experiments was a very high priority in the development work. After the commercialization of FLACS in 1997, maintenance fees from commercial users gradually became the main funding source for the further development.

For dispersion studies to estimate the cloud sizes distribution to ignite in an explosion study FLACS is often used, but for these studies some consultants have also been using Kameleon FireEx KFX (KFX) (www.dnvgl.com) as well as general purpose CFD-tools FLUENT and CFX (www.ansys.com). KFX has had a parallel develop history to FLACS, however, with main focus on the modelling of hydrocarbon fires, and has been the preferred tool for CFD fire modelling on the NCS.

It can be mentioned that in recent years GexCon has developed fire simulation models (FLACS-FIRE), while ComputIT (now DNV GL) developed explosion functionality (thus the X in FIREX). With purchase of the right to the EXSIM CFD-tool in 2016 the explosion model development at ComputIT changed focus from developing own models as part of KFX to integrate the EXSIM-models into the KFX-package, as both KFX and ExSim are based on the same combustion modelling principles. Neither FLACS-FIRE nor KFX /EXSIM has so far been used much for NCS-installations. With gradually improved functionality and robustness, and once a satisfactory validity is demonstrated, this may change.

Gaussian based dispersion tools, often referred to as 2D-tools (best known is DNV GL tool Phast) are not capable of modeling effects of cloud accumulation inside 3D platform modules, still these tools are sometimes used for offshore platform studies elsewhere in the world. On the NCS the weaknesses of such dispersion prediction methods are generally acknowledged (e.g. in NORSOK Z-013) and the approach is not considered acceptable.

Simplifications and variations among consultants

Since a NORSOK Z-013 type explosion risk assessment is expected to consider at least 9 different leak rates, several different wind speeds, wind directions, preferably various gas compositions and various leak locations and directions, with ignition at any time step, millions of scenarios should preferably be evaluated. This is not feasible, and likely not optimal, to cover with CFD-modeling. An approach "simulating it all" would likely spend disproportionally longer time to model the small releases (very time demanding due to finer grids, shorter time steps and often longer duration of the dispersion scenarios), while it could be expected that the smaller releases have a low or negligible impact on the risk and could well be simplified in the modelling.

To cover the required (or optimal) scenario variation various simplifications are done.

- Ventilation studies are carried out and for 8 to 12 wind directions and one or more wind speeds. Based on the ventilation study the several wind speeds and directions are thereafter represented by 2-3 wind directions and 2-3 wind speeds in the CFD dispersion studies.
- Frozen cloud approach is used by some consultants who will simulate about half of the leak rates and interpolate/extrapolate the rest, for instance using the frozen cloud scaling rules (double leak rate gives double concentration etc.). The frozen cloud approach may work reasonably well, but should be used with caution for wind speed scaling.
- With ExploRAM/Express/ASAP models a more limited number of wind speed and leak rate combinations are typically simulated and the results from these simulations are used to estimate transient gas dispersion results for a significant number of other leak rates. The models will not follow the actual location of gas clouds within a module, and extra calculations will typically be required to consider external ignition. The models are weak in situations with several modules next to each other, as gas leaving one module is not entering another module. There are further significant challenges estimating transient cloud development needed for the transient ignition models for release rates not simulated.
- The transient leak decay is modelled in different ways. Several of the consultants would do steady state simulations and use these to estimate the cloud behaviour for a transient leak rate. Others would try to model the transient leak rates and adjust the time scale of transient cloud results after the transient leak rate decay.
- The consultants may use different approaches to estimate anticipated congestion, see next section.

The consultants will further have their different special skills which can influence the focus of the assessment, and there will be differences in experience and understanding among consultants from different organizations but also within the same organization.

Most consulting companies have to some extent standardized their approaches, full standardization is however not always an advantage. There may be major differences among the various platform studies with regard to layout and input parameters, and a fully standardized approach will not necessarily be the most optimal for any situation. Optimally the chain of events to be modelled should be assessed, and an evaluation of where to do simplifications and where this is not feasible should be carried out. Such an exercise requires that the consultants have a good understanding of the underlying physics, the modelling tools and the overall risk assessment.

