JIP: Risk informed decision support in development projects (RISP). Version 2

equinor

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Summary

This is an update of the RISP main report from 2019 (version 1). To provide full traceability, the original report is provided in full, including the original workgroup reports. During 2021 and 2022 there have been updates and additional work on some of the models and guidelines. These reports are now also included.

This version comprises:

1. **Risk informed decision support in development projects (RISP). Main report**. Prepared by Tore Sagvolden, 13 December 2019.
2. **Workgroup 1 - Risk management.** Prepared by Joar Dalheim et.al., 1 February 2019.
3. **Workgroup 2 – Explosion**. Prepared by Linda Fløttum et.al., 10 March 2019.
4. **Workgroup 3 – Fires**. Prepared by Espen Gåserud et.al., 4 November 2019.
5. **Workgroup 4 - Other accidents.** Prepared by Joar Dalheim et.al., 4 November 2019.
6. **Workgroup 5 - Risk management and regulatory framework including standards**. Prepared by Rune Nerland et.al., 6 December 2019.
7. **RISP – Ship collision risk**. Prepared by T. Dammen and C.S. Madsen, 4 November 2022. *This is an update of chapter 3 in the Workgroup 4 report.*
8. **High Voltage Hazards**. Addendum to "RISP Report: Work Group 4 - Other Accidents”. Prepared by Lars Rogstadkjernet, 17 November 2022. *This is an update of chapter 6 in the Workgroup 4 report.*
9. **RispEx-decision support for explosion load design**. 22.09.2023. *This report describes a simple model for estimation of explosion design loads in an early project phase, complementing the Workgroup 2 report.*

Note that using the RISP methodology with insufficient consideration of the validity envelope might give wrong results. For example, referenced NORSOK requirements (e.g. NORSOK N-003) are part of the validity envelope. Results that contradict NORSOK requirements are therefore not valid.

Regarding transformer fires described in document 8, the 2023 Norsok Z-013 revision provides additional information regarding fires in transformers using a synthetic oil as cooling fluid.

A separate joint industry project, RISFIM (Risk-based simplified fire models and methods), has been performed. This project builds on the RISP philosophy but was run as a separate project with Safetec as project owner and support from the Research Council of Norway. Reference: Safetec, RISFIM – Risk-Based Simplified Fire Models and Methods Summary Report, Doc. No. ST-15386-1, Rev. 2.0, 26.06.2023.

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

Main report

Report for:
RISP Participants, att: Equinor Energy AS

Report no: LaC-P0647-R-0125 Rev: Final

Date: 13 December 2019

Summary

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

Main report

Security classification of this report: Distribute only after client's acceptance

Report no:	Revision:	Report date:
LaC-P0647-R-0125	Final	13 December 2019
Prepared by:	**Reviewed by:**	**Approved by:**
Tore Sagvolden, Lilleaker Consulting	Unni Nord Samdal, Equinor	Unni Nord Samdal, Equinor
Tore Sagvolden		Unni Nord Samdal

This report presents the Joint Industry Project (JIP) called risk informed decision support in development projects (RISP). The project has been carried out in 2018 and 2019. The project is related to management of major accident hazards (MAH) in development projects on the Norwegian Continental Shelf (NCS).

The task for the project has been to further develop and concretise principles and ideas provided by a former NOROG project, into new methods and models. The methodology established is based on the risk-based decision-making framework given by ISO 17776, which differentiate the assessment technique dependent on the complexity of the development project.

The intention for the project has been to provide risk informed decision support needed in typical development projects. The information needed has been screened considering both the timing of when decisions are or should be made, and the available information for decision making.

Risk assessment methods and models have been established suited to the information available when the decisions are normally taken. The recommendations given by the models are considered robust as to avoid the need to reiterate the decision based on more detailed information available at a later stage provided premises for the decision are not changed.

The methods and models are established for proven design where prequalified solutions can be applied. Validity envelopes for the various models have been established.

As far as possible the methodology is based on design requirements given by standards. It is acknowledged that NORSOK S-001 is a key standard in this respect.

The methodology has been reviewed in relation to the present regulative regime to identify possible conflicts and need to update regulations and standards.

Document history

Revision	Date	Description/changes	Changes made by
Final	13 December 2019	Comments from RISP participants implemented	Tore Sagvolden
Draft	13 November 2019	Issued to RISP participants for comments	

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1. List of abbreviations and definitions

1.1 Abbreviations

AIS	Automatic Identification System
ALARP	As Low as Reasonably Practicable
ALS	Accidental Limit State
BAT	Best Available Technology
CAD	Computer-Aided Design
CAPEX	Capital Expenditure
CCR	Central Control Room
DDT	Deflagration to Detonation Transition
DeAE	Design Accidental Event(s)
DeAL	Design Accidental Load(s)
DiAL	Dimensioning Accidental Load(s)
DP	Dynamic Positioning
DP2	Dynamic Positioning – Redundancy Class 2
EERS	Escape Evacuation and Rescue Strategy
ESD	Emergency Shutdown
FEED	Front End Engineering and Design
FES	Fire and Explosion Strategy
FPSO	Floating, Production, Storage and Offloading
GBS	Gravity Based Structure
G-OMO	Guidelines for Offshore Marine Operations
HAZAN	Hazard Identification and Analysis
HAZID	Hazard Identification
HC	Hydrocarbon
HSE	Health, Safety and Environment
ISD	Inherent Safe Design
ITT	Invitation to Tender
JIP	Joint Industry Project (In this case the RISP project)
LD	Lethal Dose
LEL	Lower Explosion Limit
MAH	Major Accident Hazard
MEG	Mono Ethylene Glycol
MeOH	Methanol
NCS	Norwegian Continental Shelf
NOROG	Norwegian Oil and Gas
PDO	Plan for Development and Operation
PFP	Passive Fire Protection
PIO	Plan for Installation and Operation
PPE	Personal Protection Equipment
PRV	Pressure Relieve Valve
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Analysis
RISP	Risk Informed Decision Support in Development Projects
SC	Steering Committee
SoW	Scope of Work

SPR	Sudden Pressure Relay
SSIV	Subsea Isolation Valve
TEG	Tri Ethylene Glycol
TRA	Total Risk Analysis
TSS	Traffic Separation Scheme
ULS	Ultimate Limit State
W2W	Walk to Work
WCPF	Worst Credible Process Fire
WG	Workgroup

1.2 Definitions

Terminology as used in the RISP project:

- Safety premises: Identified aspects presumed to be true and therefore used as a basis for the management of MAH. This can typically be presumptions (constraints and conditions) made in the HAZAN as a basis for concluding that the design is within the validity envelope of the RISP models. It can also cover other aspects such as operational restrictions. Safety premises typically needs to be verified at a later stage.
- Safety program: The safety program is a high-level plan describing the goals, means (resources), activities and analyses planned to manage MAH in a development project. Responsibilities, organisation and interaction arenas related to implementation of MAH design in the development project should be described. The safety program may also be called the HSE program or similar.
- Safety strategy: The safety strategy is a high-level plan giving the link between the safety program and the design development regarding MAH. The strategy describes how the end goals will be achieved. The safety strategy should also cover the needs related to fire and explosion strategy (FES) and escape, evacuation and rescue strategy (EERS). The safety strategy should outline applicable overall principles for design, layout, arrangements, philosophies and other high-level design and operational aspects related to barriers, e.g.:
    - Describing MAH relevant for the development (e.g. area by area) and describing key design measures and safety premises.
    - Describing how specific MAH are managed by the use of barrier functions, systems and elements. Typically, this should include a reference to standard requirements (e.g. NORSOK S-001) and whether there are special solutions required not covered by the standards.
- Proven design: Design or concepts that are considered prequalified through operational experience and/or previous engineering documentation and analyses to such a degree that the RISP methods and models can be applied.
- RISP methodology: The principles that have been used to establish methods and models in the JIP. The term is also applied as the totality of RISP methods and RISP models.
- RISP methods: The work steps and procedures proposed to be used for risk-based decision support in development projects.
- RISP models: The assessment tools proposed to be applied for risk-based decision support in development projects

2. Introduction

2.1 General

This is the main report from the Joint Industry Project (JIP) named "Risk informed decision support in development projects (RISP)". The project has been carried out in 2018 and 2019. The report summarises the work performed, results and conclusions obtained and recommendations for the way forward.

The major part of the work is documented by separate reports produced by 5 work groups. The reports are attached to this main report and includes:

- Appendix A: WG 1 report – Risk management
- Appendix B: WG 2 report - Explosion
- Appendix C: WG 3 report - Fires
- Appendix D: WG 4 report – Other accidents
- Appendix E: WG 5 report – Risk management and regulatory framework including standards

Possible discrepancies or conflicts between the main report and the reports from the work groups, are due to maturing through the project execution. The content of the main report is prevailing in this respect.

2.2 Background

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project) with results and proposals for further work was presented in the Operations Committee meeting in NOROG, and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The NOROG project concluded:

> *Risk analyses have played an important role in the HSE work in the petroleum industry, and these have helped to give the industry detailed and comprehensive knowledge about risk conditions and design principles. Specific risk acceptance criteria have been used to a great extent in the industry and the advantage is that it provides clear answers on what is good enough and what is not. It is set a clear line.*
>
> *The models and tools, however, require input data at a very detailed level, and in many cases there is a mismatch between a) necessary input and the time it takes to set up and use the tools and b) the information and the time that is available at the time the key decisions are taken. Decision making support in many cases comes too late.*
>
> *Experiences and insights gained through years of risk analyses, has only marginally influenced the way the analyses are conducted. To a large extent, everything is analysed from scratch every time an analysis is required – the knowledge and experienced gained about potential accident scenarios and how an installation/module/system can best be designed, are not adequately exploited.*
>
> *Traditional quantitative risk analyses with emphasis on detailed calculations of total risk level and comparison against risk acceptance criteria (e.g. FAR and 1.0 x 10^{-4}) should be replaced by simplified risk analyses with the aim to provide the best possible decision support. Rather than trying to continue the quest for perfect descriptions of what the risk is, the goal should be to give better decision support at the right time.*
>
> *The recommended practice represents a significant simplification of the current risk analysis practice, especially when facing situations characterized by known technology, considerable experience and little uncertainty, i.e. what can be termed "standard solutions".*

The risk analyses will to a greater extent provide decision support at the right time, thereby contribute to the avoidance of late changes in development projects following results from risk analyses carried out at a late stage in the project. The analyses will also aid Operations in becoming familiar with the barriers' functions and ability to deal with potential events, both those that the facility is designed to handle and those that one cannot expect are handled. The new methodology will make it easier to demonstrate that a given development meets the minimum authority requirements, and the methodology also meets the intention of the authorities' recent definition of risk where uncertainty is a key aspect.

It is therefore recommended to continue the project with the following aim;

- To provide an overview of decisions in a project where risk analyses would provide improved decision support

- To establish risk- and consequence models to provide this improved decision support

- To establish guidelines for risk management in development projects

- To establish overview of where the proposed models and processes are not in accordance with the requirements and standards and propose regulatory changes

The RISP project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is expected to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

2.3 Objectives and scope of work for RISP

The overall objective of the RISP project is to further develop the principles and ideas provided by the NOROG project into methods, models and guidelines, and establish a new common "industrial practice". This practice should describe how various decisions in a development project are to be based on general and specific knowledge about the incidents that the installation may be exposed to (such as leaks, fires and explosions).

Traditional quantitative risk analyses with considerable focus on detailed calculations of total risk and measurement against risk acceptance criteria such as FAR and frequencies of loss of main safety functions (1×10^{-4}) should, when technology and challenges are known, be replaced by input based on knowledge and experience acquired by past projects and analyses, providing a robust safety level. Instead of searching for detailed descriptions of what the risk level is, the objective should be to provide valid decision support at the right time.

The principles for risk-related decision support provided in ISO 17776, see Figure 1, shall be used as basis for the RISP project. The figure also illustrates the focus area for the work carried out as part of this JIP (RISP).

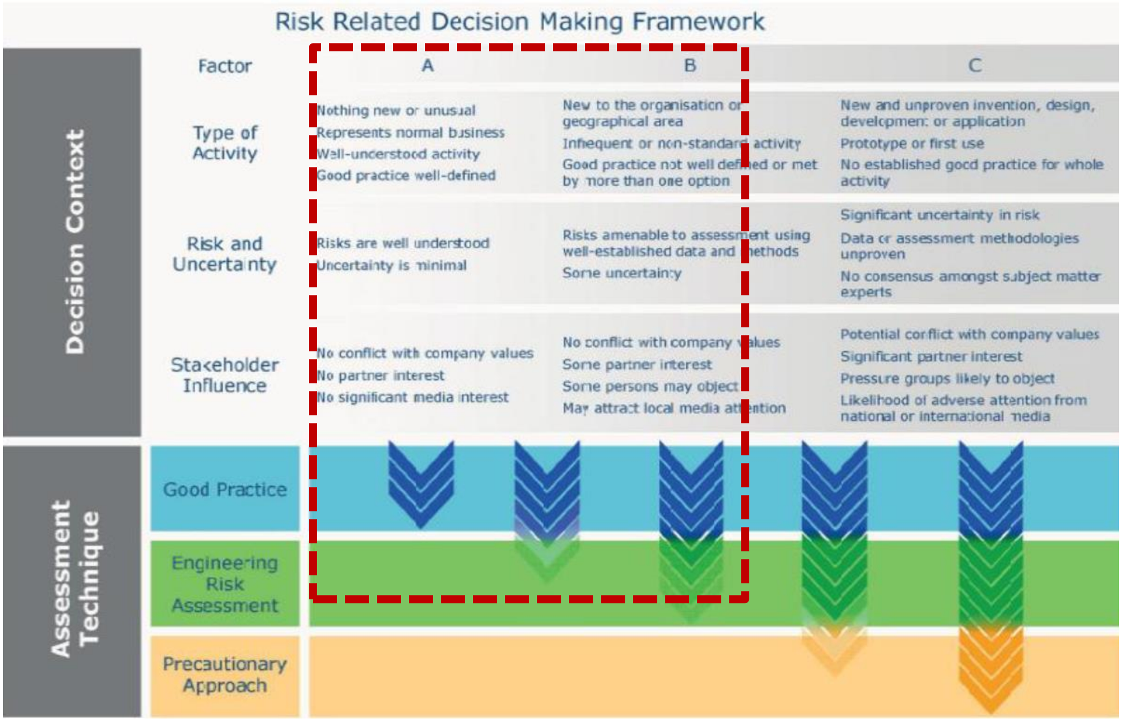

Figure 1 - Risk related decision-making framework from ISO17776 (Ref. /2/). The red doted box illustrates the focus area for the work carried out as part of this JIP (RISP).

The new «industrial practice» developed aims to clarify:

a) if a potential type of hazard/incident is sufficiently covered by using systems and solutions indicated by requirements in standards, established good practice and results of former analyses. Typically, left part of situation A in Figure 1. Or

b) if a potential type of hazard/incident can be sufficiently covered by simplified methods and models established based on knowledge and experience acquired by past projects and analyses. Typically, right part of situation A and major part of situation B in Figure 1 . Or

c) if there is a need for obtaining and using additional assessment techniques (compared to item b) for the hazard/incident. Typically, situation C in Figure 1.

When situation b) applies, the new "industrial practice" must specify the methods and models that should be applied and give guidance on how results (and the conditions/assumptions they are based on) can/should be used in the decision-making process. In this way the decision maker should also be made aware of the importance of the decision and the impacts of the various decision options.

The methods and models to be included in the new «industrial practice» will be adapted to the knowledge and information typically available at the time when the specific decisions of interest are normally made. The decision support provided shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the input used and the restrictions related to further design development) has not been changed throughout the project. This will minimise the need for late design changes, when e.g. more detailed information is available. An as-built total risks analysis/quantitative risk analysis (TRA/QRA) will thus not be required within the new "industrial practice", but verification activities need to be developed. Verification shall ensure compliance with the validity envelope of the new approach, and that any changes in assumptions made during the development project are considered.

Barrier management, in its wide context, should found the basis for risk management in operations. A balanced description of the risk comprehensive enough for the operational phase, should be established also within the new "industrial practice".

The RISP methodology includes decision gates related to whether the MAH hazard in question can be handled with use of the established RISP methods and models as decision support in development projects. The need for additional assessment techniques for the risk related decision-making process is identified. However, no details are established as part of this RISP project for these additional techniques except referring to ISO 17776, PSA regulations and present practices for management of MAH.

The RISP methods and models established are applicable for proven design where technology and challenges are known, and decision support can be based on experience and knowledge acquired by past projects and analyses. The intention has also been to identify the design standards which should be used as basis for the design.

2.4 Requirements to methods and models

Important requirements specified for the methods and models established include:

a) The methods shall ensure that at least the same level of safety is achieved as the level given by the current practice.

b) The methods and models shall be based on best available knowledge.

c) The theoretical and empirical basis for the methods and models established, including the assumptions made, shall be available for review. Possible differences in perceptions amongst experts (related to a subject) shall be stated, and an explanation for how this has been accounted for shall be given. Lack of general knowledge on a specific subject, and how this has been accounted for in the methods and models provided, shall also be described and be available for review.

d) The methods and models must be transparent, meaning that information on how the results have been produced and which factors are important for the results shall be available for review

e) The methods must be traceable, meaning that each assumption and parameter used in the model shall be available and documented.

f) The methods and models shall be openly available to the industry

In order to ensure that the methods and models established in the project remains updated over time (i.e. “at all time” are based on the latest/best available knowledge and experience), a process for when and how to update them needs to be established.

2.5 Project organisation

The RISP project is organised as a research project with 14 participants. The participants include sponsors, vendors and project owner.

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

The vendors are nominated by the sponsors. Different work packages are defined for the work to be carried out by the vendors organised as workgroups. The vendors are: Lilleaker Consulting, Gexcon, DNVGL, Lloyd’s Register, Aker Solutions, Proactima and Safetec. The vendors have provided a considerable in-kind contribution.

The JIP consists of two subprojects. Subproject 1 has been carried out in 2018 and includes WG 1 and WG 2. Subproject 2 has been carried out in 2019 and includes WG 3, WG 4 and WG 5.

Aker Solutions was the project owner for Subproject 1, while Equinor has taken over the role as project owner from 2019. The ownership rights to the project results shall accrue to Equinor. All participants have a free right to access project results within their operations.

The PSA has been involved as observer in the RISP project.

The RISP project organisation for Subproject 2 is illustrated in Figure 2. Please note that communication with union representatives has been postponed and needs to be dealt with in a possible continuation of RISP work.

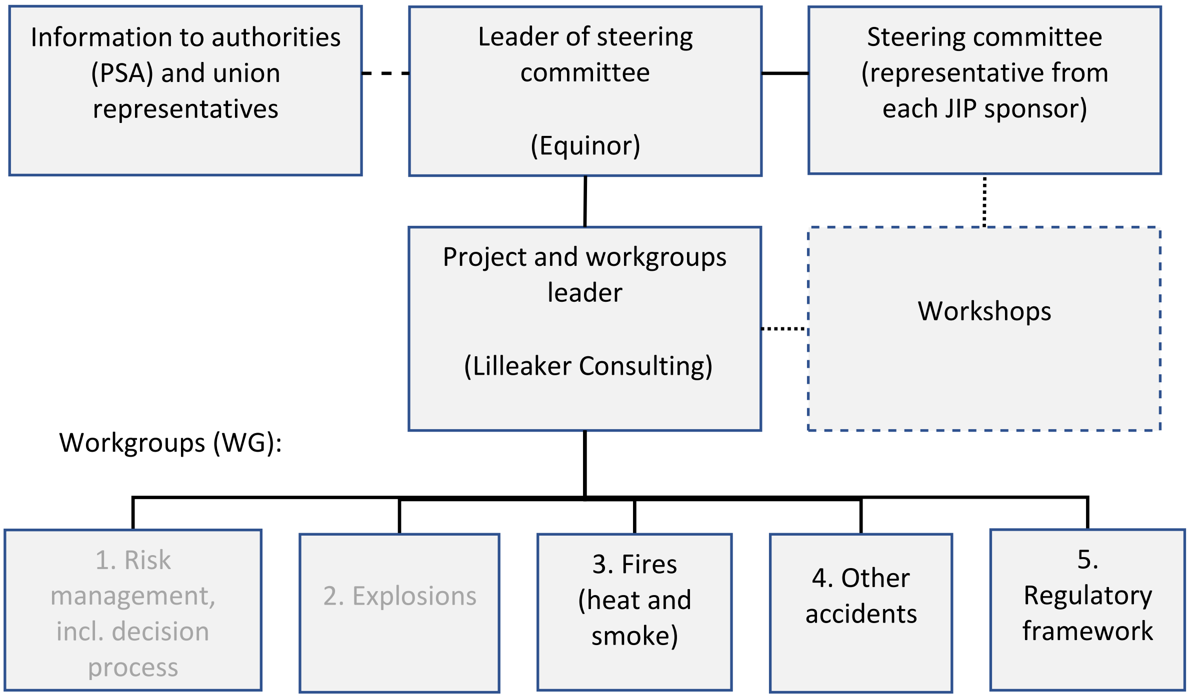

Figure 2 – The RISP project organisation overview (Subproject 2)

3. The RISP methodology

3.1 Framework for RISP

The RISP methodology has been developed with the main intention to improve the decision support provided related to MAH (major accident hazards) in the early design phases of offshore development projects on the NCS.