The reader of the above summary could get the impression that explosion risk studies give arbitrary results and are extremely consultant dependent, and that a better alternative could be to throw the dices. This is definitely not the case. The estimation of explosion risk for an offshore platform is a challenging task, and the various consultants do an extensive job to take into consideration and model a range of different mechanisms in the best possible way.

That said, the operators being the problem owners and responsible if there would be an accident should do more to evaluate models used and to stimulate continuous improvement. It is now 17 years since (Ref. /5/) presented a model benchmarking study among the Norwegian consultants. In these 17 years the general knowledge and understanding have been improved in many areas, and the computer capacity has increased. By not repeating such benchmarking at regular intervals, preferably with mandatory reporting of various intermediate results at, one can expect that differences among the various approaches may grow.

Representation of equipment (ACM)

Over the past decades there have been various challenges with regard to characterizing congestion level for FLACS explosion studies, both actual level in an imported geometry, and a representative level for as-built geometries. This is due to several factors.

Continuously, since the first CAD-imports to FLACS were performed around 1998 there have been problems with objects not being properly imported that either disappeared, would increase in size (size interpreted as inch instead of mm), or be rotated. In the recent versions of the FLACS CAD-import these issues are less of a problem than some years back.

A decade ago it was discovered by users that if parts of the geometry were duplicated in the imported CAD-model, this would give a sometimes significant increase in explosion pressures. Due to this discovery GexCon initiated work both in the porosity program and in the congestion analysis program COFILE to preprocess geometry models to remove "objects-in-objects" to prevent FLACS from defining flame folding parameters or subgrid turbulence from objects trapped into other objects. This work has helped reduce the problem, but still objects trapped inside other objects are found to influence explosion simulations in some cases. For this reason, it is important to remove all objects inside tanks and smaller buildings as a part of the geometry import cleaning process.

Like previously mentioned KFX is sometimes used for dispersion simulations being a part of the explosion study. In this situation there is a need for a geometry model both for KFX and for FLACS. When this model was prepared in KFX and thereafter exported to FLACS, the KFX export tool translated certain objects (e.g. rounded ends of cylindrical tanks or non-aligned pipes/beams) into FLACS by representing the objects by often 100s of smaller objects. It was then discovered that this strongly increased the predicted explosion pressures in FLACS. After this was discovered the practise of preparing explosion models for FLACS inside KFX has been stopped.

Still there are challenges when importing CAD-geometries. One challenges that has been seen in recent years is that structural beams are sometimes imported in a way that creates almost closed channels, thus an explosion can manage to propagate into these nearly closed beams, resulting in 8 bar overpressure or more locally inside the beam (likely leading to "freak-values" for overpressures onto local panels), and if there is an opening somewhere, very high drag loads may similarly be reported. Such issues can be identified by running test simulations and thereafter manual cleaning of the beam system is required.

A further problem seen in recent years is that the detailed CAD geometries get extremely detailed in the CAD-models, with a handrail consisting of 10 surface elements, similarly a rectangular instrument panel can consist of numerous smaller object rather than one rectangular box with legs. In FLACS simulations this detailed geometry description seems to exaggerate the flame acceleration. GexCon should take action to find a satisfactory solution to this problem, for instance introducing some kind of geometry density limitations or to replace the very detailed objects by simpler bounding box objects.

The above elements put requirements on the consultants importing the geometry that a proper job must be done cleaning the geometry prior to evaluating congestion and adding anticipated congestion (AC). The cleaning will both be to identify potential objects that are wrongly imported, or that can lead to flame acceleration like inside the beams, or due to objects remaining inside other objects.

As mentioned it is still not a straight-forward task to evaluate the congestion of a geometry model. 10 years ago a packing density parameter was defined as congestion (pipelength/m^3), however as long as the diameter of the pipes was not considered this parameter had significant weaknesses. Around 2011 it was proposed rather to focus on object surface area per volume as a parameter for congestion. The parameter could be estimated considering both beams and piping, and in a more consistent way than before. This method seems to have been adopted by most consultants.

The current status of the import tools, cofile and porcalc programs, combined with the very detailed as-built models that tend to exaggerate overpressure is a challenge. The solution in the mean time will be that experienced consultants will go through the different disciplines of a geometry model (piping, electrical, structural etc.) and try estimate what is missing in a model. From this a level of anticipated congestion will be estimated in early stages. To solve the problem with a too detailed CAD-geometry in as-built is also a significant challenges which should be looked into by GexCon.

Time consumption

The time it takes to carry out an explosion risk study will depend on

- Time it takes to collect the necessary information
- Interaction with other studies for instance evaluating segment sizes and leak frequencies
- 3D model preparations (import, cleaning, evaluating and adding ACM)
- Preparation of simulations
- Simulation run times
- Processing of results to estimate the risk
- Reporting explosion study and DAL

A typical explosion risk project may often have duration of 2-3 months. With reasonable CPU-capacity (e.g. ~100 efficient CPUs) the simulation part of the study should not need to take more than a week (~1000 dispersion simulations and 3-400 explosion simulations), possibly a few days longer as it is good practise to perform and check some test simulations prior to starting 100s of simulations. This of course requires that the modeller understands the CFD-tool and how to optimize grid and time steps while maintaining valid results, if not, dispersion calculations may take much longer. The 3D model preparation may also require several days (or a week if much manual work must be entered). Preparation of jobs to simulate should be automated and quick, the same applies for the risk processing.

Thus, if the work flow in the other parts of the study is efficient, with automatic estimates of parameters not available (e.g. leak frequencies in an early phase study), and the reporting is done in an efficient and standardized way, a FEED-phase explosion study should be efficient to perform. This does however require that the consultant knows how to optimize simulations and avoid errors, and that there is CPU-capacity available.

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Appendix D

NOROG/RISP Model Evaluation Protocol and Model Nomination Document template

The RISP WG2 on explosion modelling was asked to develop or identify feasible ways forward with regard to developing explosion models to predict minimum design loads for offshore oil and gas platform modules *efficiently*, *with best possible precision*, and *based on limited information available* in early development phases of a project.

As the most basic level a generic model has been proposed, this only requires module dimensions and vent areas as input. For the majority of offshore platform modules this model will predict conservative minimum design loads.

A second category described in the RISP WG2 report is equation based modes, which will use somewhat more detailed input to predict minimum required design loads.
A third category of models is “Simplified NORSOK Z-013 models”. These models estimate minimum explosion design loads based on a similar approach as described in NORSOK Z-013 appendix F, however, without the use of CFD. In most cases the models will give results within moments. The modelling basis for these models will vary significantly and it is expected that the models will also have significant differences in their prediction capability.

The complexity of the third category models, and possible the second category, and the need for maintaining and improving these models make it not realistic to develop the optimal model within a project group consisting of experts from various organizations. It is instead proposed that owners of potential early phase explosion models will nominate these using the Model Nomination Document template at the end of this appendix, and thereafter to participate in a model evaluation exercise. A proposed Model Evaluation Protocol (MEP) is described below.

It is proposed that both the basic generic model, the equation based models and simplified NORSOK Z-013 models will be evaluated according to this Model Evaluation Protocol. The first part of the evaluation cases consist of existing platform modules coarsely described, for which design accidental loads exist. Since there will be inaccuracies in the description of the module and processes, variation in risk assessment approach to obtain dimensioning loads and in the way design accidental loads are defined relative to dimensioning loads, the degree of conservatism in the design loads will vary strongly among the offshore modules in the selection. For this reason model performance can not be judged based on deviation for single cases. A model that gives predictions in the right ballpark (preferably slightly conservative on average – geometric mean Predicted/Observed) and greatly follows the trends (moderate geometric variance Predicted/Observed) could be considered acceptable, while significant deviation in the geometric mean and geometric variance would be negative. Other means of evaluation should likely also be performed, e.g. fraction of cases with minimum design pressure > 80% of actual design pressure.