The framework for RISP includes the following boundaries:

- The RISP methodology includes decision gates related applicability for any development project. If the RISP methods and models are not applicable, the need for additional risk assessment techniques for the risk related decision-making framework is identified. However, no details are established as part of this RISP project for these additional techniques except referring to ISO 17776, PSA regulations and present practices for management of MAH.
- The RISP methods and models are applicable for proven design where technology and challenges are known, and decision support can be based on experience and knowledge acquired by past projects and analyses. The intention has also been to identify the design standards which should be used as basis for the design.
- The RISP methods and models are adapted to the decision support needed when the related design decisions are normally made. The models are tailored to the information typically available when the decisions are made, implying that the input often is coarse and with limited detailing.
- The recommendations given by RISP methods and models shall ensure at least the same level of safety is achieved as the level given by the present practice.
- The methods and models shall be based on best available knowledge, be transparent and traceable and openly available for the industry (see details in Chapter 2.4).
- The present probabilistic PSA requirement related to loss of main safety functions (annual likelihood of 1×10^{-4}) will not be documented quantitatively for each project. Instead the requirement will be indirectly complied with since the robustness of the new RISP designs will be based on experience from similar existing designs that comply with the requirement.
- The decision support given shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the assumptions used and the restrictions related to future decisions (e.g. detailed design), etc.) has not been changed throughout the project.
- The methods do not include requirements for an as-built TRA/QRA for verification. However, it is a prerequisite that the development project has a management of change system identifying and managing changes affecting the decisions made and that necessary verification activities to assure compliance to regulations and safety premises are identified, executed and followed-up.
- The present PSA regulations, including the standards referred to in the regulations, have been used as a basis for the RISP project. (Although referred to as the PSA regulations in this report, the sets of regulations fall within the jurisdiction of several regulatory authorities). Signals from the PSA is that the industry should propose the principles it believes provide the best solutions, and not be restricted by current regulations. The PSA pinpoints however, the ambitions to be world leading in HSE and the requirements for continuous improvement, robustness and risk reduction. If adjustments to regulations including referred standards and interpretations are proposed, it should be clear that it will lead to improved safety. Further the PSA pinpoints that when design is to be based on prequalified solutions described in standards, it is important that the solution described are robust.
- The RISP methodology can also provide relevant MAH information for the operational phase, e.g. as input to the risk picture, barrier management and emergency preparedness. However, elaboration of the risk informed decision support required for the operational phase, has not been part of the current work.

- The RISP models aims primarily to be used to define design accidental events, design accidental loads and corresponding survivability requirements. The models established cover to a lesser degree a complete input regarding risk drivers, probability reducing measures, input to robust and inherent safe design as well as recommended design standards. This needs to be considered as part of management of MAH.

3.2 Validity envelope

The RISP validity envelope describes constraints and conditions for using the RISP methods and models. The aim has been to describe the envelope as precisely as possible to simplify the application in use. The validity envelope is expected to be challenged as part of HAZAN in each development project. A topic for the HAZAN is to conclude if the RISP methods and models can be used or if there are special constraints and conditions for the use. Key elements in the validity envelope include:

- General aspects:
    - The (relevant part of) concept is considered proven for the current situation and conditions. This means that aspects considered potentially as novel or unproven, are evaluated specifically regarding the validity envelope. Examples of aspects that may be necessary to evaluate (in addition to technical aspects) includes operational philosophy, reservoir conditions, process conditions and environmental conditions.
    - The MAH causes and effects are well understood
    - Necessary resources and competence for a proper management of MAH are available for the development project. See e.g. the PSA Framework regulations section 10,11 and 12. Guidelines describing appropriate principles for management of MAH are described in e.g.:
        - ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016. See ref /2/
        - Petroleum Safety Authority Norway, "integrated and unified risk management in the petroleum industry", dated June 2018. See ref /3/.
- The intention has been to define the validity envelope for each RISP model as unambiguous as possible for each MAH as part of WG 2 – 4. It is emphasised that each model will define constraints and conditions applicable per hazard type and area. This means that within an area a RISP model for one type of MAH may be applicable while a model for another MAH is not applicable. Likewise, a RISP model may be applicable for one area of a concept while not applicable for another area.
- It is acknowledged that the NORSOK S-001, 2018 edition is a key document providing design premises related to MAH. The standard contains both prescriptive and functional based requirements to the performance required for safety barriers/-systems. It is concluded that application of this NORSOK standard as a basis for the design development, will be a valid and important premise for the RISP methods and models. Other standards giving design premises are identified as part of WG 2- 4.

3.3 HAZAN

HAZAN is a key element in the RISP methodology. It is based on and includes the present practice of performing a hazard identification (HAZID) as described in NORSOK Z-013. However, it contains further elements to assure a proper basis for applying the RISP methods and models as decision support. In addition, it contains an assessment (or analysis) part to obtain a deeper understanding of the MAH and the associated strength of knowledge for the specific concept/design. By describing and understanding the MAH involved including risk drivers, an important basis for risk reduction and communication with affected stakeholders and disciplines is obtained.

The HAZAN is considered a crucial and important basis for management of MAH in a development project and it needs to be comprehensive and well planned. The HAZAN typically includes one or more documented and structured workshops with stakeholders and subject matter experts involved.

By following the HAZAN process, the following is considered:

- It is evaluated whether there is something unique with the proposed design
- Relevant hazards are identified and classified (HAZID)
- It is evaluated whether hazards are different than normal for the areas on the facility. This includes evaluation of uncertainty, strength of knowledge and whether criteria for use of the simplified RISP methods are met per area and type of hazard.

The above provides decision support to conclude if the RISP methods and models can be used or if special studies or considerations are needed.

The HAZAN process may provide useful decision support at early stages of the project execution for any type of project. It can limit the need for changes to design caused by new or changed safety requirements at later stages.

The HAZAN process is carried out by performing the following steps:

1. Describe characteristics of the suggested development.
2. Identify and analyze initiating events including hazards and uncertainty factors. This includes:
    - Identify, evaluate and classify MAH
    - Identify key risk drivers
    - Identify and consider risk reduction issues
3. Evaluate and demonstrate strength of knowledge
4. Check predefined validity envelope for RISP methods and models and identify safety premises
5. Decide on use of RISP models and identify any need for additional information and special studies or considerations to be performed.

For an elaborative description of the HAZAN, reference is given to the WG1 report. See also the illustration of workflow using RISP methods and models in Figure 4.

3.4 Typical workflow using RISP models in development projects

The new RISP methodology compared to a more traditional approach is illustrated in Figure 3.

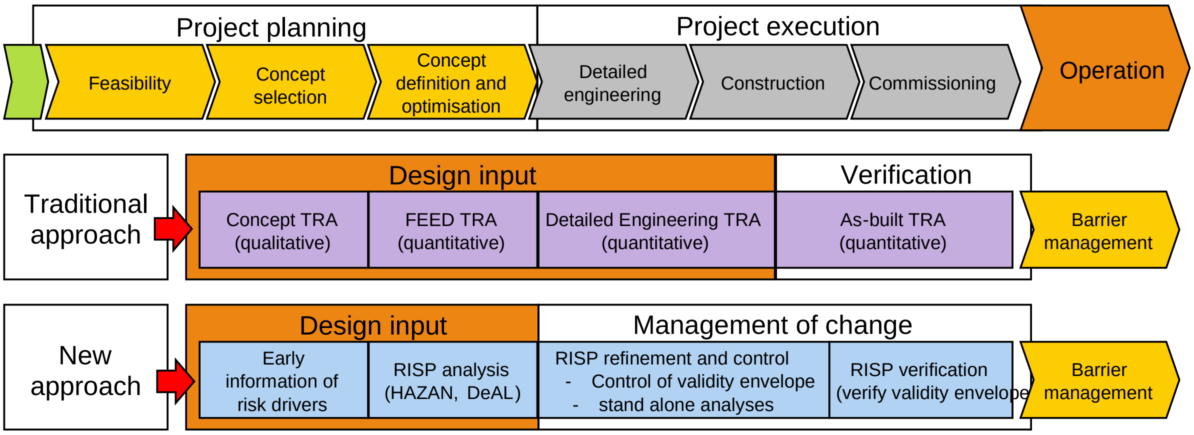

Figure 3 - Early design input delivered by RISP within the validity envelope

An illustration of a typical workflow using the RISP methods and models in development projects has been established. The workflow during Project Planning phase and Project Execution phase is illustrated in Figure 4.

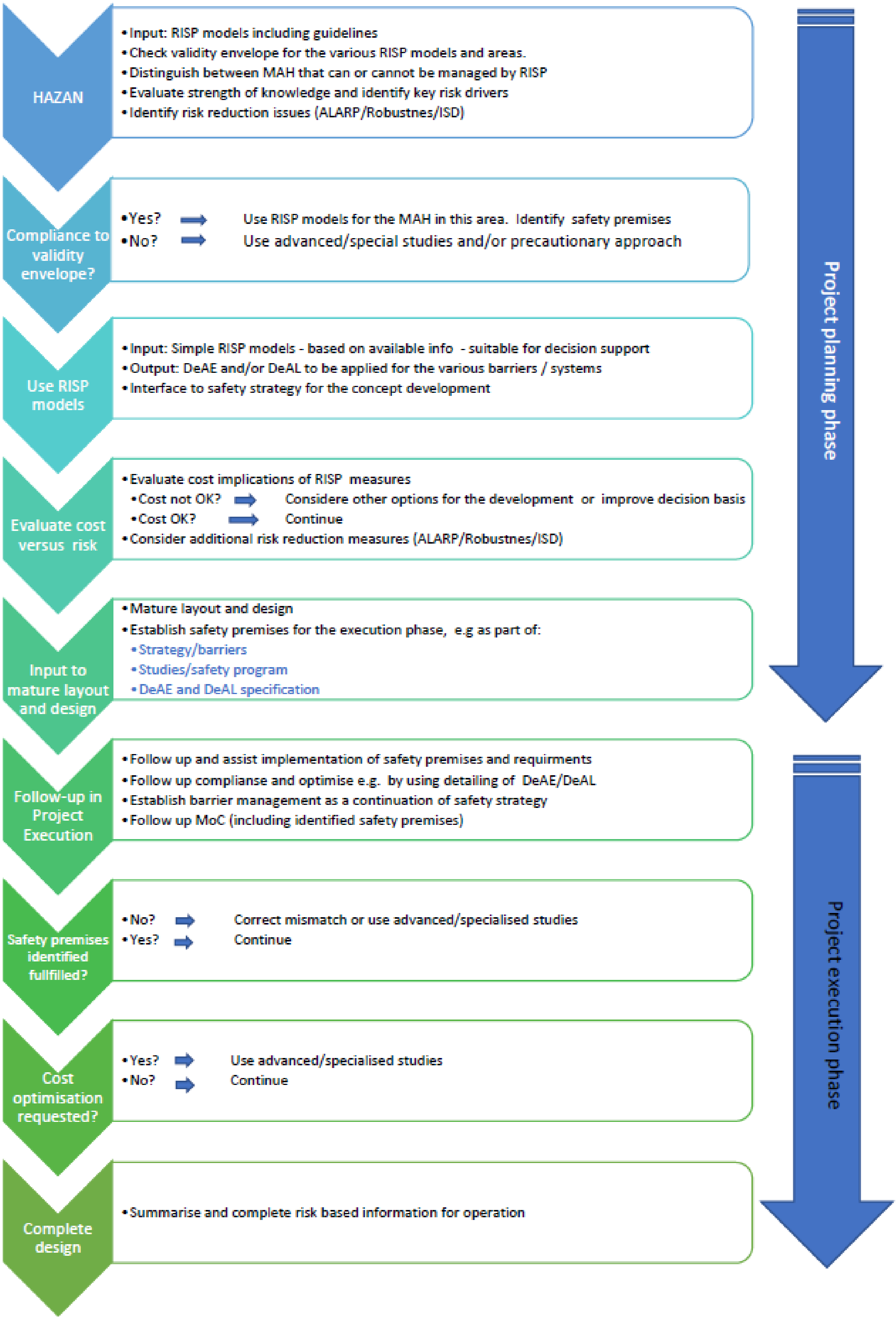

Figure 4 – Workflow using RISP methods and models - illustration

3.5 Type of decision support provided by RISP models

The need for decision support in development projects has been collected based on the experience of the RISP participants as well as by workshops and communication with engineering and oil companies.

It is found challenging to extract single decisions made at a specific time in the design process. The design process more typically implies a lot of dependencies and iterative work in decision making. A main task during Project Planning phase is to establish the technical basis for the subsequent Project Execution phase. The design premises (in addition to requirements given in regulations, standards and good practices) for handling of MAH should as far as possible be established in the Project Planning phase.

Decisions made in the Project Planning phase with respect to MAH will, have to include safety margins to avoid later changes unless a very strict management of change strategy is implemented. The extent and quality of the work in the Project Planning phase is hence crucial to obtain valid design premises that are not overly conservative. During Project Execution phase a main task is to detail the safety premises for implementation into design and to follow up effect of changes. It is expected that in many projects the design premises, detailing of the premises and way of implementation of the premises, will be challenged from a cost optimisation point of view. This may imply that the validity envelope of RISP is challenged and that other risk assessment techniques are applied for decision support. The focus for RISP is primarily to establish safety input and premises for handling MAH in a proper and efficient manner at the right time. As the concept, layout and technical basis for Project Execution phase are to be established in the Project Planning phase, the screening of decision support performed has focused on this phase.

The design accidental load specification normally plays a key role in design requirements related to MAH, especially related to survivability requirements. A main task for the RISP workgroups has hence been to establish models for recommending design accidental events and loads and the application of the loads.

It is acknowledged that the NORSOK S-001 2018 edition, is a key document providing design premises related to MAH. The standard contains both prescriptive and functional based requirements to the performance required for safety barriers/-systems. It is concluded that compliance to this NORSOK standard shall be a premise for the RISP methods and models.

The RISP methodology aims at contributing to accountability of decision makers for decisions affecting MAH. It is judged that that this can be achieved by providing simplified and transparent information that makes decision makers:

- understand importance of decisions being made,
- understand effect of decision on vulnerability and robustness and
- understand safety premises related to the decision.

The intention has been to provide the following results relevant for MAH by use of the RISP models:

- Recommended Design Accidental Events and Loads (DeAE and DeAL)
- Description of key/critical risk drivers and their:
    - importance for DeAE, DeAL and robustness
    - effect on layout and design solutions.
- Premises for use of standards, e.g. NORSOK S-001, rev 2018
- Input to extended HAZID i.e. the HAZAN including:
    - Check list for topics to be evaluated in the HAZAN
    - Description of validity envelope for the RISP models.
    - Design recommendations for handling of the MAH

3.6 Sample of RISP models

Table 1 presents some samples of RISP models established with key characteristics. The table is included to illustrate type of solutions for various models. This includes whether the hazard is a design event or not (DeAE/DeAL), how the scenario is specified and corresponding survivability requirements for key safety barriers. A complete presentation of the RISP models established are given in WG 2, 3 and 4 reports. For explosion there is an ongoing work to establish a RISP model (Ref. /4/).

Table 1: Samples of RISP models established.

Hazard	Key model	Comment
Ignited process fire	- Structural integrity (including secondary structure): DeAE = WCPF. Method to establish DeAL and potentially generic loads. - Escalation to process equipment: DeAL – 250 kw/m^2 for 2 minutes (no escalation) and 350 kw/m2 for 15 minutes (no escalation causing > 30 kg/s). - Global main safety functions (escape routes, evacuation means, muster area): DeAE 30 kg/s. Duration 15-60 minutes.	- Initial fire > 30 kg/s: Estimated annual frequency of 0.7 x 10^{-4} per year for a large process module. - Typical WCPF for structural integrity in a naturally ventilated module: 5-30 kg/s
Ignited riser fire	DeAE: Ignited leak in any of the riser segments that will give the worst fire exposure of the main load bearing structures, safe area and evacuation means.	- DeAE covers annual fire frequency levels between 1 x 10^{-5} and 1 x 10^{-3} - ESD valves and SSIVs can be credited as segregation for the riser segments. The closure time needs to be reflected regarding heat loads and duration. This presumes the valves are treated as safety systems with testing and performance requirement (typical reliability level of 98 % or higher). This implies that the valves have requirements for closing time and internal leak that are verified through testing. - The assessment of DeAE shall include possible escalations (to other risers, wells, and/or process equipment). - Main load bearing structure shall be intact to ensure escape to safe area and time for evacuation. Default time for evacuation is set to 60 minutes but should preferably be based on installation specific considerations. - Safe area/mustering area shall be intact and functional to allow time for evacuation. Default time for evacuation is set to 60 minutes but should preferably be based on installation specific evaluations. - Evacuation means for minimum 100 % of maximum manning onboard at any time shall be available for evacuation. Requirements for availability of an extra lifeboat for redundancy, shall also be included. The evacuation means shall be available from 15 minutes after onset of the DeAE until evacuation can be considered complete. For bridge connected installations the

Hazard	Key model	Comment
		requirement can be fulfilled by availability of the bridge. - The applicable fire loads can be established by CFD tools or conservatively applying simpler methods (e.g. as described in NORSOK S-001). - The DeAL shall reflect/cover loads from at least 90 % of representative scenarios (DeAE) within each leak size category for each riser segment. The 90 % requirement is stated to cover variations in weather conditions, leak location, leak direction etc.
Ignited blowout	DeAE: Long lasting ignited blowout in all areas of topside except mud/module/shaker room (Subsea ignited blowouts not a DeAE). Fire rate to cover up to maximum blowout rate (Default value up to 100 kg/s).	- DeAE covers annual fire frequency levels between 1 x 10^{-5} and 1 x 10^{-4} - Main load carrying capacity to consider typically 5-30 kg/s - Other main safety functions to consider maximum rate (100 kg/s)
Collision from passing vessels	Not a DeAE	- Presumes compliance to traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) - Presumes installation location away from traffic separation scheme (TSS), at least half of the width of TSS. - Important to do a Vessel traffic survey of AIS data and assess degree of operational barriers in place.
Collision from supply-vessel – Manoeuvring from standby position to operating position	DeAE: Head-on collision with larges vessel with impact speed of 4 m/s.	- Presumes compliance to G-OMO-procedure - Presumes waiting position for vessel to be downwind the facility
Collision from supply-vessel – Manoeuvring at operating position	DeAE: The corresponding speed in head-on collisions with largest vessel shall be 0.5 m/s and 3.0 m/s for ULS and ALS checks respectively.	- Presumes compliance to G-OMO-procedure - Presumes loading position to be downwind the facility
Crane boom fall	Not a DeAE	- Crane boom fall can be expected with a frequency of no more than 5 x 10^{-5} per platform year. - Crane boom fall should be considered as part of ALARP process. Guidance is given on protection energies and layout

Hazard	Key model	Comment
Dropped object impact on seabed arrangements	DeAE: Probabilistic model given a drop of the lifted load over sea. Pipelines must survive impact from 95% of all loads.	- A 95% survivability corresponds to an average annual fire on sea frequency in the order of 5×10^{-5}
Accidental heel	Accidental heel is a DeAE on floaters. Credible heel scenarios shall not cause a static heel exceeding 17 degrees. Static heel to be combined with 1-year weather condition giving dynamic roll and pitch as calculated for the installation.	- Presumes design according to regulations and standards. - Consequences of DeAE needs to be assessed and survivability requirements for safety systems to be defined.

4. Regulatory framework and standards

WG 5 has considered the outcome of WG 1, 2, 3 and 4 reports and evaluated where there may be a mismatch/conflict between the proposed methodology and the requirements given in the existing regulatory framework, including standards referred to in the regulations. The task has primarily been to identify needed changes, if any, to be able to implement the RISP methodology.

Since WG 5 is based on all previous work packages, also topics relevant for the overall scope for the RISP project is commented by WG 5 when found relevant and appropriate.

Key conclusions are summarised below:

- The regulative regime is ambitious and includes functional based requirements. The regulations have not explicitly expressed requirements for quantification of risk numbers. Hence, no direct conflict or mismatch has been found between the RISP methodology and the regulations. Although the regulations can be interpreted in different ways, the PSA underlines that it is a task for the responsible parties to establish practices that are compliant to the regulations and suitable for the industry.
- The regulations refer to several standards of good practice that relates to management of MAH and for proper safety design. These standards have included the concept of risk quantification to various levels. Alignment between the standards and the results provided by the RISP methodology may hence be beneficial to consider.
- The regulations refer especially to NORSOK Z-013 for the requirement that loads/actions with an annual likelihood greater than or equal to 1×10^{-4}, shall not result in loss of a main safety function. This has been interpreted as a quantitative requirement by the industry. Likewise, the practice related to probabilistic explosion analysis included as informative materiel in NORSOK Z-013, has been included as a best practice by operators. It is concluded that this standard should be updated to better stimulate good practices for use of risk assessment techniques and management of MAH for decision support. The RISP methodology as a way of documenting prequalified solutions should be a part of this update.
- The NORSOK S-001 2018 edition, is a key document providing design premises related to MAH. It is concluded that compliance to this standard shall be a premise for the RISP methods and models. The standard describes parts of management of MAH which is not well aligned with the RISP methodology. Also, the word should, is used a lot in the standard to describe "a suggested possible choice of action deemed to be particularly suitable without necessarily mentioning or excluding others". This causes some uncertainty to what is required to be compliant to the standard and to the regulations. These challenges need to be considered when applying the RISP methodology in development projects.
- The regulations give ambitious requirements for continuous improvement and risk reduction. These requirements are challenging to fulfill. It is judged that both quality and efficiency in management of MAH may be improved by establishing suitable best practices.
- The RISP methodology can play a role and be part of a good practice for management of MAH. The methodology is judged suitable to provide valid decision support at the right time during development projects. Strong focus needs to be put on the HAZAN, both the methodology and involvement of stakeholders and subject matter experts in the work process.

5. Summary, conclusions and recommendations

5.1 Summary and conclusions

This report presents the Joint Industry Project (JIP) called risk informed decision support in development projects (RISP). The project has been carried out in 2018 and 2019. The project has further developed, and concretised principles and ideas provided by a former NOROG project into new methods and models. The project is related to management of major accident hazards (MAH) in development projects on the Norwegian Continental Shelf (NCS).

The project has screened the risk informed decision support needed in typical development projects. Risk assessment methods and models have been established suitable for decision support based on information available when the decisions are normally taken. The recommendations given by the models are considered robust as to avoid the need to reiterate the decision based on more detailed information available at a later stage provided premises for the decision are not changed.

The methodology established is based on the risk-based decision-making framework given by ISO 17776 which differentiate the assessment techniques dependent on the complexity of the development project. The methods and models established are valid for proven design where prequalified solutions can be applied.

As far as possible the methodology is based on design requirements given by standards. It is acknowledged that NORSOK S-001 is a key standard in this respect.

The methodology has been reviewed in relation to the present regulative regime to identify possible conflicts and need to update regulations and standards. The regulative regime is ambitious and includes functional based requirements. The regulations have not explicitly expressed requirements for quantification of risk numbers. Hence, no direct conflict or mismatch has been found between the RISP methodology and the regulations.

Reflections based on the performed work includes:

- Although management of MAH in the Norwegian oil industry has been successful, there is an obvious potential to improve both quality and efficiency in application of risk assessment techniques as decision support in development projects.
- A considerable maturation of views on the RISP principles and ideas has taken place among the participants during the execution of the RISP project. Clearly it has been different views on the degree of the challenges with the present practice, the causes of the challenges and on the best solutions.
- The ambitions of the RIP project have been large and the complexity of the tasks and project organisation considerable in comparison to the resources available for execution of the project. As must have been expected, the ambitions of the project are not fully completed, and thus for some of the methods and models further work is needed.
- Methods and models for risk-based decision support in development projects have been established. A workflow for use of the RISP methods and models has been established to support management of MAH. The extended HAZID called the HAZAN is an important part of the workflow. The models established covers a number of hazards, both those which can be managed primarily by following design standards and those requiring simplified assessments models. The assessment models established focus on establishing design accidental scenarios and loads (DeAE and DeAL) and corresponding requirements for survivability of safety barriers.
- A set of requirements has been defined for the RISP methods and models (see Chapter 2.4). The requirements are fulfilled to various degrees for the different models. A review of the models from subject matter experts as well as by potential users of the models would be beneficial to identify improvement areas. During the work performed, different perceptions amongst experts have not been documented. Further, the basis for the models are only partly documented and available for review. How to assure that models remain updated over time has not been answered. However, in order to comply with the expectations in the

regulations, the RISP models must be placed in a context of continuous improvement, and this context should be owned by the operators (as the responsible party) in terms of overseeing the use of models and identify an initiate improvement actions when deemed necessary.

- The ambition to assure at least the same safety level as present practice is considered achieved within the validity envelope of the models. This is obtained by a conservative approach regarding the scenarios, loads and survivability requirements included.
- The decision support provided by the methods and models are considered to give the essential input needed during development projects – especially during planning phase for proven design.
- The PSA is positive to and support the initiative taken by the industry in this project. They pinpoint the ambition to be world leading related to HSE and the requirements for continuous improvement, robustness and risk reduction. The regulation includes functional requirements, it is a task for the industry to establish good practices for compliance.
- Topics covered to less degree in the present RISP project includes:
    - Measures to reduce the likelihood for an incident to occur
    - Methods and models to use outside the validity envelope of RISP
    - Best practices for management of MAH within development projects
    - Risk based decision support in operations

5.2 Recommendations

A new methodology replacing traditional quantitative risk analysis with simplified experience-based methods for improved decision support in development projects has been outlined and substantiated in this report. In order to qualify the new RISP methodology and improve its ability for risk-based decision support in development projects, the following recommendations are given for the SC members to consider:

1. Through the JIP execution, considerable maturation and consolidation has been achieved among the RISP participants. The common understanding of context and basic ideas for the RISP methods and models has been improved along the way of the project execution. For a successful implementation and use of the RISP methodology, it is recommended to continue and extend the effort on anchoring the methodology with important stakeholders, including authorities, union representatives, operators, engineering, consultants and subject matter experts.
2. Although a considerable effort has been made to establish the RISP methods and models, it is recommended to evaluate the need for additional work to make them qualified and ready for use. Topics to consider include:
    a. Establish a precise description of the validity envelope for the methods and models
    b. Assure that the RISP methods and models are based on best available knowledge, documented to show compliance to the 10^{-4} criteria and fulfilling risk reduction requirements (such as ALARP/ISD/BAT/Robustness).
    c. Assure that required input to topics for the HAZAN is established and identified
    d. Assure that valuable design recommendations are captured and provided where relevant for the different hazards.
3. The regulations are ambitious regarding management of MAH and requirements for continuous improvement, robustness and risk reduction. The requirements are generally functional based, and it is a task for the industry to establish good practices for compliance. In the same way as it is a potential for better methods and models for risk-based decision support, it is judged valid to stimulate improved management of MAH within the development projects This includes work

practices within the project organisation, scoping of risk assessment work and anchoring of relevant decisions. Although the requirements are functional based and complex, it should be an ambition to establish simple practices that are compliant with regulations. Hence, it is recommended to establish best practices for management of MAH. The PSA document "Integrated and unified risk management in the petroleum industry" as well as present various procedures applied by operators and contractors are considered to give valuable input to the context for such practices. The practices could include:

- Practices for risk reduction. A key aspect will be how to assure efficient integration into the normal design development.
- Practices for how to include robustness into design
- Practices for barrier management in development projects. The practice may reflect the need to assure that required barriers are included in the technical basis for the design during Project Planning phase (e.g. as part of safety strategy) while more detailed performance requirements are established in the Project Execution phase.

4. Based on experience from performed projects, it has been expressed that requirements for verification activities at the as-built stage are important to assure high focus and commitment on HSE aspects during project execution. As the practice of as-built QRA/TRA is not part of the RISP methodology, it is recommended instead to consider implementing verification at the as-built stage that all identified safety premises for the design are fulfilled.
5. The focus of the JIP has been on decision support needed in development projects. The need for decision support in the operational phase has not been considered as part of this JIP. The idea for the RISP methodology is that barrier management should be governing for the risk management in the operational phase. Traditionally, the QRA/TRA with comprehensive and detailed risk assessment, has been used as a basis for the barrier management. It is recommended to perform further work to evaluate how the needed and required risk picture should be established as a basis for management of MAH and barrier management in the operational phase.
6. It is recommended to update the NORSOK Z-013 standard to reflect the RISP methodology and establish best practices for use of the RISP methods and models. The updated standard should reflect the risk related decision-making framework in ISO 17776 and the PSA definition of risk and risk reduction. The standard should be more open for different approaches to risk assessments including required risk assessments for prequalified solutions.

6. References

/1/ Norsk Olje & Gass (NOROG): Prosjekt «Formålstjenlige risikoanalyser» Resultater og forslag til videreføring, Versjon: 6. februar 2017

/2/ ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016.

/3/ Petroleum Safety Authority Norway, "integrated and unified management in the petroleum industry", dated June 2018.

/4/ DNVGL and Aker Solutions: "RispEx – decision support for explosion design loads", DNVGL report no 2019-1329. Not yet issued.

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

Main report Workgroup 1 - Risk management

Report for:
RISP Participants, att: Aker Solutions AS

Report no: 107522/R1 Rev: Final A

Date: 1 February 2019

Summary

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

Main report Workgroup 1 - Risk management

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Document history

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Final A	1 February, 2019	Comments from RISP steering committee implemented	Workgroup 1
Final	23 November, 2018	Comments from RISP participants implemented	Workgroup 1
Draft A	8 October, 2018	Issued to RISP participants for comments	

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0. List of abbreviations

ALARP	As low as reasonably practicable
BAT	Best available technology
DeAL	Design accidental load
DiAL	Dimensioning accidental load
ESD	Emergency shutdown
FEED	Front end engineering and design
HAZAN	Hazard identification and analysis
ISD	Inherent safe design
MAH	Major Accident Hazard
NCS	Norwegian continental shelf
NOROG	Norwegian oil and gas
PSA	Petroleum safety authority
QRA	Quantitative risk analysis
RISP	Risk informed decision support in development projects
SSIV	Subsea isolation valve
TRA	Total risk analysis
WCDE	Worst credible design event
WCPF	Worst credible process fire
WG	Workgroup

1. Introduction

This report describes the work undertaken by Workgroup 1 as a part of the joint industry project RISP (Risk informed decision support in development projects).

A new methodology has been developed to allow for consistent use of industry experience rather than more analyses to support robust design of offshore facilities. The new methodology and its context are documented in this report.

This report is one of the five workgroup reports constituting the basis for the overall RISP report, see also Figure 1.

1.1 Background

1.1.1 Overall RISP project

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project) with results and proposals for further work was presented in the Operations Committee meeting in NOROG, and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The RISP joint industry project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is likely to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

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.

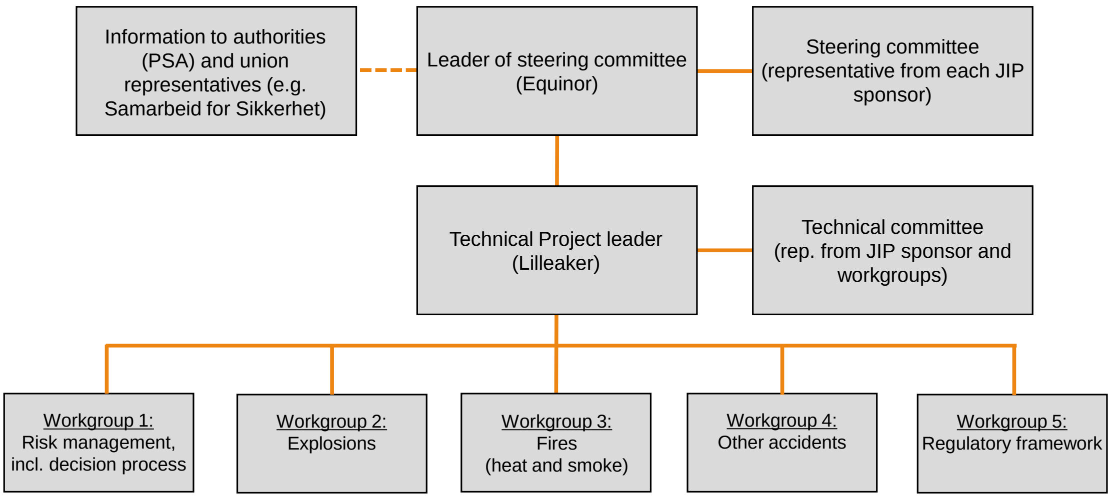

Figure 1 – The RISP project organisation overview

The five workgroups are undertaken 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 1 (Risk management, including decision process). The workgroup 1 has been constituted by representatives from Lloyd's Register (lead), DNV GL, Lilleaker Consulting, Proactima and Safetec.

1.1.2 Overall RISP context

Risk analyses have played, and still play, a key role in the safety work of the petroleum industry, and have given the industry detailed and broad knowledge about risk factors and design principles. However, the 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. Consequently, the decision support often arrives too late. In the cases of the new development being a standard design the benefit from performing detailed analyses may not be worth the wait as the risk sources are already known through experience from similar previous developments.

Experience and insight gained throughout the years from making analyses have barely impacted the way analyses are made. In general, "everything" is looked at anew each time, the knowledge acquired from incidents that may occur and how plants can be optimally designed is not sufficiently utilised or reflected in the way the analyses are performed.

A main recommendation from the NOROG project was that during a development project, traditional quantitative risk analyses should for standard designs as a main rule be replaced by simplified assessments. This should be done to provide the best possible support for decisions being taken on an on-going basis. Thus, the emphasis on detailed calculations of total risk, and measurement against risk acceptance criteria such as FAR and 1x10-4, should be changed. Rather than continuing to seek very detailed risk descriptions, the aim in the future should be to provide better decision support at the right time when the developed concept is well known. This is also in line with the "new" definition of risk given in Norwegian regulations (see guidance to PSA Frame agreement §11), which will be an important basis for the project.

The NOROG project drafted several principals and ideas for how to better deal with the above-mentioned factors. These ideas and principles has been further matured and specified in the RISP project, and proven and acceptable methods and tools can be developed for the industry's use based on the methodology outlined in this report. This will move risk management of standard designs away from total (quantitative) risk analysis as the governing element, and towards specific decision support related to each individual decision. Applying NORSOK S-001 as basis for safe design, the totality of the risk is considered ensured even though each RISP model covers only one specific part of the design (see also Section 1.3.4).

1.1.3 Overall RISP objective

The overall objective of the RISP project is to further develop the principles and ideas provided by the NOROG project into methods and guidelines, and establish a new common "industrial practice". This practice should describe how various decisions in a development project are to be based on general and specific knowledge about the incidents that the installation may be exposed to (such as leaks, fires and explosions).

Traditional quantitative risk analyses with considerable focus on detailed calculations of total risk and measurement against risk acceptance criteria such as FAR and frequencies of loss of main safety functions (1 x 10-4) should, when technology and challenges are known, be replaced by input based on knowledge and experience acquired by past projects and analyses, providing a robust safety level. Instead of searching for detailed descriptions of what the risk level is, the objective should be to provide valid decision support at the right time.

All models to be developed as a part of the RISP methodology should, as far as possible, be based on the principles for risk-related decision support provided in ISO17776, se Figure 2.

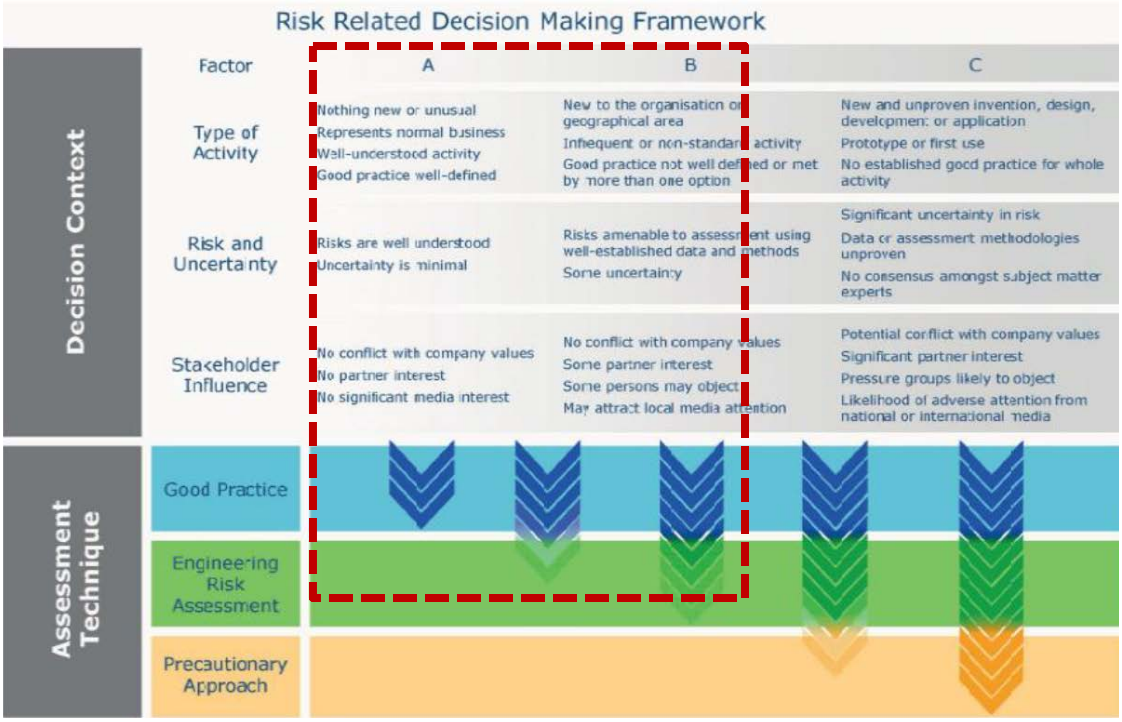

Figure 2 - Risk related decision making framework from ISO17776 (Ref. /8/). The validity envelope for the RISP methods and models is illustrated by the red dotted box, see also Section 1.3.3.

The new «industrial practice» developed aims to clarify:

a) if a potential type of hazard/incident is sufficiently covered by using systems and solutions indicated by requirements in standards, established good practice and results of former analyses (Ref. situation A and B in Figure 2), or

b) if there is a need for obtaining and using specific knowledge about the potential type of accidents associated the facility/project of interest, by making various forms of analyses of the course of events and/or potential consequences, to be able to make sufficiently robust decisions (typically situation C in Figure 2).

When there is a need for additional knowledge compared to situation a), i.e. situation b) applies, the new "industrial practice" must specify the methods or analyses that should be applied, and how analytical results (and the conditions/assumptions they are based on) can/should be used in the decision-making process. In this way the decision maker will also understand the background for the decision and the impacts of the various decision options.

The methods and solutions included in the new «industrial practice» will be adapted to the knowledge and information typically available at the time when the specific decisions of interest are normally made. The decision support provided shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the assumptions used and the restrictions related to future decisions (e.g. detailed design), etc.) has not been changed throughout the project. This will minimise the need for late design changes, when e.g. more detailed information is available. An as-built total risks analysis/quantitative risk analysis (TRA/QRA) will thus not be required within the new "industrial practice", but verification activities need to be developed. Verification shall ensure compliance with the validity envelope of the new approach, and that any changes in assumptions made during the development project are taken into account.

Barrier management, in its wide context, will replace as-built QRA/TRA as the basis for risk management in operations. A description of the risk sufficient for the operational phase will be established also for facilities designed based on the new RISP methodology.

1.2 Objectives and benefits – workgroup 1

1.2.1 Main objective

The main objective of workgroup 1 has been to identify the decisions to be made during a development project concerning the design of the facility where risk informed decision support (in terms of input from analyses / assessments) must/should be included as a part of the decision basis. Installation and commissioning activities and decisions made in operational phases is not part of the scope. The basis for the work has been a fully integrated topside facility, including subsea accidents that may affect the facility. The PSA regulations, including the standards referred to in the regulations, have been used as a basis. However, the current regulation has not been realised as a limitation to reach expedient solutions, see also Section 1.3.

The basis for the methods and models developed were to be founded on the decisions requiring risk informed decision support, and their importance in robustly designing against major accident hazards. When relevant, the timing of the decision and the level of information available are reflected in the description of the decisions.

Also the risk management principles used in a development project were to be considered, i.e. how should/could decisions makers use the risk informed decision basis that is provided by the methods and models developed when making their decisions? An important part of this was to enable the decision makers to understand the consequences of the decisions they make instead of using the QRA to show that the risk is within the risk acceptance criteria. How will their decisions affect the project in later project phases and in operations (e.g. to show the consequences of a riser fire if the installation is not designed for this scenario)?

The robustness in the decisions support provided (e.g. its sensitivity to changes), and how to deal with uncertainty (lack of general and/or specific knowledge) were also to be addressed. ALARP (as low as reasonably practicable), ISD (inherent safe design) and BAT (best available technology) were to be reflected.

This work package 1 has constituted the basis for the work packages 2-5.

1.2.2 Benefits

The RISP methodology described in this report is developed to provide better support for risk informed decisions taken during the early stages of development projects of standard designs.

The improved decision making process is expected to be achieved through better use of already existing industry experience and less use of new and time costly analyses.

The robustness of new designs developed by use of the RISP methodology shall be at least equal to the robustness of the existing similar designs. Robustness in this regard means ability to prevent and withstand major accident hazards.

The main benefits that can be achieved by use of the new RISP methodology are:

Better use of existing knowledge

Re-use of knowledge and experience gained throughout the years of designing and operating offshore facilities on the NCS, including the knowledge gained through the various risk analyses performed.

Speed-up of development process

Provide the designers with sufficient and timely decision support in order to define and implement robust design solutions.

Reduced uncertainty related to late changes

Basing the design on experience from previously proven developments will potentially allow for early establishment of robust design accidental loads against major accident hazards, and at the same time remove the need for late design phase scrutiny and rigorous verification of the design and its robustness. This will restrict uncertainty in the development projects from developments in the leak frequency models and the geometry congestion models and hence reduce the likelihood for significant design changes towards the end of the development projects. Note, however, that the reduced uncertainty is linked to understanding the risk impact of a decision (which in a traditional approach is not fully documented until the as-built TRA), and does not cover the uncertainties of having to make late changes due to other needs than managing major accident hazards (e.g. changing process conditions, changing ventilation, etc.).

Improved consistency

The new RISP methodology is founded on open and available robustness principles based on industry experience, and the same experience models are consistently applied for all similar developments. This is expected to increase the consistency in design and robustness between the different designers and risk analysts.

Early development stage information of risk drivers

The simplified RISP models will represent valuable information about risk drivers also in the feasibility and concept selection phases of the developments. This can improve the ability to understand possible safety challenges with concepts discussed in these early development stages.

Clearer responsibility for changes affecting risk level

The RISP methods and models intend to clarify the risk effect from important decisions, and hence provide a framework for management of change. RISP will provide an improved picture of the effect of the decision to be taken, and the premises for further design development.

The new RISP methodology is illustrated in Figure 3.

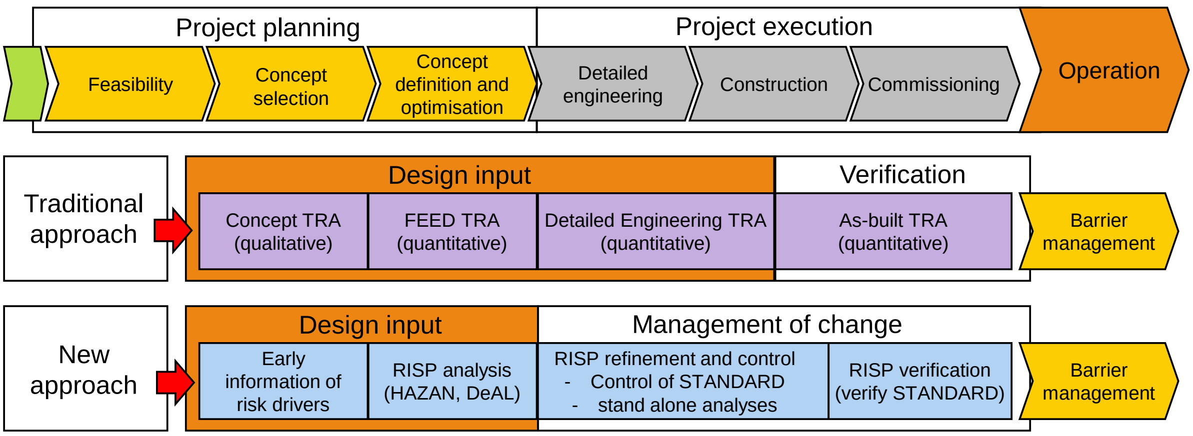

Figure 3 - Early design input delivered by RISP within the validity envelope

1.3 RISP Boundary limits

The new RISP methodology has been developed with the main intention to improve the safety decision processes in the early design phases of offshore facilities. The RISP methodology has been established within the framework of the following boundaries:

1.3.1 The Norwegian PSA

It is expected that the new RISP methodology will comply with the intentions of the existing regulatory framework defined by the Norwegian PSA. However, if it is perceived that the formulations in the existing regulatory framework are preventing an expedient solution, the RISP methodology could disregard the current regulatory framework.