To conclude, the evaluation from part one should be pragmatic and take the uncertainties of the material into consideration. Still significant deviations in level and trends should be commented.
The second part of the evaluation is carried out for three different concept platforms, these are a) a limited sized wellhead platform, b) a moderately sized compressor module and c) a larger process platform. Coarse, relevant information typically available in early design phase will be provided and minimum design loads for the three platforms shall be reported. For these three studies the models shall also include intermediate information (e.g. about ventilation, dispersion, ignited cloud sizes) and illustrate capability to report more than only the minimum design loads. For each of these studies a number of sensitivity assessments are thereafter requested in which input parameters shall be modified, for these assessments only the predicted pressures/frequencies shall be reported. The evaluation of this set of cases will be less quantitative due to lack of reference design pressures, but will focus more on whether the predicted trends seem consistent. If several models are evaluated the trends predicted by the different models will also be compared.

User thresholds and that the model is easy to use and can give useful output, including intermediate reporting, will also be part of the evaluation.

All model owner submitting a model for evaluation must:

- Provide an *executable version* of the model (protected and license controlled to the degree found necessary) with proper *user guidelines*, so that the evaluation group can verify that any user of the tool will obtain the same results as reported. If the input includes "fuzzy expert coefficients" not clearly explained in the user documentation, this will be a negative element to be commented in the evaluation.
- Document all input parameters for all evaluations in the evaluation report, this should normally be possible to do in a compact format.
- Accept that the model performance can/will be compared with other models evaluated, if e.g. the generic model and 4 different simplified NORSOK Z-013 models are compared these will be named e.g. like "Generic Model 1" and "Simplified NORSOK Model 1, 2, 3, 4" etc. Each model owner will receive information about which model is theirs, while the RISP project sponsors and evaluation group will have information about identity of all models. It may be relevant to publish results of the evaluation, and if so, the model owners can choose that their tool remains anonymous in the publication. Modellers that agree to identify their tool in a publication will be given the possibility to give a short comment if there are aspects of the evaluation they think should be improved.

Evaluation protocol

Input:

- Module dimensions (m) X_DIM, Y_DIM, Z_DIM
- Module volume porosity (-) PorV (1.00 if open, reduce for significant enclosures/rooms)
- Module confinement (-) PorXL, PorXH, PorYL, PorYH, PorZL, PorZH (0=closed, 1=100% open)
- Wind statistics Wind speed/direction frequencies for area
- Platform orientation Direction platform North
- Segment information Indicative leak frequency distribution Oil, 2P and Gas (%) Average segment sizes and typical segment pressures
- Part 2 For part 2 the information provided will be more detailed

The modellers of all tools accepted for evaluation will under confidentiality receive necessary details of the modules to be assessed in Part 1 of the exercise, including the actuel design loads. The organizers of the assessment must at this stage decide which among the selection of 65 modules collected that shall be included in the evaluation.

Output

For all benchmarks the following information must be provided:

A. Frequency of local panel pressures **0.5 bar**, **0.7 bar** and **1.0 bar**
B. Estimated dimensioning/minimum design pressure **1E-5/year**, **3E-5/year** and **1E-4/year**
C. If possible also provide load durations
D. For each case all adjustable input parameters used by the model must be listed so that the evaluation group can check the user dependency. Any use of input parameters beyond the case parameters provided must be justified based on submitted model user guidance.

The evaluation process consists of two parts:

Model Evaluation Part 1

Estimating minimum design loads/dimensioning loads for a selection of platform modules. This will be a largest possible selection among the 65 modules collected within RISP, which that can be included must be decided in dialogue with the owners.

For each platform module the necessary characteristics as described above will be provided in tabulated form, including reference to relevant area wind distributions. To ensure equal possibilities for everybody, the actual design pressures for the various modules will also be provided.