No obvious discrepancies with the existing regulatory framework have been identified during the course of developing the RISP methodology, but it has been understood that the practical assessment of compliance has to be adjusted when using the new RISP methodology. E.g., the Facility regulation §11 requirement stating that

"..*dimensioning accidental loads/actions or dimensioning environmental loads/actions with an annual likelihood greater than or equal to 1x10-4, shall not result in loss of a main safety function*"

will not be quantitatively addressed, but will instead be indirectly complied with since the robustness of the new RISP designs will be based on experience from similar existing designs that all comply with the requirement.

1.3.2 Development phase focus

The new RISP methodology is developed for use in the development phase. This means that it is intended to give risk informed decision support from the "concept definition and optimisation" phase through the "construction" phase in development projects (see the NORSOK definition of development phases in Figure 3). The main focus is to provide robust safety input during the early design phases (also with reference to Figure 3).

The new RISP methodology may in addition provide useful information of risk sources and possible design challenges even in earlier development phases ("Feasibility" and "Concepts selection" in Figure 3) but use of RISP in these phases has not been a target area in the methodology development.

The RISP methodology shall also provide relevant risk management information for the operational phase, e.g. establish the risk picture and providing input to barrier management and emergency preparedness (see Figure 6 in Section 2.1), but the elaboration of RISP in the operational phase has not been part of the current work.

1.3.3 RISP validity envelope

The outlined new RISP methodology is applicable within a validity envelope. Note that this does not necessarily mean that all systems must be within this envelope; each RISP model may have different requirements for when it can be used, i.e. separate validity envelopes are assessed per RISP model (hazard and area). The exact definition of the validity envelopes for the various RISP methods cannot be defined until after all RISP work packages are completed. However, the overall process of assessing the validity envelope for both the overall RISP method and the various RISP models has been outlined in Section 2.2 and in Section 4.1. Key elements of assessing the validity envelope for use of the overall RISP process include (see Section 1.3.1, Section 2.2 and Section 4.1):

- Is the development following the principled defined by ISO17776 (Ref. /8/)?
- Is the development following the guidance for integrated and uniform management given by the PSA (Ref. /9/)?
- Is the development following the requirements defined by NORSOK-S001 (Ref. /2/)?
- Is the HAZAN (extended HAZID) process concluding with applicability for RISP?

The scope of work for workgroup 1 has been to define a feasible experience based methodology for decision support during the design of offshore facilities. In the cases where the development cannot be defined to be within the validity envelope, the applicability of the new RISP methodology has been outside scope of work to evaluate. This will be covered as a part of the Workgroup 5 scope (see Figure 1).

1.3.4 Basis in NORSOK S-001

The new RISP methodology is intended to be used within the already existing framework for risk management of development projects. This means that all design principles put forward in NORSOK S-001 (Ref. /2/) will be complied with and used also for RISP projects. The main change will be that traditional TRA analyses will be replaced by experience from similar projects (RISP analyses) for standard designs.

1.3.5 Unaltered activities not documented

In the cases when the new RISP methodology does not imply any changes in the activities and responsibilities normally undertaken during traditional development projects, these are in general not repeated in this report. In other words, only RISP activities that are different from traditional activities are documented.

1.3.6 Dependency on other RISP work packages

The current report from work package 1 is intended to define an overall framework for the other work packages (see Figure 1). Consequently, details of the final RISP methodology will be depending on the work from the other work packages, and this work package 1 report therefore needs to be updated after completion of the other work packages.

However, the RISP framework outlined in this work package is considered to define a feasible methodology for practical use in actual development projects and no potential show stoppers are expected due to the fact that the methodology needs further detailing from the other work packages.

2. The new RISP methodology

2.1 Overview of process

2.1.1 The risk management process

The main elements of the process for risk assessment according to ISO31000 (Ref. /3/) are presented in Figure 4, referred to as the risk management process. This process is general and can be applied to any risk informed decision in the organization.

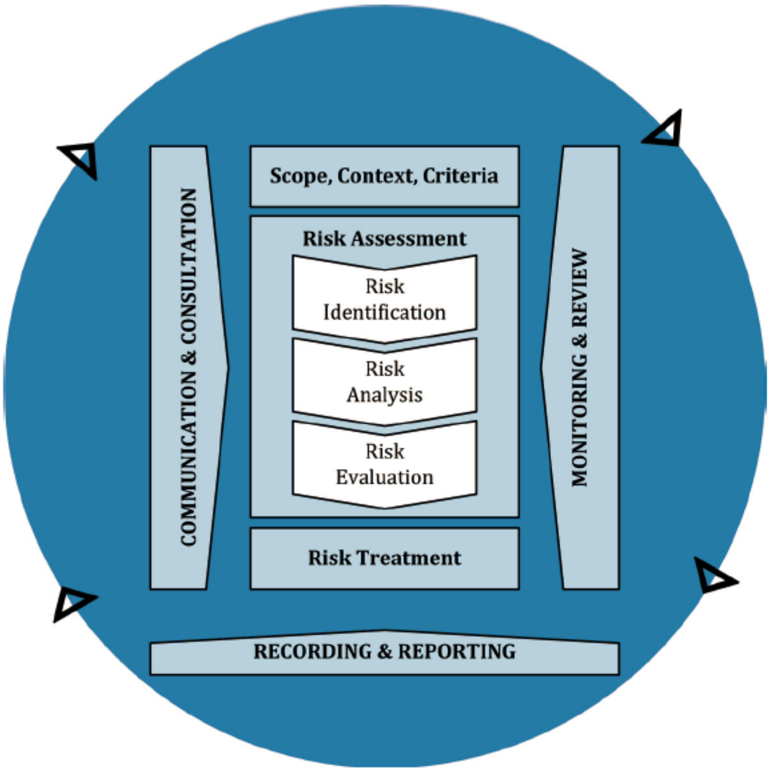

Figure 4 - The risk management process, as described in ISO31000:2018

The core of the process; a) scope, context, criteria, b) risk assessment, and c) risk treatment is consistent with common practice in the offshore petroleum industry for many years. The purpose of communication and consultation is to assist both internal and external stakeholders in understanding risk and the basis for supporting decisions, see also NOROSK Z-013 (Ref. /4/). Communication seeks to promote awareness and understanding of risk, whereas consultation involves obtaining feedback and information to support decision-making. Both of these aspects are needed when risk assessment results are being implemented in an organization. Monitoring and review include periodic evaluation of the risk management process and its outcomes in order to continuously improve the risk management process, Ref. /5 /. In a risk assessment context, this includes learning from previous development projects and how risk assessments can be applied to provide decision support.

The element on the bottom of the figure; recording & reporting, was introduced in the 2018 version of ISO 31000, Ref. /6/. As emphasized in the NORSOK Z-013 standard, recording and reporting should be documented to provide decision support, communication and improvement of risk management as well as interaction with other stakeholders.

Both the NORSOK Z-013 and the ISO17776 standard, Ref. /8/, include figures explaining their own content relative to the ISO31000 standard. For the ISO17776 standard, this is explained in the right part of Figure 5 below. This means that the figure explains how the 'general' ISO 31000 risk management process can be applied to major accident hazard prevention.

The ISO 17776 standard suggests three different approaches for MAH prevention depending on the decision context. This is exemplified in the left side of Figure 5. For development projects with no new or unusual design elements, it is accepted to design the installation according to good practice. The more new and unproven aspects that are included in the design, the more analysis is expected to be performed. This principle has been implemented in the RISP method.

The RISP methodology establishes safety design requirements in the early phases of the engineering utilising extensive experience doing risk analyses for several decades. The method also includes processes to ensure that these requirements are met and verified throughout the execution phase and validated in as-built design. The RISP method covers several concepts for the frameworks A and B given by ISO17776, a shown in Figure 5. The right side of the figure shows overview of the major hazard management process according to ISO17776.

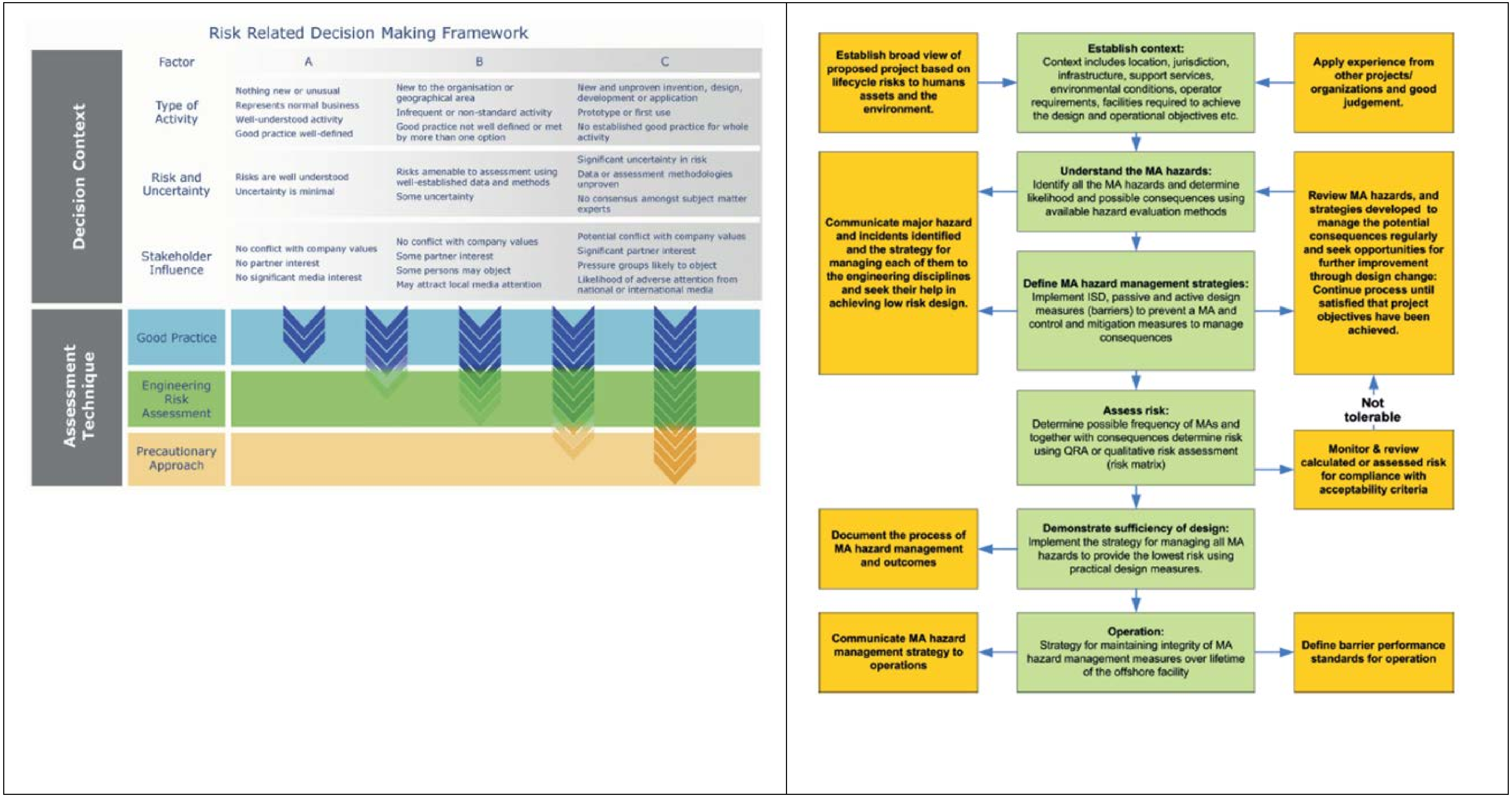

Figure 5 - Framework for risk-related decision support (ISO17776, Annex A and Figure 1)

2.1.2 Establishing the context

The overall RISP methodology is illustrated in Figure 6. This illustration shows how the methodology fits into the NORSOK Z-013 methodology framework.

The first step in the methodology framework is the establishment of context. In a RISP process this is even more important than for traditional processes, since this first step includes identification of the relevant decisions that are to be risk informed. A work process shall be set up in such way that all relevant stakeholders are identified and the relevant decisions (to be risk informed) are specified.

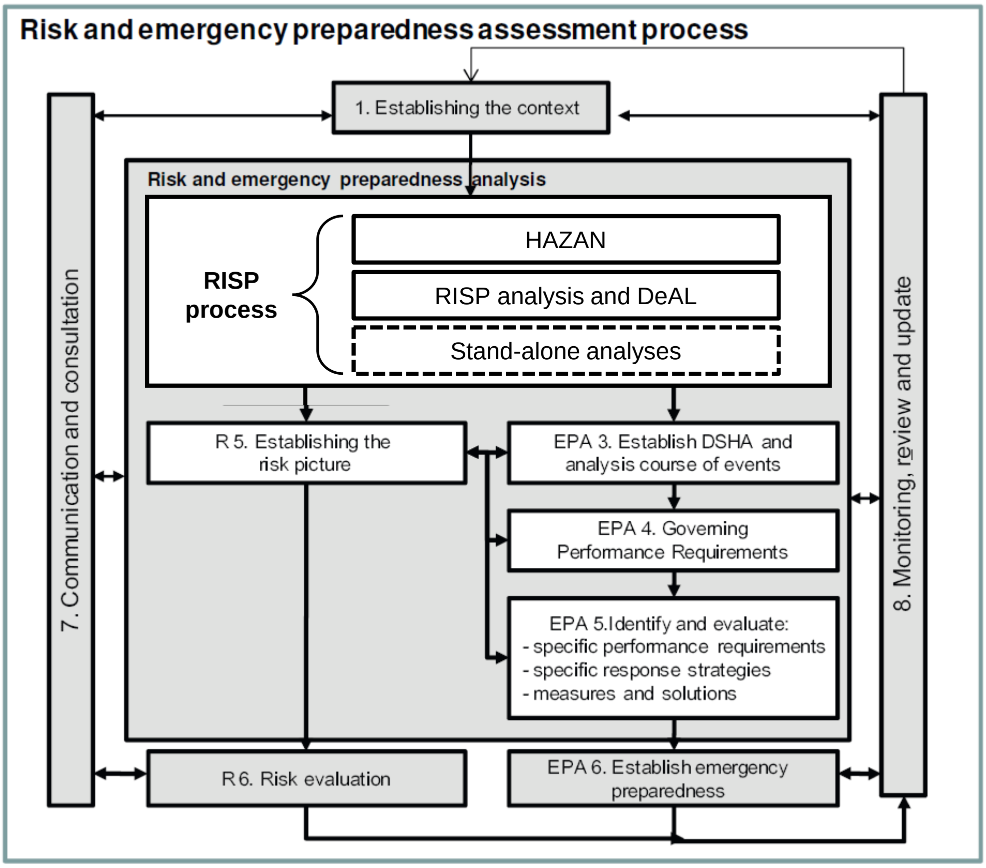

Figure 6 – The RISP process and modified NORSOK Z-013 process.

A vital part of the context process is to clarify selection of approach and the appropriate methods. The applicability of RISP will in this phase be considered and evaluated against factors such as the overall project strategy (conservative or challenging), the expectations among stakeholders regarding the requirement for safety demonstration and the level of novelty in the concept.

Timing of typical project deliverables are found in Annex B of ISO17776 and relevant decisions for RISP projects are given in Section 4. The selection of hazard evaluation and risk assessment methods is one important decision which must be established in a project (as described in Section 4.6 of ISO17776). The new HAZAN method (described in Section 2.2) is proposed as a tool to guide the project in the selection of risk assessments and how detailed these analyses have to be in order to provide a robust decision basis for a safe design.

Given the establishment of the context and selection of RISP, a set of initial criteria needs to be defined, to qualify a simplified approach for establishing risk informed decision support and demonstrate a robust safety level.

Main criteria for selecting a RISP process are:

- That the validity envelope for the method and models are adhered to.
- Acknowledged Safety Standards and design practices are adhered to. Engineering of safety systems are in accordance with proven standards such as NORSOK S-001.
- The major accident hazards (MAHs) potential causes and consequences are well defined. This implies that the dependencies and connection between the hazards and their control measures are clear and understood.
- Safety margins can be demonstrated qualitatively (robustness) with adequate strength of knowledge. This means that concept uncertainty is limited, and a tolerable safety level may be demonstrated in a reliable manner with a qualitative risk assessment approach.

These main criteria can be seen in conjunction with the planning and performance of the HAZAN (see Section 2.2). In many respects the level of detail for the required analyses lays in the interaction between design solutions and the MAHs.

2.1.3 Risk identification, assessment and evaluation

The initial risk identification and assessment method in RISP is called HAZAN. The HAZAN covers both a traditional HAZID and a process to assess and map the overall risk. It includes a process to check and assess whether the predefined design criteria are met. The HAZAN therefore both identify the hazards, but also assesses whether a design is qualified for RISP. Once qualified, the HAZAN demonstrates that overall safety criteria can be met and that simplified approaches can be used for risk informed decision support. Another important function of the HAZAN is to identify important uncertainty factors which may impact the risk level and map the knowledge strength in the assessments and assessment basis. Identified uncertainties may have to be reduced through special studies to gain better and more detailed knowledge of the uncertain aspects, or by implementing a more robust design. The outcome of the HAZAN is then both a demonstration of acceptable safety level and a qualification of using simplified approach to establish risk informed decision support. It will also identify areas or specific hazards where the risk cannot be controlled by simplified approaches and more detailed studies are required. It should be stressed that the conditions for simplified methods may still be valid although certain aspects are identified as uncertain and needs special consideration. The HAZAN method is detailed in Section 2.2.

2.1.4 RISP activities and reports

The RISP activities and resulting reports are illustrated in Figure 7. The main content of the RISP reports are outlined in Figure 8.

The formal RISP activities start with the HAZAN, and the details of this activity can be found in Section 2.2. The HAZAN report will in addition to producing a comprehensive hazard register, also document the risks and barriers compared to an acknowledged safety standard (including uncertainties) and conclude whether or not a RISP analysis is appropriate.

If the HAZAN concludes that the development (assessed for each RISP model) is appropriate for RISP, all risk informed decision input can be expediently produced by undertaking the simplified RISP methods. These methods will be further developed in the next phases of the project. In this phase a simplified method to establishing explosion DeALs has been focused at. The complete RISP analysis can provide all necessary experience-based knowledge for safe design quicker and easier than with traditional quantitative methods, providing very early decision support to the development projects (see also Figure 3). The RISP analysis contains of two mandatory parts and one optional part, the optional part is illustrated with dotted lines in Figure 7.

The first mandatory part is to establish the recommended design accidental loads (DeAL). The documentation of this process (including calculations) will be done in the RISP report, whereas the design loads will be documented in the Input to DeAL report.

The second mandatory part is to document all risk informed decision support that are not covered by the DeAL, but will represent important robustness against MAH. Examples of this can be design of robust escape ways and design of robustness against riser events, see Section 2.3.2 and Section 3.3 for more details. Another example can be to document the residual risk, e.g. by illustrating which scenarios that are not covered when designing against a given DeAL. Also general safety assessments relevant for e.g. barrier management and emergency preparedness are included in this part, see Section 4. The non-design load decision support is documented in the RISP report.

As an option one can perform stand-alone analyses to refine the details of parts of the design. This can be done as a part of the ALARP/Robustness process or as an optimisation of the design. As long as the refinements are made within the defined framework, they will not trigger a need for additional safety studies to be performed. Stand-alone studies can be reported in the RISP report, or in additional technical notes if deemed appropriate.

More details about the RISP report can be found in Section 2.3, and more details about the Input to DeAL report can be found in Section 2.4.

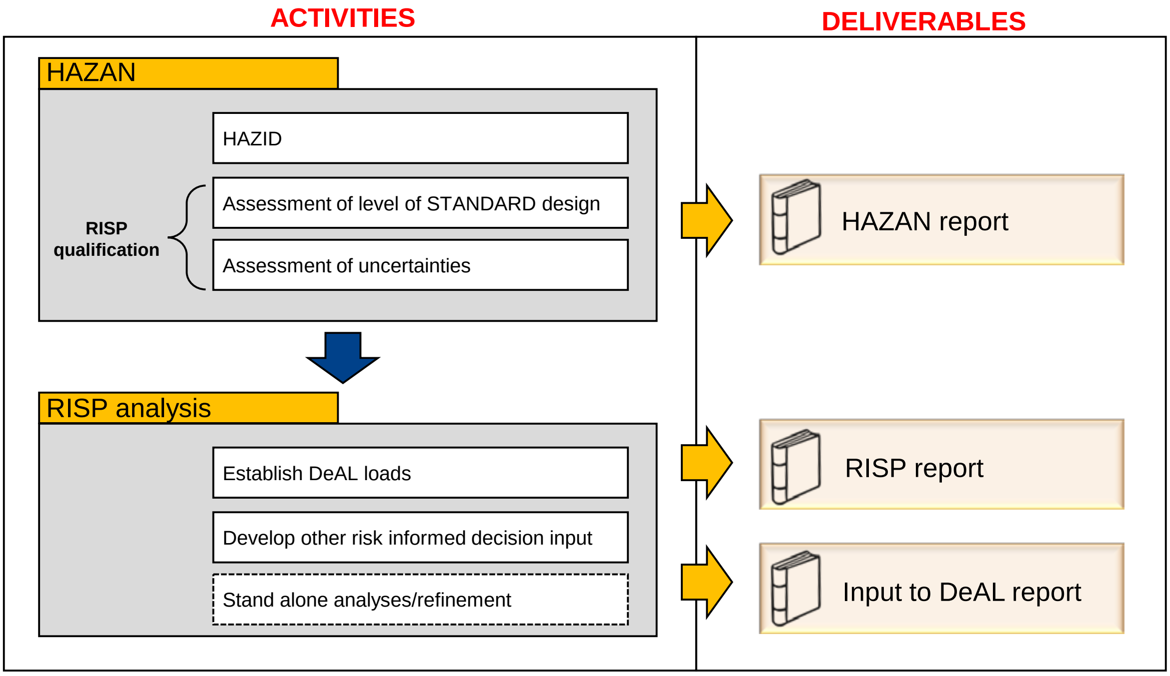

Figure 7 - Overviews of RISP activities and reports

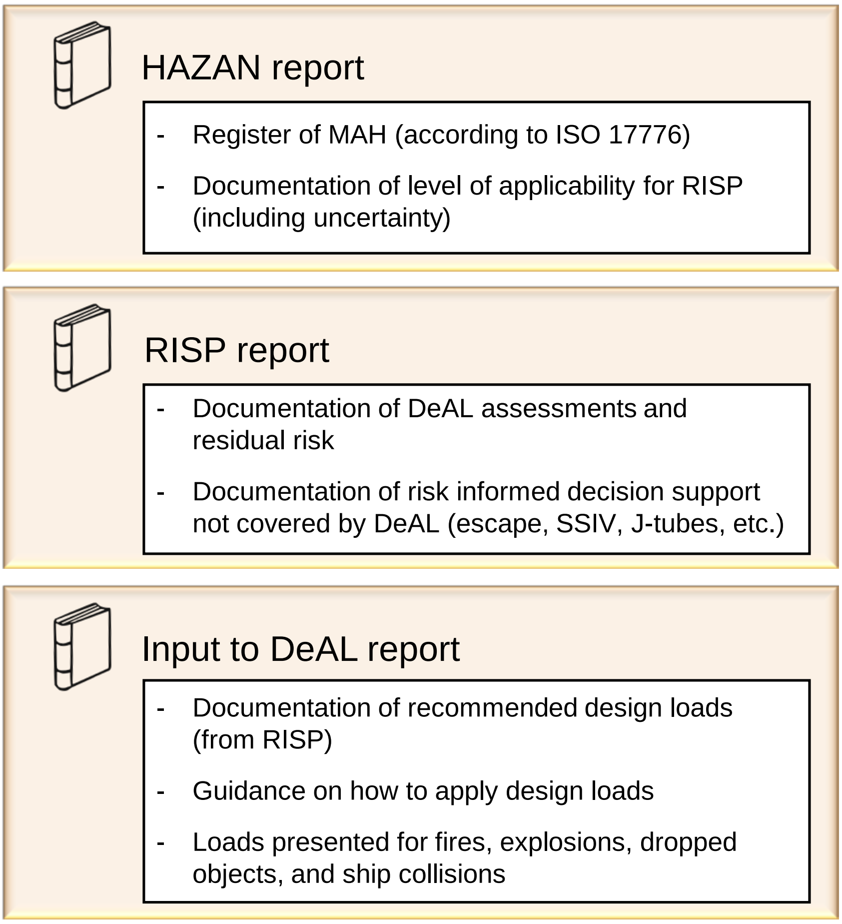

Figure 8 - Outlined content of the RISP reports

2.2 The HAZAN

2.2.1 Context

HAZAN is a process to evaluate and document if the proposed design is applicable for the RISP models and hence allow decision support to be based on good practice instead of comprehensive analysis. The naming of the HAZAN indicates that it contains all the elements of a traditional HAZID plus an additional assessment (or analysis) part to obtain a deeper understanding of the MAH and the associated strength of knowledge. By following the HAZAN process, the following is considered:

- It is evaluated whether or not there is something unique with the proposed design
- Relevant hazards are identified (HAZID)
- It is evaluated whether hazards are different than normal for the areas on the facility. This includes evaluation of strength of knowledge and whether criteria for the simplified method are met
- It is concluded whether or not the predefined RISP criteria are met for the proposed design of each of the areas on the facility

The above provides decision support to conclude if the RISP method can be used or if special studies are needed.

Since uncertainties and strength of knowledge is addressed as part of the HAZAN process, the process can be a useful supplement to a traditional HAZID also in situations where a decision has already been made to not perform the development project within the framework of the RISP method (e.g. if a high level of optimisation is required). The HAZAN process may provide useful decision support at early stages of the project execution for any type of project, limiting the risk of late changes at later stages.

The HAZAN process is carried out by performing the steps presented in Figure 9. Each of the steps is described in Sections 2.2.1 to 2.2.6.

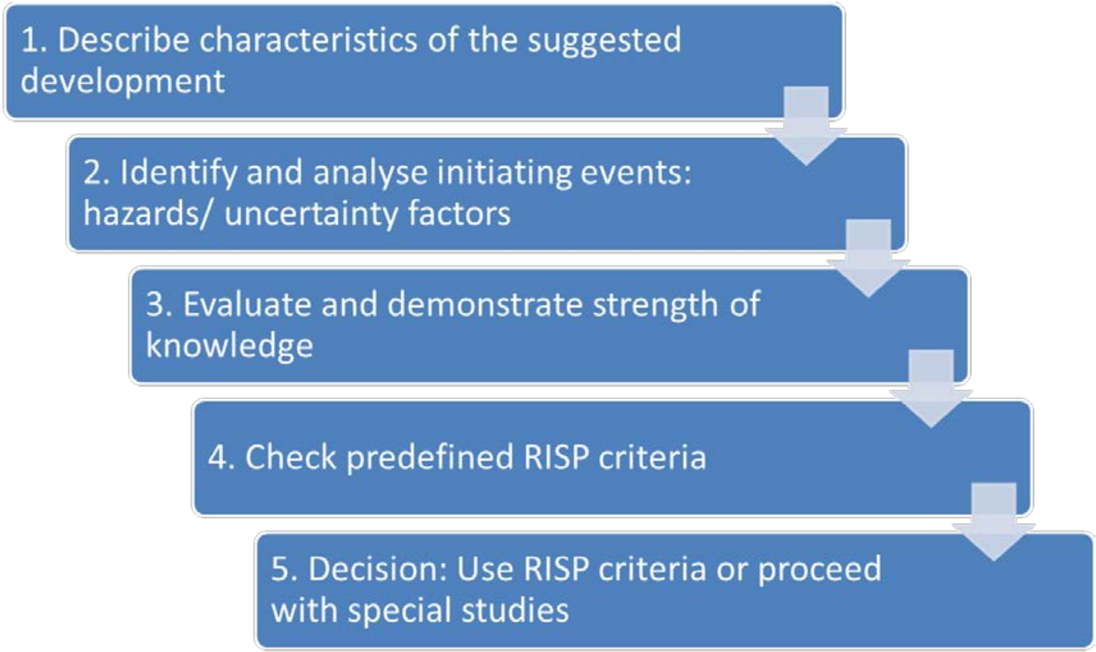

Figure 9 - Steps included in the HAZAN process

In practice, designing an offshore facility is an iterative process. This means that even though the HAZAN process is presented as sequential steps in Figure 9, it may not always be performed sequentially. What is important in the end is that all steps are sufficiently documented to ensure the decision to use RISP method or to proceed with special studies is well-founded. It is essential that the HAZAN is performed by personnel with relevant and sufficient competence.

2.2.2 Step 1: Describe characteristics of the suggested development

In the first step, special and/or abnormal uncertainties and system's characteristics are identified. This is carried out with the following objectives:

1. To achieve sufficient knowledge about the proposed design to be able to perform the following steps of the HAZAN process with sufficient quality. In particular this can be useful when performing step 2: During hazard identification it is often useful to spend more energy on unique parts of the design, since there may be non-evident hazards hidden behind the unique characteristics.
2. As early as possible to provide decision-support to whether or not it will be useful to apply the RISP method for the proposed design (if this is not already discovered before HAZAN): If, for example, Step 1 ends up with a number of significantly unique characteristics, we may already have sufficient information to suggest that the RISP method should not be recommended for the particular development.

3. To ensure important **uncertainties** are addressed as early as possible. Special or unique uncertainties are often related to uncommon or special design. Therefore, addressing special characteristics of the design, as described above, can contribute to identifying particularly important uncertainties.
4. To reduce the chance that unknown knowns or unknown unknowns are introduced in the project. One example is a situation where the RISP criteria are formally met, but where the design still is considered 'outside the boundaries' of the RISP criteria.

There are two main categories of uncertainties and system characteristics:

- *Design characteristics:* This includes relevant information from design basis. Examples are uncommon equipment being used, low ventilation rates, abnormal geometry of modules etc.
- *Location characteristics:* Situations where the design in itself can be conventional, but where it is being used in an unconventional way or at an unconventional location. Examples are uncommon weather, water depth, well characteristics, location within a ship lane, lack of infrastructure nearby etc.

It is recommended to organize step 1 as a brainstorming session including personnel from all relevant disciplines in the same way as HAZIDs are commonly performed today. In general, it is often useful to start the session with 'open' brainstorming and later go in detail on each hazard (fire, explosion, external impacts etc.).

One rationale of identifying uncommon/unique characteristics of the design is that the following situation has frequently been seen in accident investigation reports:

1) At some point, an abnormal or a special system characteristic was present. In some cases, the characteristic was recognized, in other cases it was not.
2) For some of the cases where the system characteristic was recognized, a (risk) assessment was conducted, although it was concluded that the characteristic did not cause an increased risk, or that the risk increment was marginal. Therefore, the activity continued.
3) An accident occurred.
4) With hindsight, it turned out that the system characteristic was an important contributor to the occurrence of the accident. However, this was not recognized before the accident occurred.

As part of HAZAN, it is essential to detect characteristics/challenges early to ensure these challenges are taken into consideration in the design.

2.2.3 Step 2: Identify and analyze initiating events: Hazards/uncertainty factors

Step 2 includes a hazard identification process. By use of creative brainstorming in a workgroup with specialists from all relevant disciplines, relevant hazards are identified. In the workshop the following should be identified and documented:

- Initiating events/ hazards (based on HAZID guidewords) and related risk sources
- Potential causes and consequences to each of the initiating events/ hazards
- Existing preventive and suggested mitigating safeguards are documented
- To what extent it is suggested an inherently safe design
- Uncertainties and the knowledge that the evaluations are based upon is highlighted

Step 2 may be performed as one or several traditional HAZID workshops, with a particular focus on uncertainties and evaluation of the strength of knowledge that the evaluations are based upon. In case some unique characteristics have been identified in Step 1, it is essential that these issues are focused on in particular in Step 2. Otherwise there is a chance that the development project proceeds with safety related unknown knowns as described in Step 1. This may result in a situation where the development project is believed to be similar or close to similar to previous developments, but where in fact there were unknown unique characteristics with untreated risk.

Since steps 1 and 2 require the same competence, the two steps may be organized as one or several workshops.

Hazards/ risk sources (fire, explosion, ship collision etc.) may be used as guidewords. It is essential to discuss and highlight accidental sequences and address uncertainties regarding how the hazards will be treated. As always in HAZID sessions, it is essential to avoid discussing solutions and risk reducing measures initially, but to ensure hazards and uncertainties are sufficiently analyzed before risk reducing measures and other risk treatment options are suggested.

In most cases it will be useful to start initially with an open discussion/brainstorming, and afterwards go more in details by asking relevant questions. Questions starting with why may help the group understand potential causes to each of the hazards being discussed. Questions starting with how or what may contribute to highlighting potential consequences. Uncertainties can be addressed by questions like for example:

- To what extent is this design resulting in the hazards developing 'as usual'?
- Is there anything in this design contributing to hazardous scenarios being more likely? To what extent is this inherently safe design?
- Is there anything in this design contributing to consequences becoming more severe than 'as usual'?
- Can we use the principles (barrier strategy etc.) that we normally use to treat this risk, or are there anything special requiring another approach?
- Do we need additional/other/special risk reducing measures to treat this risk?

2.2.4 Step 3: Evaluate and demonstrate strength of knowledge

In step 3, the strength of knowledge that the evaluations in step 2 are based upon is assessed and documented. The rationale behind step 3 is to challenge the evaluations in step 2 and to discuss how certain we are about the evaluations being done in previous steps. Since this is closely related to the hazard identification and analysis in Step 2, step 2-3 (or steps 1-3) may be performed in parallel during the workshop(s). Examples of questions that may contribute to highlighting the strength of knowledge:

- Is it possible that this scenario will change during the lifetime of the installation? How and why?
- We have assumed that the design will be such and such. If this is changed in later project phases, are our evaluations still valid? What is required to ensure our evaluations are valid? Can these issues be seen as constrains that the project will have to adhere to? How should such constrains be followed up?
- Considering the scenario we have now been considering; what is the worst case consequence? What is the best case consequence? What contributes to the scenario becoming less severe? Are we sure that these systems/functions will perform as assumed? What is our experience with such systems?
- Is there anything else that may cause such an event or contribute to severe consequences? Is there something important we have not addressed in this workshop so far?
- Is the design we are considering 'business as usual'? Are there any other development projects having experience with such a solution? Can we improve our knowledge by transferring experience from that project?

As suggested by Flage and Aven, Ref. /7/, strength of knowledge can be evaluated by addressing the following aspects:

a) *Validity of assumptions: To what extent does the design basis, layout etc. reflect how the* design actually will become? Do we have reasons to believe there will be changes, or can we assume that what we see is what we get?
b) *Level of understanding of relevant phenomena:* Are there any reasons that the suggested design should end up with particular challenges for each of the hazards (fire, explosion etc.)? Are the hazards being discussed in the meeting similar to what we normally can expect, or are there any indications that this will be a special case?
c) *Availability of data:* What is the quality and maturity level of the design basis, layout drawings etc.? Do we have knowledge supporting that it is or is not correct? Are there any other projects with similar challenges that we can address and validate the design against? To what extent are there available relevant accident statistics and is the quality of the data sufficient to conclude on the need to design against the hazard?
d) *Level of agreement/consensus among experts:* After all discussions; is there a common agreement in the HAZAN group? Do we have reasons to assume that anyone outside the group would disagree? Based on the discussions so far; are we confident that the risk is understood and controlled sufficiently?

2.2.5 Step 4: Check predefined RISP criteria

In Step 4 it is evaluated if the suggested design will meet all predefined RISP criteria for each hazard and area combination (making the RISP method relevant). This is achieved by considering and evaluating each area and hazard combination one by one, and compare the proposed design with a predefined generic list of RISP criteria relevant for the hazard that is considered. Some of these criteria may be established in the subsequent work groups 2-4 as check or validation criteria for allowing a simplified RISP method for establishing DeALs or worst credible events, etc. to be applied. It is important to follow-up that the RISP criteria are implemented in design and monitored throughout the risk management process so that later design changes are not compromising the important assumptions and criteria allowing for using the simplified methods established in RISP.

For each area/hazard combination, if the RISP criteria are met, the suggested design of the area is RISP with regards to the considered hazard. If some RISP criteria are not met for particular hazards/areas, special studies will have to be performed for these hazards/areas. Exactly how these studies should be performed in order to give decision support cannot be described in advance for all hypothetical situations. This will have to be determined in the scope/context/criteria part of the risk assessment, as described in Figure 4. In general, special studies should be designed is such a way that they can assist to close uncertainty gaps. Examples of questions that should be considered are;

- Which hazard/hazards are affected by the non-conformity with RISP criteria? For which areas?
- How does the non-conformity affect the hazard? Is the non-conformity related to a barrier function, barrier performance or design principles? How can this be compensated?

In general, the more explicit the RISP criteria are defined, the easier it will be to evaluate if they are met.

2.2.6 Step 5: Decision: Use RISP criteria or proceed with special studies

Step 5 includes a decision. In case it is decided to proceed with the RISP criteria, this means that the predefined list of RISP criteria (defined by workgroup 2-4) must be implemented as constrains in the design of the area. Since the RISP constrains may affect many disciplines and future decisions, the resulting constrains should be anchored at a sufficient level in the project organization. In case special or unique uncertainties have been identified in Step 1, this may influence on the recommendation on how to proceed. In some cases additional studies can be carried out to reduce the uncertainties. In extreme cases, it can be recommended not to use the RISP method at all.

Management of change must also include a continuous verification that all maturing/refinement during the development project remains within the defined RISP constraints of design.

As an example, if one of the RISP criteria is that the aspect ratio should be within certain limits, the decision to use the RISP method implies that the aspect ratio limit becomes a limitation that any future changes will have to adhere to. Such limitations must be followed up in later phases.

If the following criteria are met, the project can be defined as RISP:

- Documentation of the HAZAN process has been performed with the quality as expected
- All RISP criteria are met. If not, relevant special studies have been performed and provided sufficient knowledge for the RISP criteria not being met
- Selected concept is in accordance with the above and reflected in the safety strategy, or sufficient special studies have been performed to close uncertainty gaps
- It has been qualitatively demonstrated that all barrier functions are met by use of barrier elements/ performance measures

2.2.7 The HAZAN report

The activities undertaken in the HAZAN shall be documented in a separate HAZAN report, see Figure 8. The HAZAN report contains two main parts:

The first part is similar to a traditional HAZID, representing a register of MAH (according to ISO 17776) with an assessment of the severity of the hazards and the relevant barriers to reduce the risk (both frequency of occurrence and consequence).

The second part contains the documentation of all additional RISP processes, including the documentation of level of standard design and applicability for RISP according to the processes outlined in Section 2.2.1 through Section 2.2.6.

2.3 The RISP report

The RISP report shall document the activities undertaken after the HAZAN as a part of providing and documenting the risk informed decision support delivered to the development project. The RISP report will have three main elements:

2.3.1 Documentation of DeAL calculations

In this part of the RISP report the input used to all RISP calculations and assessments are documented. As an example, the input parameters used to calculate the recommended explosion design loads will be documented in this section. The recommended design loads will also be documented in the Input to DeAL report, see Section 2.4.

The RISP models will give the recommended design loads (DeAL). However, the robustness in the recommended DeAL should be provided, and this could be done by making a reference to the estimated dimensioning accidental loads (DiAL). Nevertheless, DeAL will be the «formal» RISP load and if this is applied as a minimum then no additional assessment is necessary. Also note that the DiAL (and hence the DeAL) will reflect if a module is alone or sharing the impairment frequency of a barrier (main area partition) with other modules.

2.3.2 Documentation of risk informed decision support not covered by DeAL

In this part of the RISP report all assessments of design input that are important for the robustness against MAH but not covered by the design accidental loads will be documented. Such design input must also be included in the facility Safety Strategy, and some relevant examples are listed below (see also Section 4).

Escape ways

Escape ways are defined as a main safety function. Establishing robust escape ways from all main areas can be challenging and will traditionally require a demonstration of compliance with a probabilistic and quantitative impairment criterion.

RISP must include a method to ensure that escape ways are robust from all areas replacing the traditional quantitative risk analysis verifying 10^{-4} /year compliance. Note that the meaning of robust when talking about the safety function escape is not only linked to the capacity to resist an explosion or fire load; it is also linked to having optional ways for escape in case one or more alternatives are impaired from the event.

Such a method should be performed as a part of concept definition phase prior to main layout design freeze. For a known concept, experience can be used to establish qualitative rule sets to validate an escape way layout and identify requirements to improved protection. This should be performed in a layout review assessing important risk sources contributing to the loss of the function.

The rule set and method must consider aspects such as

- need for enclosed escape ways due to increased risk of split scenarios
- local shielding from heat exposure or need for central escape alternative from an area
- location of stairs and ladders as escape options between elevations

A prerequisite for such an approach is that all main areas have been defined.

A detailed method description is not developed as part of the work package 1 for RISP, but will be developed as part of the next phase of the project (workgroup 3). The method must consider typical design events and how these events affect the escape function in different areas.

Design against riser accidents

Riser and pipeline accidents are characterized by scenarios with low probability and severe consequences. Such severe scenarios may be difficult to design against due to their size or duration.

Dependent on the risk intensity from riser accident risk, the effort required to prevent and mitigate the risk from these events may vary. An experience based approach must demonstrate a robust and safe design applying a method to assess the risk intensity and required measures to control the risk. Elements to be considered in this respect are:

Parameters contributing to the frequency of the event

- Type and number of risers
- Pressure and type of inventory (wellstream, liquid, gas)
- Location and susceptibility to external impact

Parameters contributing to the consequence of the event

- Concept and layout, distance to safe areas and critical safety functions
- Use of guide tubes to control the release location
- Escalation to other inventories and areas
  - Protection requirements
  - Inherent safe design principles
- Duration of fires
  - Segment size
  - ESD and SSIV

A rule set can be developed dependent on the concept in question and a structured assessment of required performance of preventive and mitigating measures dependent on the assessed risk intensity. The method should be aligned with requirements introduced by the latest revision of NORSOK S-001 with respect to need for SSIVs. A detailed method description is not developed as part of the RISP work package 1, but will be developed as a part of the work package 3 scope.

The RISP report will also describe relevant safety information that is not covered by the DeAL or loss of main safety function, e.g. describe the residual risk associated with the chosen design.

2.3.3 Documentation of stand-alone studies

If assessments are done in addition to the basic RISP assessments, e.g. ALARP or optimisation studies on parts of the design, these can be documented in the RISP report.

If the stand-alone studies are comprehensive they may be documented as appendices to the RISP report or as separate technical notes. If they are documented as separate technical notes, they should be referenced in the RISP report.