Model Evaluation Part 2
In this activity minimum design or dimensioning loads will be estimated for 3 prototype platform cases, and thereafter a number of sensitivity assessments will be performed. The base cases are:

Base Case 1: Wellhead platform module (4800m^3)
- Dimensions: 30m x 20m x 8m
- Fully confined YH, ZL, ZH, 50% weather cladding XL, XH, YL, fully grated mezzanine deck at 4m
- Generic release rate frequency distribution to be provided, 60% 2-phase (50 bar, 20%/10 mole/mass fraction gas, 5000 kg segments) and 40% gas (150 bar, 2000 kg segments)
- Wind statistics as for Troll-field, Platform N = True N
- Sensitivity 1: Adjust shape to 15m x 40m x 8m (1a) and 40m x 15m x 8m (1b)
- Sensitivity 2: Adjust confinement to no weather cladding (2a) or full confinement XH (2b)
- Sensitivity 3: Increase segment sizes factor 2 (3a) or reduce by factor 2 (3b)
- Sensitivity 4: 100% leak frequency gas (4a) or double original assumed frequencies (4b)
- Sensitivity 5: Assume Platform N = 270 degrees (5a) or Platform N = 90 degrees (5b)

Base Case 2: Compressor module (5000 m^3)
- Dimensions: 40m x 20m x 8m
- Fully confined YL, YH, ZL, ZH, 50% weather cladding XL, XH, fully grated mezzanine deck at 4m
- Local equipment room (LER) 20m x 8m x 8m centrally along North wall
- Generic release rate frequency distribution to be provided, 30% oil (100 bar, 2%/1% mole/mass fraction gas, 5000 kg segments) and 70% gas (150 bar, 1000 kg segments)
- Wind statistics as for Troll-field, Platform N = True N
- Sensitivity 1: Move LER to XL&YL corner (1a) or rotate and block XL-boundary (1b)
- Sensitivity 2: Remove weather cladding (2a) or change YL from closed to 50% cladding (2b)
- Sensitivity 3: Increase segment sizes factor 2 (3a) or reduce by factor 2 (3b)
- Sensitivity 4: 100% leak frequency gas (4a) or double original assumed frequencies (4b)
- Sensitivity 5: Change mezzanine deck to fully plated with oil only at lower level and gas at upper, report lower deck results (5a), upper deck results (5b) and combined loads (5c)

Base Case 3: Large process module (15000m^3)
- Dimensions: 50m x 25m x 12m (5m x 20m x 6m lifeboat station behind blastwall in XH&YH&ZL corner
- Fully confined YH, ZL, ZH, 50% weather cladding on all open areas of XL, YL and XH, fully grated mezzanine deck at Z=6m (except over lifeboat station)
- Generic release rate frequency distribution to be provided, 30% 2-phase (70 bar, 30%/15% mole/mass fraction gas, 10000 kg segments) and 70% gas (70 bar, 3000 kg segments)
- Wind statistics as for Troll-field, Platform N = 320 degrees
- Sensitivity 1: Rotate lifeboat station to 20m x 5m x 6m (1)
- Sensitivity 2: Adjust confinement to no weather cladding (2a) or close XH wall by extending life boat station to 5m x 25m 12m (2b)
- Sensitivity 3: Increase segment sizes factor 2 (3a) or reduce by factor 2 (3b)
- Sensitivity 4: 100% leak frequency gas (4a) or double original assumed frequencies (4b)
- Sensitivity 5: Change mezzanine deck to fully plated with 2P only at lower level and gas at upper level, report lower deck results (5a), upper deck results (5b) and combined loads (5c)

Deliverables; model evaluation part 2:
For all cases output as described as A)-D) above should be provided for all scenario variations, in addition:
E) For Base Case scenarios other useful output parameters should be reported to highlight capabilities of the model, including specific load information that can be useful for design, as well as intermediate results useful to build confidence to the analysis.