2.4 The input to DeAL report

The content of the Input to DeAL report is illustrated in Figure 8.

The Input to DeAL report will serve a similar purpose as the corresponding technical note in a traditional QRA, i.e. it will document and recommend the minimum accidental loads one need to withstand in order to meet the risk tolerance criteria. However, for the RISP version of this report there is no definition of dimensioning accidental load (DiAL) corresponding to an estimated 10-4 per year impairment frequency, but instead the recommended design accidental loads (DeAL) from the experience based RISP analysis are presented. Note that while traditional DiAL load usually never ends up as the actual design load (since it per definition has no margin to the tolerance criteria), the new DeAL proposed by RISP will represent the minimal acceptable design load to ensure robustness at least similar to traditional QRA approach. The proposed DeAL from RISP can therefore be applied directly as the applied design loads.

Additional robustness can of course be added also to the RISP DeAL (e.g. to include for possible future modifications) if deemed necessary.

The RISP Input to DeAL report contains two main elements which are intended to present the DeALs in a format readily applicable for use in the further safety work both in the development project and in the operational/modification phase.

The first main element of the Input to DeAL report is the definition of the design accidental loads including their intensities and durations (when relevant). As an example, for explosions the global loads, the local loads, the drag loads and their durations must as a minimum be presented.

The second main element of the Input to DeAL report will give guidance on how to properly apply the given design loads. By defining clear load combination of design accidental loads one will achieve more consistent use of the loads, and hence more consistent designs and robustness. Included in the guidance to use loads will as an example include instructions on how to combine local and global loads for explosion response calculations, and it will give guidance on which other load conditions (e.g. utility load and weather conditions) that shall be applied in combination with the design accidental loads.

Input to DeAL will be given for at least the following accidental loads:

- Fires
- Explosions
- Dropped objects
- Ship collisions.

2.5 Other stand-alone studies

The minimum “clean cut” RISP methodology does not require additional studies than the ones defined in Figure 7, but limited optimisation of the design is possible to obtain also within the RISP framework. As long as the key parameters required are within the validity envelope, see Section 2.2, RISP will allow for optimisation of parts of the design.

An optimisation may require a somewhat more detailed analysis than the RISP analysis, but without triggering the need for a full traditional risk analysis.

The additional stand-alone analyses may be documented as a part of the RISP report if deemed appropriate.

This work package 1 report is intended to define the "clean cut" RISP analysis, and the various refinements through more detailed stand-alone studies are therefore only partly pursued and documented herein (see Appendix A).

3. Robustness of design

3.1 Understanding of robustness in RISP

The robustness of design when using the new RISP methodology (experience based) shall be at least equal to traditional developments (QRA based). The understanding of robustness in the RISP context is that the new facility shall have at least the same robustness against all typical major accident events as the existing similar facilities, i.e.:

- Process fires (heat and smoke)
- Process explosions
- Riser accidents
- Blowouts
- Ship collision
- Dropped objects
- Helicopter accidents
- Occupational accidents.

This also implies that the robustness measured in traditional risk numbers, both personnel risk and loss of main safety functions, implicitly shall be at least as good as for traditional similar facilities. While no risk numbers will be explicitly calculated as a part of the RISP analysis, the level of robustness will be consolidated through experience from similar developments. The risk numbers inherently (or implicitly) covered by the RISP methodology are:

- Prevention of escalation
- Maintaining the main load bearing capacity
- Maintaining operability of safety critical rooms
- Impairment of the facility safe area/evacuation
- Loss of escape.

The interpretation of loss of main safety function when using RISP will follow the guidance given in NORSOK Z013 Annex B, assuring the same basis for understanding robustness as applied for traditional developments. Since the RISP process will safeguard these main safety functions, personnel safety will also be ensured.

The robustness of standard facilities developed by use of the RISP methodology will be documented through the design loads established from the RISP analysis (see Section 3.2) and by documenting that the experience based robustness requirements put forward in the RISP analysis are complied with for all risk driving parameters not covered by the design accidental loads (see Section 3.3).

3.2 Robustness provided by DeAL

In a traditional risk analysis the dimensioning accidental loads (i.e. the minimum accidental loads one need to design against to meet the risk tolerance criteria) are normally documented in a technical note. If the actual design loads are known these are also documented together with the dimensioning loads to demonstrate one robustness aspect of the design.

From a RISP analysis robust design load recommendations will be provided from the experience based RISP models, implying that if the new facility can withstand the recommended RISP design loads then a safety level equal or better than existing similar facilities can be achieved. The design accidental loads recommended from the RISP models shall therefore be considered the minimum design load to obtain the same level robustness as the existing reference designs. Selecting loads below the recommended RISP loads requires additional documentation.

3.3 Robustness provided by other RISP models than DeAL

The robustness of elements being a part of the realisation of a main safety function, or being a key element of defining integrity against MAH will be provided through the RISP methodology also when these elements cannot be defined through a design accidental load.

Most of these elements are related to fires and will therefore be subject to more elaboration as a part of the work package 3. The sections below list the main elements where robustness cannot be defined through a DeAL, and this list will also define the challenges that need to be addressed by RISP work package 3. The below elements are further discussed in Section 4 and Appendix A.

3.3.1 Escape

RISP need to define a framework to support experience based design of escape ways, i.e. develop a method to ensure that escape from all main areas as at least equally robust as achieved by use of traditional quantitative risk analysis verifying 10-4 /year compliance. The details of this RISP model will be defined by workgroup 3, but it is foreseen that this could be achieved e.g. by requiring central escape (in addition to peripheral escape) to be defined appropriate for RISP?

3.3.2 SSIV

RISP also need to define a framework for experience based design of riser termination, and also this will be defined by workgroup 3. The details of this RISP model will be defined by workgroup 3, but it is foreseen that this will include assessments of key parameters such as number of risers, content of the riser/pipeline (length, diameter, pressure, composition) and the design of the topside riser valve. The guidance given in the new NORSOK S-001 is considered a robust basis for SSIV design.

3.3.3 J-tubes

Applying J-tubes may have a significant effect on the robustness against riser events. The need for J-tubes are often not related to the DeAL specification, and the risk based decision support for applying J-tubes or not must therefore be based on other input than the DeAL loads. RISP need to provide an experience based decision support around the need for J-tubes based on key elements such as robustness of main load bearing against riser fires. RISP models for J-tube assessments will therefore be addressed by workgroup 3.

3.3.4 Other design support challenges

There could be other design decisions which today are supported by the traditional QRA that need to be provided also when using the new RISP methodology. One example could be plating/grating discussions (what could be good for explosions could be bad for fires, and opposite). It is expected that workgroup 2 will cover assessment of plating/grating (together with other typical design issues such as use of wind walls/relief walls and location of high intensity ignition sources such as air intakes), but there may also be other design challenges that will benefit from decision support provided by RISP. This list of other design challenges supported by RISP will be concluded after completion of the work packages 2 – 5.

4. Risk informed decision support during design

4.1 Use of RISP in decision making

This work package 1 shall also define the risk management principles to be used in a development project. I.e. how should/could decisions makers use the risk informed decision basis that is provided by the methods and models developed in this JIP project? An important part of this will be to enable the decision makers to understand the consequences of the decisions they make. How will their decisions affect the project, in later project phases and in operations? The robustness in the decisions support provided (e.g. its sensitivity to changes), and how to deal with uncertainty (lack of general and/or specific knowledge) must also be addressed. ALARP, ISD and BAT issues must also be reflected.

The execution of management of MAH is a key issue to assure a proper handling of risk.

The principles to be used are well described in standards such as:

- ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016. See Ref. /8/
- Petroleum Safety Authority Norway, "integrated and unified risk management in the petroleum industry", dated June 2018. See Ref. /9/.

Adherence to the risk management principles described is a premise for use of the RISP methods and models developed as part of a new "industrial practice".

In applying these principles in development projects important/key tools are found to be:

- Safety program
- HAZAN (extended HAZID)
- Design Accidental Load Specification (DeAL)
- Safety Strategy and Performance Requirements

It is observed that adherence to the risk management principles is challenging and that the practice varies. It is hence recommended that the industry continue to development and improve guidelines and practise for management of MAH in development projects. It is noted that the experience from project execution is that as-built verification and external audits are viewed to be important factors to obtain a good balance between cost optimisation of safety measures and to assure regulatory compliance.

The establishment of the safety strategy as well as performance requirements for safety barriers play a key role in implementation of safety premises into design. Likewise, the documentation of these aspects can play an important role in communicating basis for handling of MAH in the operational phase. Illustrations using bow-tie diagram can be useful in this respect.

A key challenge in use of traditional quantitative risk analysis for defining design premises and requirements related to MAH, is the limited predictability resulting from probabilistic studies evaluating hazards with large consequences but scarce statistical basis (due to very rare events). It can be argued that the development phases are significantly influenced by uncertainty in terms of lack of knowledge in the statistical parameters as well as the lack of ability to include the operational factors' (organisational and human elements) quantitative effect on the expected frequency of hazardous events to occur. Consequently, within the validity envelope continuous re-calculation of frequency-based design scenarios during the development phases could be replaced by selecting industry agreed worst credible design scenarios that shall be used in the design. The selection and definition of such design scenarios based on an industry practice such as RISP could ease implementation of requirements into design considerably. It will hence be a task for the work groups developing RISP methods and models for the various hazards, to evaluate the possibility to define criteria for use of design scenarios as an alternative to probabilistic criteria.

4.2 Mapping of decisions and decision support needed

The need for decision support in development projects has been collected based on the experience of the RISP participants as well as by workshops and communication with engineering and oil companies.

The typical case considered has been:

- A fully integrated topside facility (fixed or floating)
- Well known design and operational aspects, reservoir and process conditions as well as environmental conditions
- Operators and engineering companies experienced with the NCS regime

It is found challenging to extract single decisions made at a specific time in the design process. The design process more typically implies a lot of dependencies and iterative work in decision making. A main task during Project Planning phase is to establish the technical basis for the subsequent Project Execution phase. The design premises (in addition to prescriptive requirements given in standards, regulation and good practices) for handling of MAH should as far as possible be established in the Project Planning phase.

Decisions made in the Project Planning phase with respect to MAH will have to be robust to avoid later changes unless a very strict management of change strategy is implemented. The extent and quality of the work in the Project Planning phase is hence crucial to obtain valid design premises that are not overly conservative. During Project Execution phase a main task is to implement and detail the safety premises into design and to follow up effect of changes. It is expected that in many projects the design premises, detailing of the premises and way of implementation of the premises will be challenged from a cost optimisation point of view. This may imply that the validity envelope of RISP is challenged and that traditional risk assessment methods are applied. The focus for RISP is primarily to establish safety input and premises for handling MAH in an efficient manner at the right time. As the concept, layout and technical basis for Project Execution phase are to be established in the Project Planning phase, the further mapping of decision support needed is focused on the Project Planning phase (see Appendix A).

A key part of the decision support normally extracted from traditional risk analyses is related to establish a design accidental load specification for the development project. A main task for the RISP workgroups handling the various MAH is hence to establish methods for recommending design accidental loads and the application of the loads.

It is further acknowledged that the NORSOK S-001, 2018 edition is a key document providing design premises related to MAH. The standard contains both prescriptive and functional requirements to the performance required for safety barriers/-systems. It is concluded that application of this NORSOK standard as a basis for the design development will be a valid premise for the RISP methods. Hence, the NORSOK S-001, 2018 edition has been reviewed to identify:

- Decisions to be made in the development project relevant for RISP
- Input requested from WG 2, 3 and 4.
- Decisions that needs to be taken in a development project to establish the design of safety barriers/-systems
- Premises for the RISP methods to be established and input needed from the RISP methods (to be established by WG 2,3 and 4)

The review is documented in Appendix A. Typical results obtained are:

- Clarification of prescriptive requirements to the performance of safety barriers/-systems which shall be basis for the RISP methods
- Solutions to be used in a standard design for functional requirements specified to safety barriers/-systems. This can be:
  - Transferring functional requirements into a set of specific prescriptive requirements
  - Identifying studies that need to be performed in a traditional way. These studies can typically be performed in a suitable/expedient way to give the decision support needed in the development project.
  - Identifying evaluations that can be done qualitatively by qualified personnel in the development project
  - Identifying topics that needs to be evaluated as part of the HAZAN

5. Discussion of new methodology

This section discusses the robustness of the proposed RISP method and the challenges related to the new method's ability to comply with the mandate.

5.1 Strengths

The main framework of the RISP method is based on the overall principles for risk-related decision support provided in ISO 31000 and ISO 17776. The RISP methodology also fits into the NORSOK Z-013 methodology framework.

The intention with RISP is to establish decision support in the early phases of the design of an offshore facility utilising extensive experience doing risk analyses for several decades. The method must also include processes to ensure that expedient decisions related to MAH are made throughout the execution phase and verified in as-built design. A concept qualified as proven in use in a RISP process allows for more simplified methods to establish design requirements.

The strengths of a risk decision process based on experience rather than traditional quantitative analyses include (see also Section 1.2.2):

- Better use of existing knowledge
- Speed up of development process
- Reduced uncertainty related to late changes
- Improve consistency between designers/risk analysts
- Early development stage information of risk drivers
- Clearer responsibility for changes affecting risk level

The focus on the context is the main strength of the RISP. The identification of the relevant decisions that are to be risk informed and identification of all relevant stakeholders are the essence of the RISP process. Ensuring stakeholder commitment in the method is essential for the success of the process. This includes consensus that demonstration of safety level is achieved based on defined RISP criteria.

The robustness in the decisions support provided, and how to deal with uncertainty is addressed as part of RISP. Through the RISP process the strength of knowledge is evaluated and demonstrated clearly and transparently. This is also in line with the "new" definition of risk given in Norwegian regulations (PSA). The RISP is clearer on reasons for introducing other studies to provide improved knowledge strength of an identified uncertain element.

Since uncertainties and strength of knowledge is addressed as part of the HAZAN process, the process can be a useful supplement to a traditional HAZID also in situations where a decision has been made not to develop within the framework of the RISP methodology. It may provide useful decision support at early stages of the project execution, limiting the risk of late changes at later stages.

The benefit of RISP is that the safety level can be demonstrated more efficiently and provide risk informed decision support in a timely manner. It is further acknowledged that the RISP fit very well with the NORSOK S-001, 2018 edition, as a key document providing design premises related to MAH.

5.2 Challenges

One of the main challenges applying a RISP process is ensuring commitment from all stakeholders in the method. This is relevant both for the justification of the method (documented and pre-qualified) but most of all the by-in for specific projects. This includes consensus that demonstration of safety level is achieved based on defined RISP criteria. The use of RISP is only applicable where there is a consensus among the Stakeholders related to a preference for proven standardised solutions within the validity envelope.

An important part of the RISP process is to enable the decision makers to understand the consequences of the decisions they make. This consequence of decisions may be perceived as more visible using RISP, hence more demanding for stakeholders who may then be reluctant to use a RISP approach. On the other hand, the clear link to consequences is also a strength of the RISP method.

In RISP, the traditional quantitative risk analysis to document and demonstrate an acceptable safety level is replaced by a simplified experience-based risk assessment. It may be challenging to achieve both efficient use of experience and efficient adaption of improvements (new design or new technology) with RISP. The RISP method will to some extent be a conservation of known designs. The challenge of an experience based and prescriptive approach is however that demonstration of acceptable safety level must be achieved differently from traditional developments made by means of quantitative probabilistic criteria (such as main safety function impairment). A prescriptive and experience based method will not be able to evaluate risk directly towards quantitative criteria and only indirect demonstration of the same level of safety is achieved. The RISP model has limited ability to achieve quantitative overview over the total risk and risk contributors to each main safety function and possible conflicting targets. The experience based RISP models will therefore have to produce design support ensuring at least the same level of safety as the quantitative models. Hence, the RISP models must be acknowledged by all stakeholders as equivalent and equally robust as a traditional quantitative risk analysis applying the methods in NORSOK Z-013 and criteria set by the facility regulations

It is found challenging to extract single decisions made at a specific time in the design process. The design process more typically implies a lot of dependencies and iterative work in decision making. The RISP process, however, describes the link between the design decision and the corresponding risk consequence independent of the development phase i.e. the RISP models describes general relations between design solutions and resulting risk. These relations are independent of project development phase, and the phase dependency of the RISP models as such is therefore not elaborated in the report (however, the use of the RISP models may vary with the available information during the development phases, see also section 4 and Appendix A.

It is expected that in many projects the design premises, detailing of the premises and way of implementation of the premises will be challenged from a cost optimisation point of view. This may imply that the validity envelope of RISP is challenged and that traditional risk assessment methods are applied. Constrains of staying within RISP may be challenging during the whole development process. Not all stakeholders may be equally motivated to stay within RISP.

Another challenge is that decisions made in the early phases with respect to MAH will have to be robust to consider later changes. The extent and quality of the work in an early phase is hence crucial to obtain valid design premises that are not overly conservative.

The RISP models may limit the possibilities for detailed sensitivities (i.e. sensitivities on a level more detailed than the RISP models), but details of the design can be further studied with specific studies within the framework given by RISP.

6. Recommendations for further work

A new methodology for replacing traditional quantitative risk analysis with simplified experience based methods for improved decision support in development projects has been outlined and substantiated in this report. In order to qualify the new RISP methodology and document its ability for robust decision support in actual development projects, the following recommendations are given for further work:

1. The workgroup 1 should be extended with some continuation into the next phase in order to provide seamless interaction between all work groups (1 – 5).
2. The detailed definition of the validity envelope (applicable for RISP models) must be outlined for each RISP model in workgroup 2 – 5. A final definition of the validity envelope should be given after the pilot testing, see recommendation 3 below.
3. The new RISP methodology should be tested on one or more appropriate pilot developments to verify its applicability before being formally released. This will provide a real life test that experience based decision support will provide sufficient robustness while speeding up the design phase of the development projects.
4. The RISP methodology should be assessed for applicability for other safety work as a part of the work package 5 activities. Applicability for barrier management and emergency preparedness should be included in RISP work package 5.
5. The new RISP methodology when finalised should be included in the revised NORSOK Z-013 standard.
6. The work done to clarify how NORSOK S-001 should be used to identify decisions, need for decision support and premises for use of the RISP methods should be extended. At present the review made is somewhat course. It is expected that the experience gained through the work in WG 2 would give valuable input to an update both for explosions and fires. In addition, "other accidents" is only covered partly.
7. The concept of defining design accidental events to be used in design of an installation has only partly been covered in the present work. The concept may however, be valuable for efficient decision support in a development project. Benefits of the concept includes that it can provide a clear input to design where uncertainties related to probability level is solved on an industry practice level instead of as part of design development. In addition, the concept has proven to be efficient in implementation into design and optimisation of design details. The latter is linked to the ability to use suitable consequence tools using available information to consider effects on the scenarios from the design or from the scenario to the design. It is hence recommended to pursue this concept further as part of RISP. This should include a thorough review of available accidental statistics for various hazards. This review should evaluate the quality of the statistics and relevance for a standard design fulfilling prescriptive requirements. The aim should be to establish an industry standard for which hazards needs to be designed against in a functional manner and which hazards not required to design against. For those hazards it shall be designed against, conclude on the severity of the design accidental event and corresponding premise.
8. Several needs have been expressed to clarify how design accidental loads should be applied in design of an installation. These needs have been solved to various degrees in development projects performed. It is recommended to gather the experiences obtained from use of design accidental load specifications in project developments and establish a best practice document for use in future projects.

7. References

/1/ Norsk Olje & Gass (NOROG): Prosjekt «Formålstjenlige risikoanalyser» Resultater og forslag til videreføring, Versjon: 6. februar 2017

/2/ Technical safety NORSOK S-001, Edition 5. 2018.

/3/ ISO, 2018. ISO/IEC 31000 Risk management - guidelines

/4/ Standard Norway, 2010. Risk and emergency preparedness analysis, NORSOK Standard Z-013.

/5/ Flage, Roger and Aven, Terje. (2009). Expressing and communicating uncertainty in relation to quantitative risk analysis. R&RATA #2(13), part 1, volume 2, June 2009

/6/ ISO, 2018. ISO/IEC 31000 Risk management - guidelines

/7/ Flage, Roger and Aven, Terje. (2009). Expressing and communicating uncertainty in relation to quantitative risk analysis. R&RATA #2(13), part 1, volume 2, June 2009

/8 / ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016.

/9 / Petroleum Safety Authority Norway, "integrated and unified management in the petroleum industry", dated June 2018.

Appendix A: Decisions in Project Planning phase that need risk informed decision support

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
Ch. 5: Management of Technical Safety	<u>Decisions and tasks:</u> • Decide on the applicability of the RISP methods • Management decision to apply the RISP method as the method for management of MAH (deviate NORSOK S-001) • Selection of concept for continuation into project execution. • Mature the selected concept. • Definition of technical basis for the subsequent Project execution phase. (Process systems, utility systems, electrical systems, load and structural arrangement, control systems topology) • Procurement and contract strategy • Definition of tolerance criteria for MAH (e.g. definition of main safety functions) <u>Input requested:</u> • 1) Constrains and conditions for using RISP methods (validity envelope). • 2) How should the risk aspect (explosion risk) be handled in later project phases (input to management of MAH and MoC). Design aspects that need to be controlled and recommended methods to control the aspects. Presumptions w.r.t. barriers in addition to what is defined in NORSOK S-001 to be defined.	See explosions. • Criteria/strategy for local escalation and ruptures (basis for DeAL)	See explosions	Key tools in MAH are: • HAZAN (extended HAZID – ref NORSOK • Safety Program • Safety Strategy • DeAL. This phase shall define the technical basis for the project execution phase. Hence extensive studies may be required in this phase to clarify most uncertainties and possible weak knowledge. This should also include an extensive HAZAN. During Concept definition and optimisation, work to identify and define barrier functions and corresponding performance requirements should be initiated. Unless the HAZAN is enough basis for this work, additional special studies may be required. In project execution phase the requirement for fire testing related to design scenarios is challenging to fulfil.

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	• 3) Input to verification plan to avoid need for as-built verification by TRA/QRA. Can follow up using defined WCDE (Worst Credible Design Events) combined with recognised CFD tools be more effectively applied?			
Chapter 5.6 Accidental loads and resistance	<u>Decisions and tasks:</u> • Decision to deviate from NORSOK S-001 methodology (which is referring to Z-013) and use RISP instead. • Define explosion DeAL based on early phase available details only. Design values to reflect both functional and deterministic requirements in regulations. The DeAL to reflect a safety level at least equal as today. • Consideration of robustness and sensitivity for changes <u>Input requested:</u> • Input requested: (Ref Ch. 5.6.1 and 5.6.2). Recommended explosion DeAL to be given for: o 1) relevant horizontal and vertical area dividers, o 2) area loads for equipment o 3) external loads for e.g. LQ, escape and evacuation systems, critical functions/room outside the explosion area if applicable.	<u>Decisions and tasks:</u> • As for explosions. <u>Input requested:</u> • WCDE-Process system is equal to WCPF. The possibility for similar approach for riser fires and blowouts to be considered. This to minimise the probabilistic assessment as part of the development project. • Fire analysis (Extent, duration and loads) • Input to recommended DeAL o Duration, extend and loads to be used.	<u>Decisions and tasks:</u> • As for explosions. <u>Input requested.</u> • WCDE's o Boom fall? o Collision • Input to recommended DeAL	• The task of identifying safety functions during and after an accident needs to be clearly identified. This affects the systems that need survivability requirements for the accidental loads. The work needs to be risk informed and is covered in various ways today. The practise should be improved. As requirements it could be covered as part of standards, requirements in DeAL, requirements in safety strategy or as part of performance requirements.

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	• The possibility to apply a similar method as defined for fires (Worst Credible Process Fire) to be discussed and clarified. A worst credible design event for explosion, WCDE-explosion to be clarified. Set up of cases to be used and probability level for pressure outcome to be discussed. WCDE-explosion could be: o Ignition of a leak for a 2" hole or o Ignition of a 5 %, 10%, 20 % or 40 % stochiometric gas cloud. • Input to robustness e.g. effect on DeAL for extreme cases. E.g. a WCEE-Explosion (Worst Credible Extreme Event- Explosion) could be ignition of a 40 % stochiometric cloud without release of firewater. • Timely input (and detail level) to purchase orders, sub-contractors and engineering disciplines needs to be clarified with the project.			
Ch. 6: Layout	<u>Decisions:</u> • Decide and optimise layout. Why: A key factor to provide a robust and inherent safe design. Layout is a key factor in feasibility, cost and design/operation premises. • Decide on main design principles given in Ch 6.4.1. • Decide on how to fulfil explosion design principles given in Ch 6.4.10.	See explosions. <u>Input requested:</u> • Describe key design parameters influencing fire risk not sufficiently covered in NORSOK S-001. Distinguish between factors that should be used to decide on DeAL's and factors that are constrains and conditions for using RISP methods (validity envelope).	See explosions.	

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	<u>Input requested:</u> • Describe key design parameters influencing explosion risk. Distinguish between: o factors that should be used to decide on DeAL's (NORSOK S-001 Ch. 6.4.10 says that ISO 13702 should be followed w.r.t explosion design principles. Are the topics covered in ISO 13702 important for which DeAL to use or only for optimisation?) o factors that are constrains and conditions for using RISP methods (validity envelope). o factors that needs to be optimised as part of ISD, ALARP and robustness: ▪ Topics sufficiently covered in NORSOK S-001 as basis for technical safety work ▪ Topics that should be evaluated for optimisation in HAZAN • Methods or tool to establish Design Loads assuring at least same safety level as per "today". Robust to avoid later changes but not too robust giving too high cost.	• Methods or tool to establish Design Loads assuring at least same safety level as per "today". Robust to avoid later changes but not too robust giving too high cost. • Identify topics for HAZAN • Identify special studies to be performed. o Gas and fire analysis for global layout considerations (safe area, evacuation mean, escape routes, size of fire walls). Clarify use of WCDE-Fires for this use. o Hot air exposure of helideck. Premises for definition of cases.		

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	• Other: NORSOKS-001 describes several design aspects to be considered in Ch. 5.6.2 and 6.4. These should be covered either as validity envelope/ premises for RISP methods, as technical safety tasks to be performed in the development project or special studies. The HAZAN should review the totality of these aspects on a qualitative level. A possibility is also to include the aspects in an update of NORSOK S-001 as a chapter like Ch. 20 for fire.			
Ch 7: Structural integrity	<u>Decisions:</u> • Explosion DeAL for structural integrity covering both prescriptive and functional requirements in regulations and providing a safety level at least equal as today. <u>Input requested:</u> • The definition of main structure which needs to be intact for the relevant safety functions in case of an explosion should be defined (by the project organisation – safety and structure). Relevant loads to be defined unless sufficiently covered by input to Ch. 5.6. • Weather conditions to be combined with DeAL to be defined e.g. 1-year weather condition (meaning e.g. fraction of time less than 0,1% during a year)?	See explosions <u>Input requested:</u> • Basis for structural response analyses and survivability requirements. Optimisation will require special studies.	See explosions <u>Input requested:</u> • Areas and structures exposed to dropped objects and swinging objects.	

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
Ch. 8: Containment	<u>Decisions:</u> • Use of compact flanges and installation flanges <u>Premises:</u> • A premise for RISP is that work related to 8.4.3 is carried out in the development project	<u>Decisions:</u> • Use of SSIV on risers/pipelines. <u>Input requested:</u> • A method for evaluation of SSIV based on chapter 8.4.4 needs to be defined.		
Ch 9: Open drain		<u>Decisions:</u> • Design of bunds and drain piping. <u>Input requested:</u> • WCDE-leakage/fire to be used for drain and bunding (dependent on segment volumes?)		
Ch 10: Process safety				
Ch 11: ESD	<u>Decisions:</u> • (Decision on valves with ESD function) • (Internal leak rate requirement for ESD valves.) • Initiation of ignition source isolation • Initiation of EDP • Initiation of firewater <u>Input requested:</u> • Effect of segment sizes on DeAL's • Premises wrt to isolation of ignition sources • Criteria or premises wrt automatic initiation of EDP on gas detection	<u>Decisions:</u> • Decision on valves with ESD function • Internal leak rate requirement for ESD valves. • Required closure times for subsea ESD valves and SSIV's <u>Input requested:</u> • Effect of segment sizes on DeAL's • A standardised internal leak rate to be used as basis for design, e.g. 0,1 kg/s		

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	• Criteria or premises wrt automatic initiation of firewater on gas detection (to be released on 6 detectors?) <u>Premises:</u> • Unless general criteria can be given, special studies must be performed.	<u>Premises:</u> • Special study to be performed: Critical ESD valve study.		
Ch 12: EDP and flare vent	See above	<u>Decisions:</u> • Need to reduce EDP time to avoid PFP and reduce rupture time on process equipment • Required survivability time for flare system <u>Premises:</u> • Special study may be required to optimise PFP.		In Project Execution phase Detailed DeAL's may be required to optimise protection of flare system. If relevant design scenarios are described – these can be used effectively to provide optimised loads.
Ch 13 Gas detection	<u>Decisions:</u> Location and Coverage of gas detectors <u>Input requested:</u> • A standardised grid for gas detectors of e.g. 7 meters to be used as basis for RISP. Any additional guidelines or premises for location of gas detectors to be given.			
Ch. 14, 15, 16, 18, 19, 21 and 24.	• These chapters present basis for RISP methods			
Ch. 17 Natural ventilation and HVAC	<u>Decisions:</u> • Enough ventilation. <u>Premises:</u> • The ventilation rate in the various in hazardous areas shall be analysed by a special study			

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
	• It is a premise for RISP that minimum 12 ACH are provided for 95 % of time.			
Ch 20 Passive Fire Protection	Should it be established a similar Chapter covering Explosion protection? A few topics are covered in Chapter 5.6.2 but this should be extended!	<u>Decisions:</u> • The use and design of horizontal fire divisions. <u>Premises:</u> • If horizontal fire divisions are to be used, a special study should be performed to optimise structural design to avoid passive fire protection (as a minimum) on the upper side of the division. • For optimisation of PFP versus blowdown time and selection of pipe class an optimisation study should be performed		
Ch 22 Escape and evacuation		<u>Decisions:</u> • Layout and protection of escape routes. • Location and protection of safe area (including air intakes) and evacuation means <u>Input requested:</u> • WCDE-fire to be used as basis for design wrt to these decisions. Should one use the same fires as defined for structural integrity and fire divisions?		

Reference to NORSOK S-001, 2018 revision.	Explosions	Fires	Other accidents	Comments
		<u>Premises:</u> • A special study should be performed to support decisions to be made.		
General Survivability	Load exposure	Load exposure	Load exposure	

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

Main report Workgroup 2 - Explosion

Report for:
Aker Solutions

Report no: 100564 Rev: Final version

Date: 10 March 2019

Summary

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

Main report Workgroup 2 - Explosion

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Revision	Date	Description/changes	Changes made by
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.

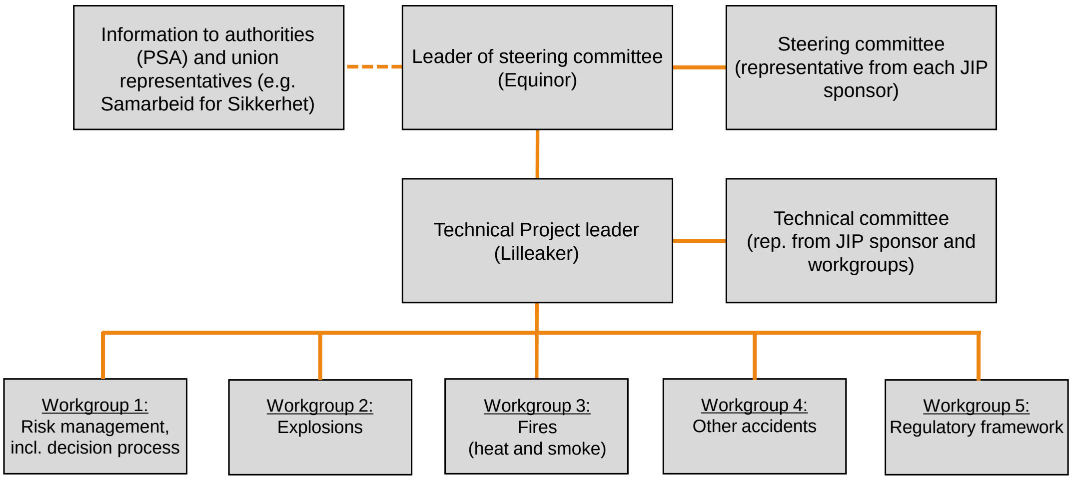


Figure 1 – The RISP project organisation overview

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.

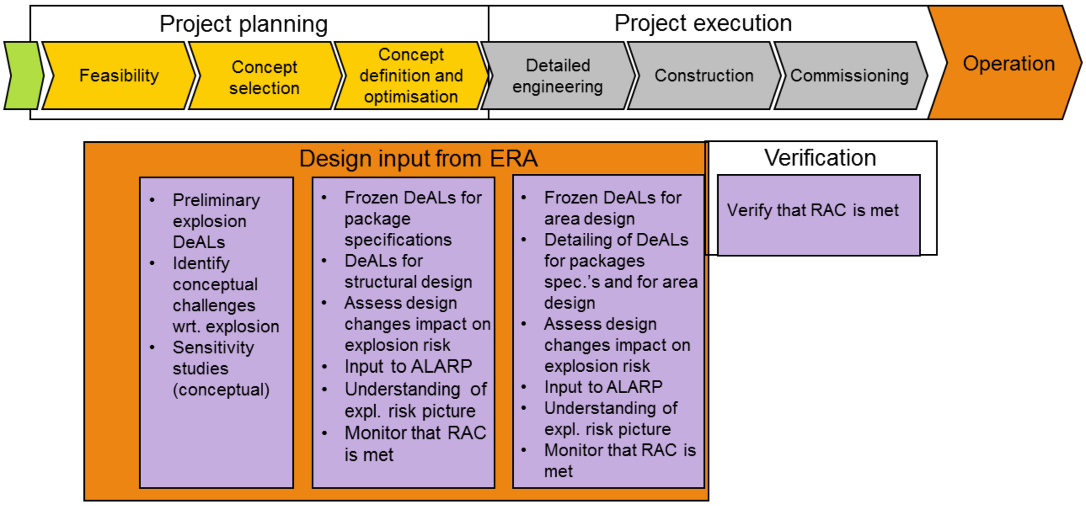


Figure 2: Design input from the probabilistic explosion analysis in different project stages (current approach)

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.

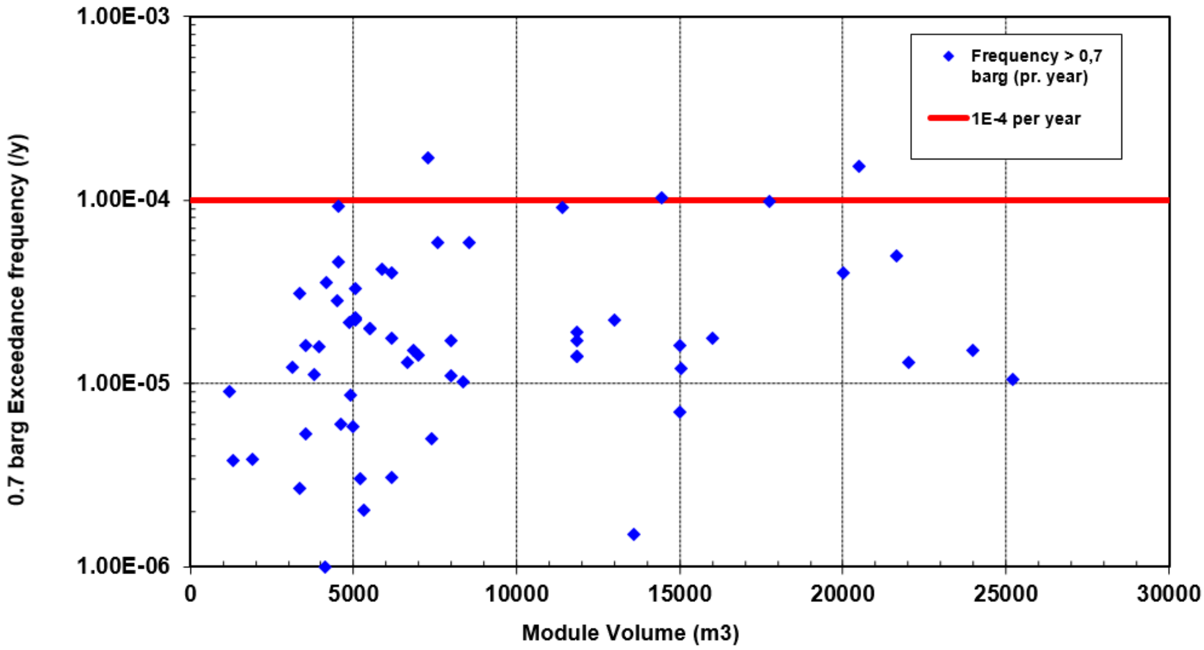


Figure 3 Size of module volume versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed

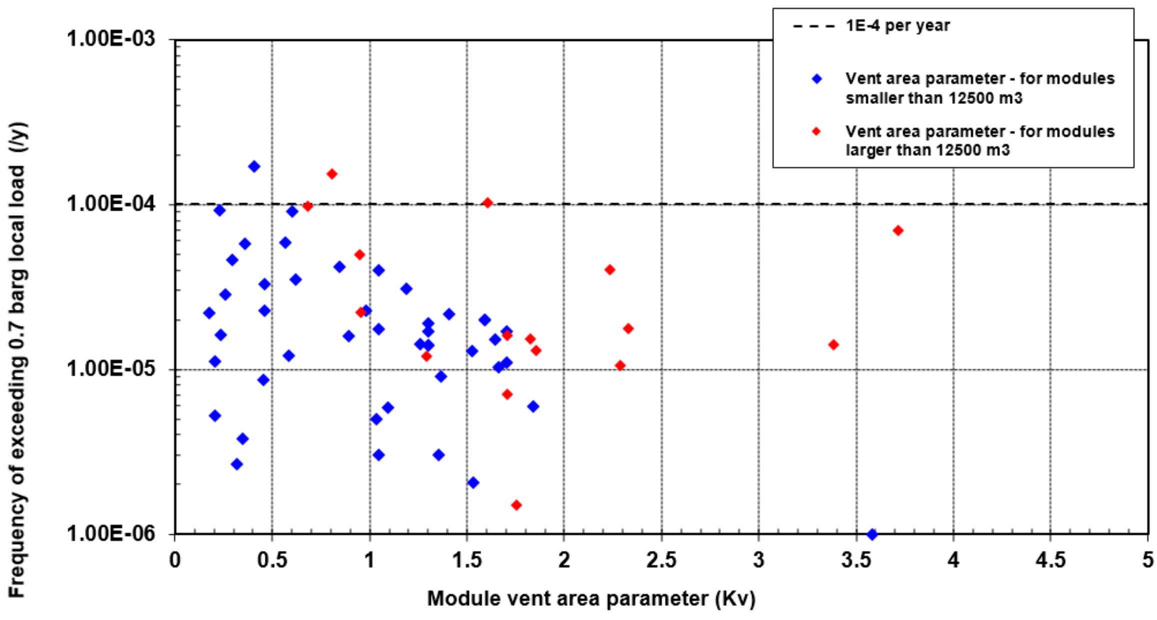


Figure 4 Module vent area parameter versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed. Scatter plot differentiates between large areas (orange dots) and smaller modules (blue dots). The split between "small"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

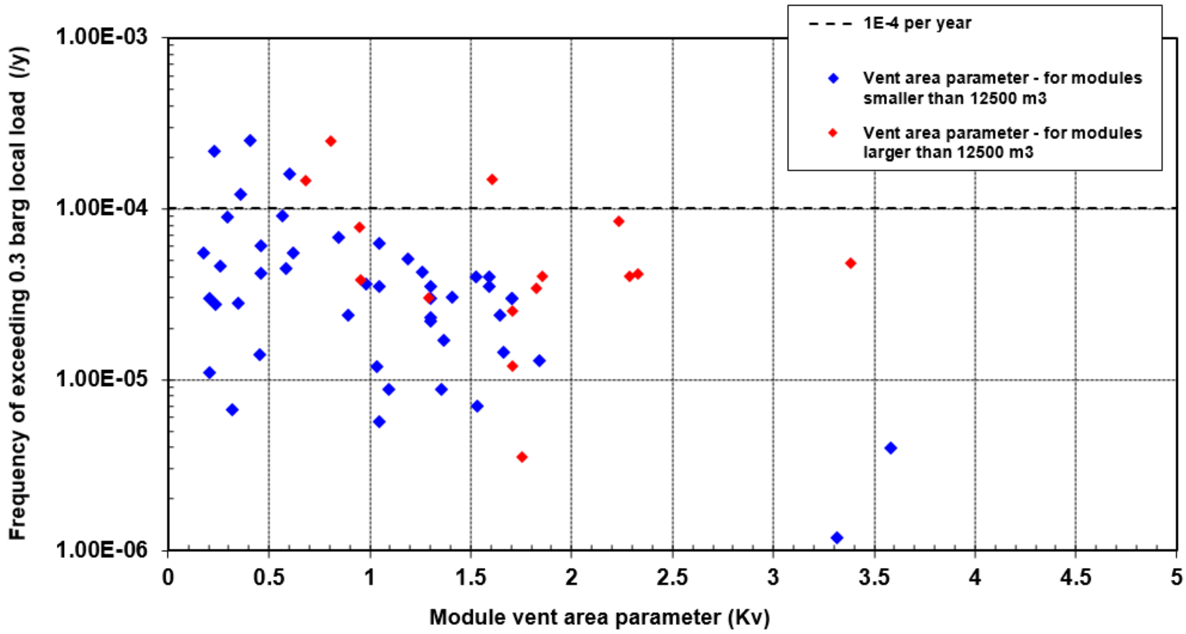


Figure 5 Module vent area parameter versus calculated frequency for exceeding 0.3 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed. Scatter plot differentiates between large areas (orange dots) and smaller modules (blue dots). The split between "small" and "large" areas is set at 12 500 m³

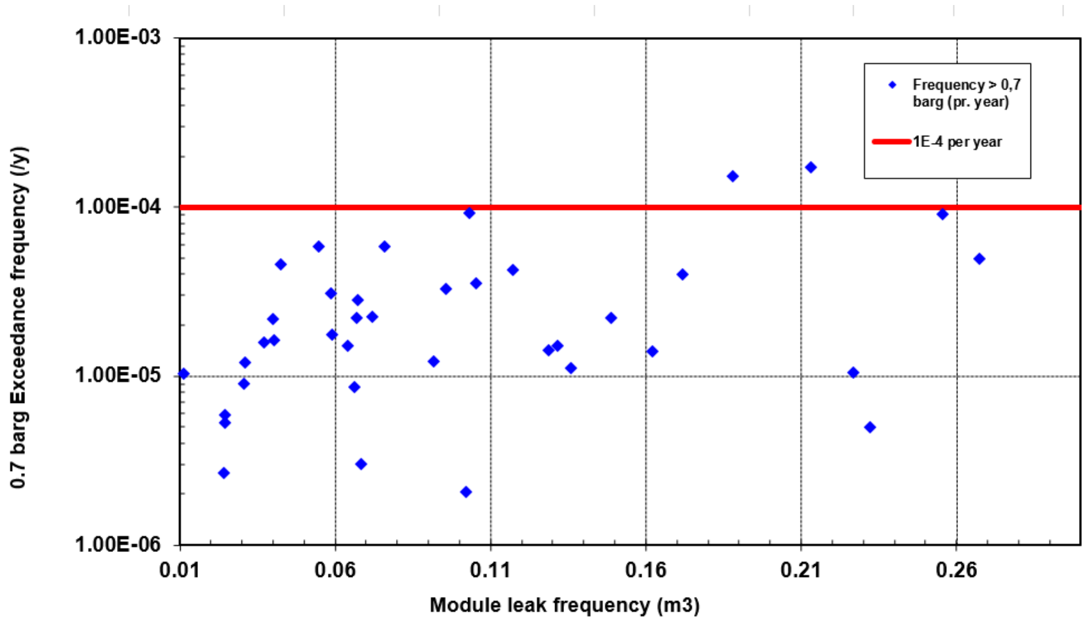


Figure 6 Calculated leak frequency versus calculated frequency for exceeding 0.7 bar local panel overpressure to physical area barrier (deck or wall) for the 65 modules assessed.

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.

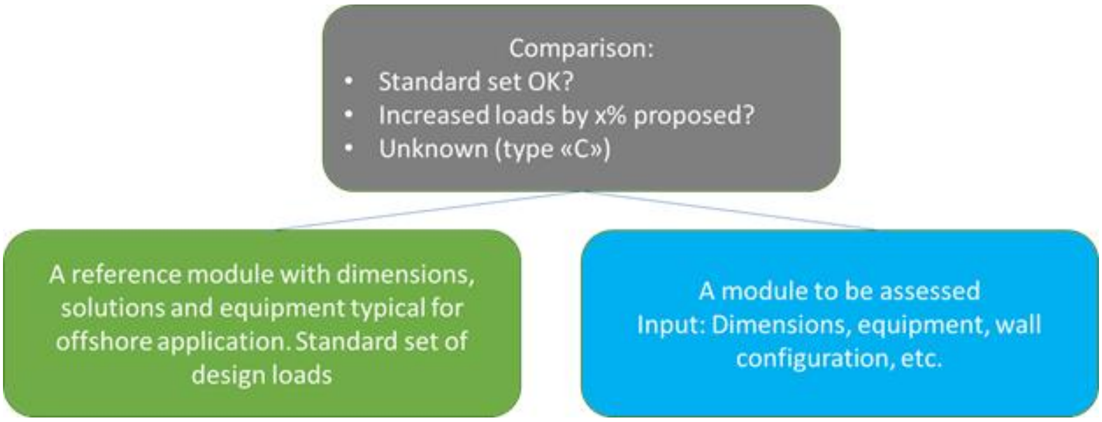


Figure 7 Module comparison methods

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.

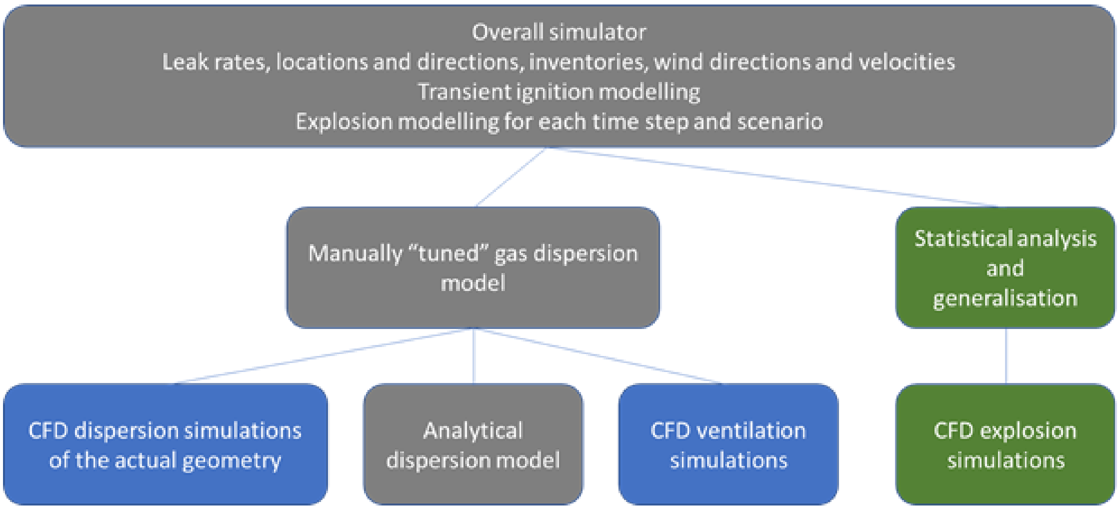


Figure 8 ASAP - NORSOK Z-013 explosion risk modelling

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:

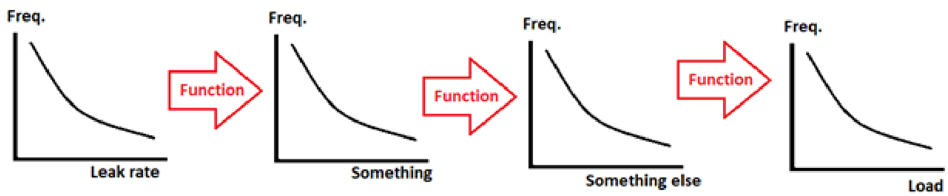


Figure 9 Frequency relationship model.

"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.

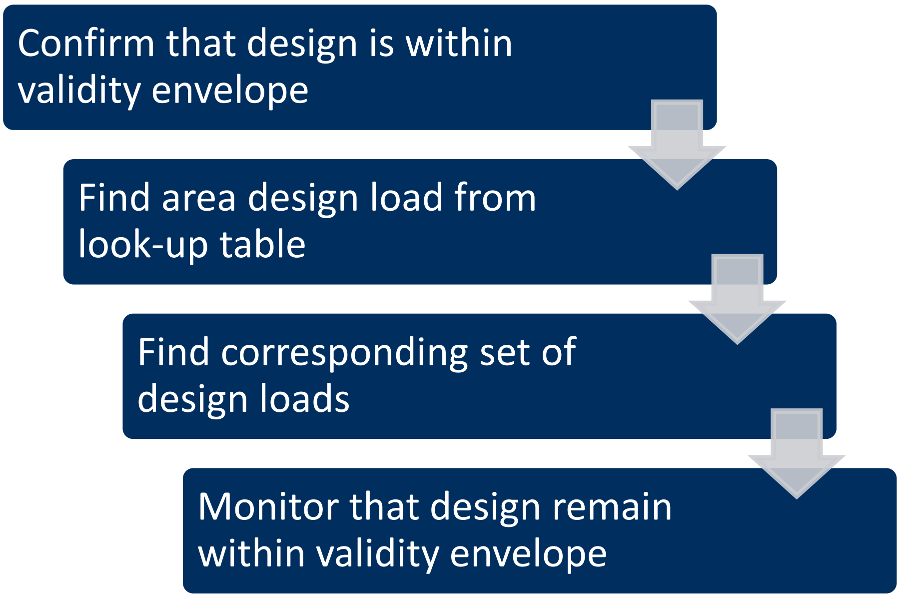
The main motivation for proposing a generic design accidental load method is to provide a consistent and efficient method to set robust design explosion loads in an early design phase, where the risk for late changes in design loads is very low. The aim is that the minimum generic design loads are set 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.

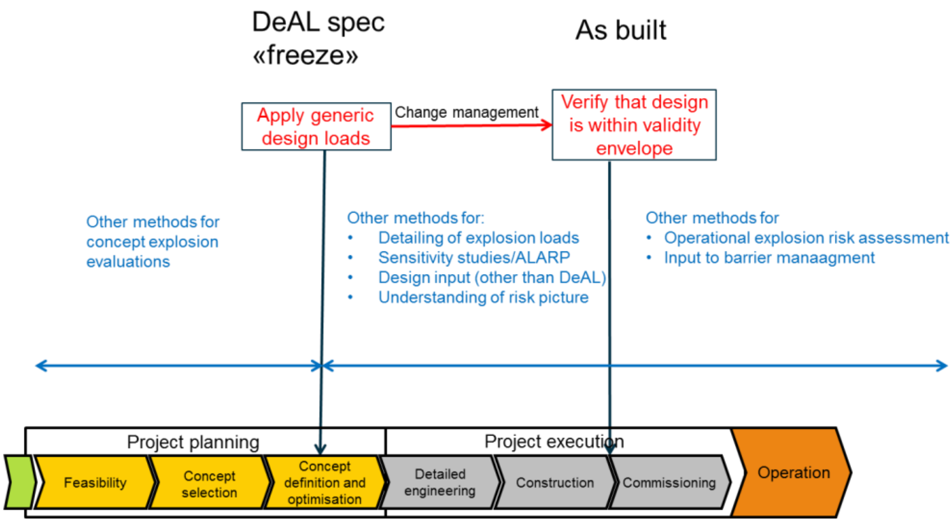


Figure 10: Application of Generic Explosion Method throughout a field development project

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).

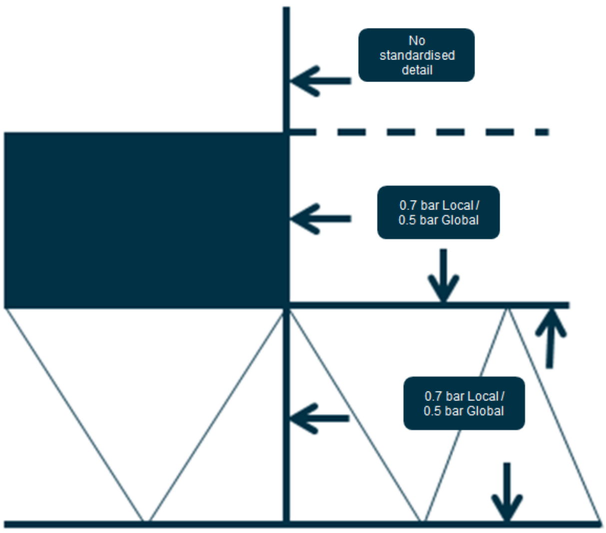


Figure 11: Standard details of main steel structures and explosion load cases in design

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.

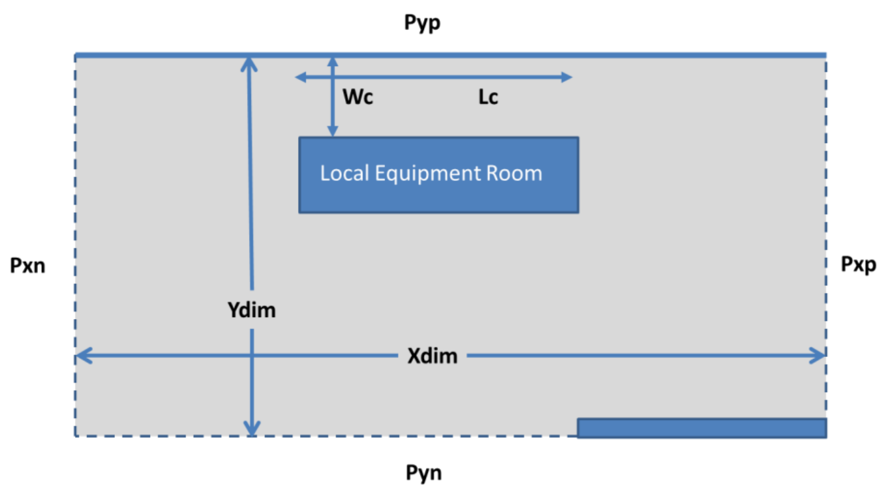


Figure 13 Illustration of horizontal cut plane through platform module, Xdim (E-W) and Ydim (N-S) are dimensions of the module, Pxn, Pxp, Pyn and Pyp are area porosities across the module openings, Wc and Lc are width and length of a "channel" between the blastwall (N) and a local equipment room, the 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.

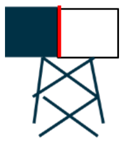
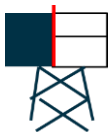
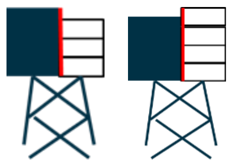
Module configuration

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.

$Av = V \times [(Pxn+Pxp)/Xdim + (Pyn+Pyp)/Ydim + (Pzn+Pzp)/Zdim]$ 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

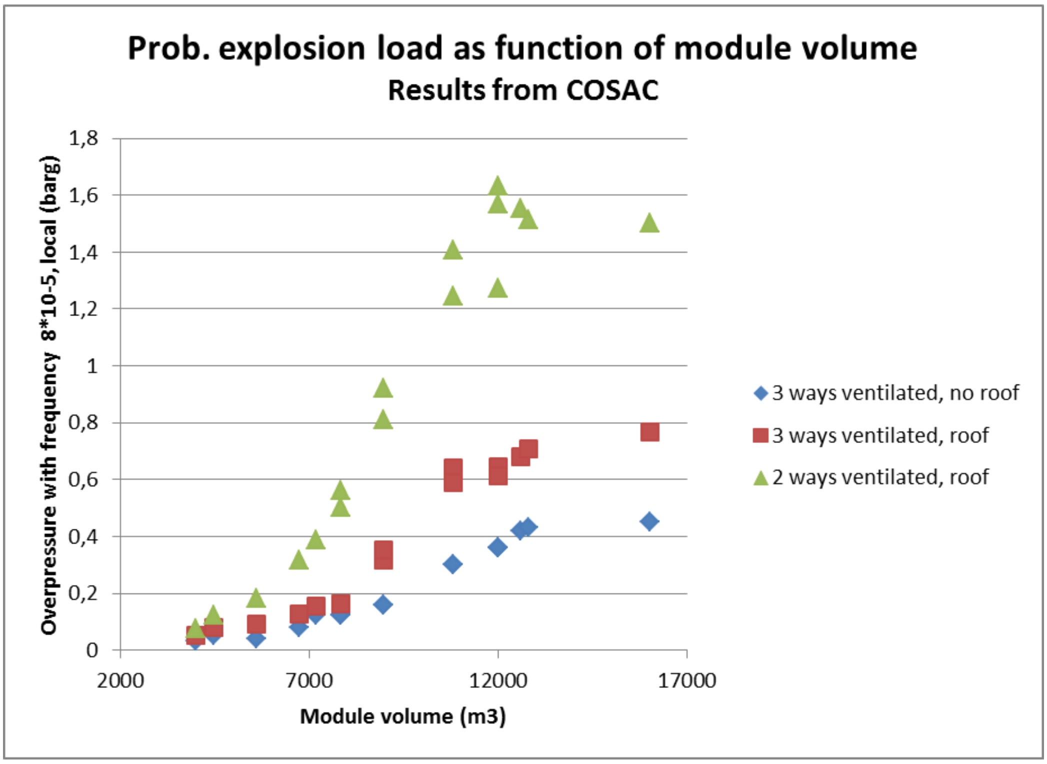


Figure 14: Example of use of COSAC for as basis or as validation of boundaries for Generic Explosion Loads method

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.

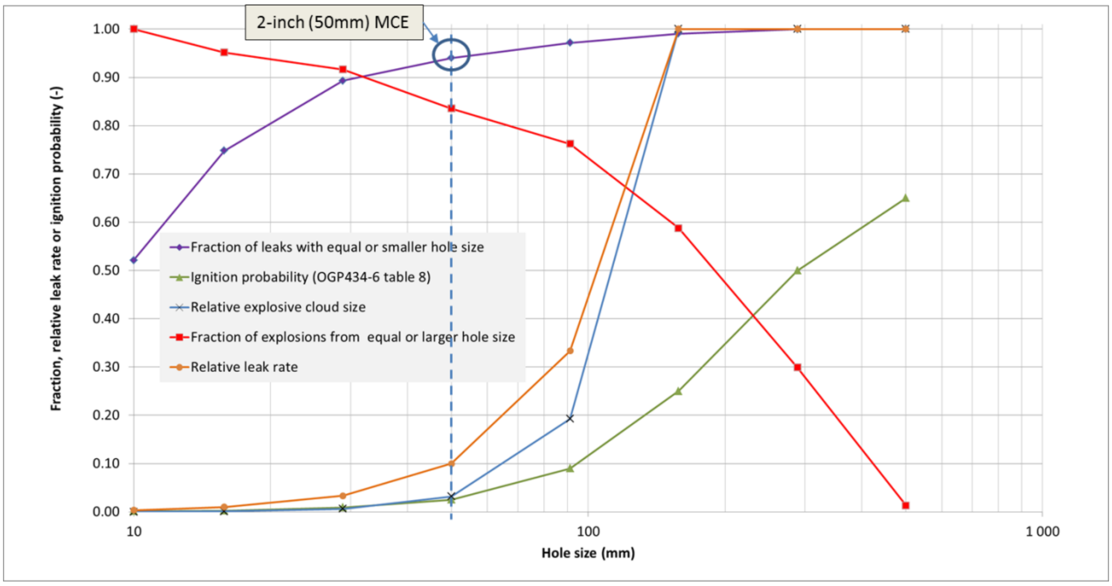


Figure 15 Illustration of possible relation between hole size distribution (purple), leak rate (orange), cloud size (blue), ignition probability (green) and probability that the next explosions will be from a given hole size or larger (red curve).

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.

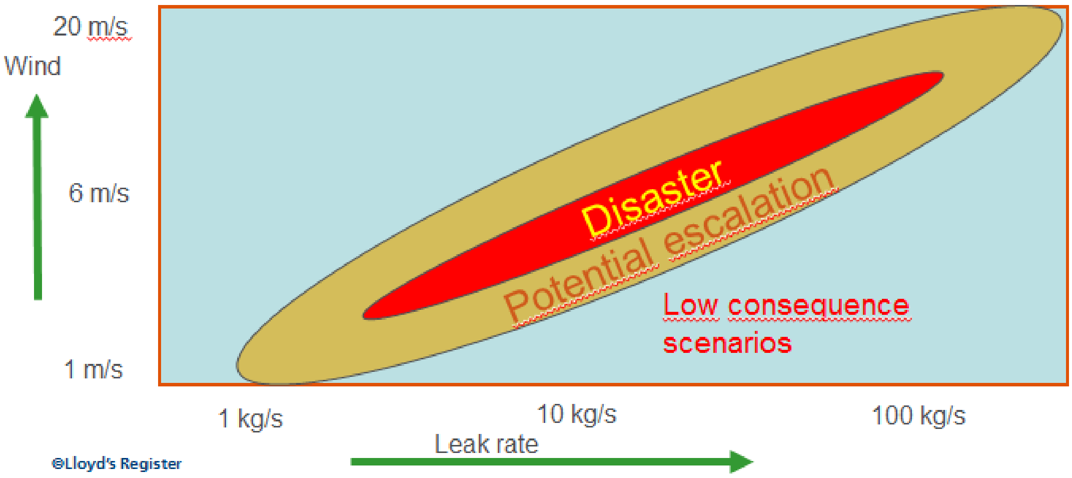


Figure 16 Simplified illustration of expected explosion severity as function of ventilation for a given platform module scenario. The worst incidents may happen for moderate leak rates in moderate wind, or with higher leak rates and more wind. A large release rate in low wind may be less severe.

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.	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.

Analysis of a specific module

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.

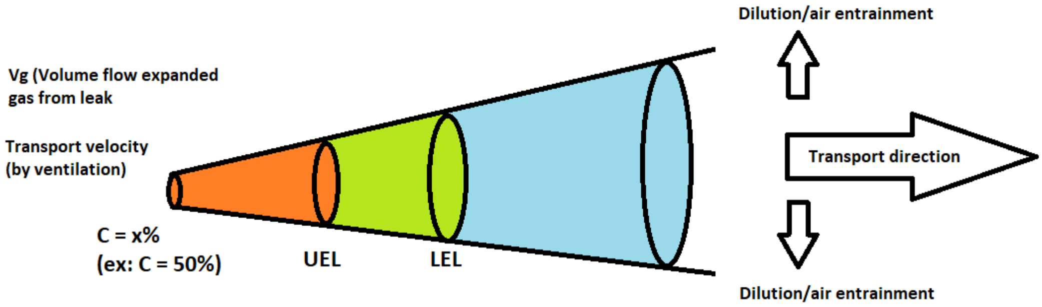


Figure 17: Conceptual model for gas dispersion

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.

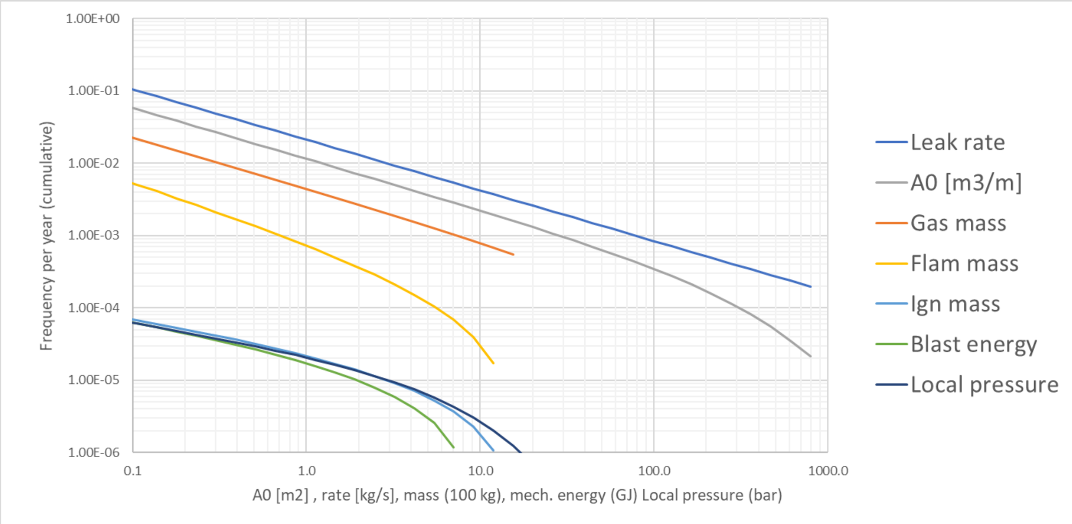


Figure 18: Prototype model results for a real case (module is 44m·40m·8m, average ACH = 261)

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).

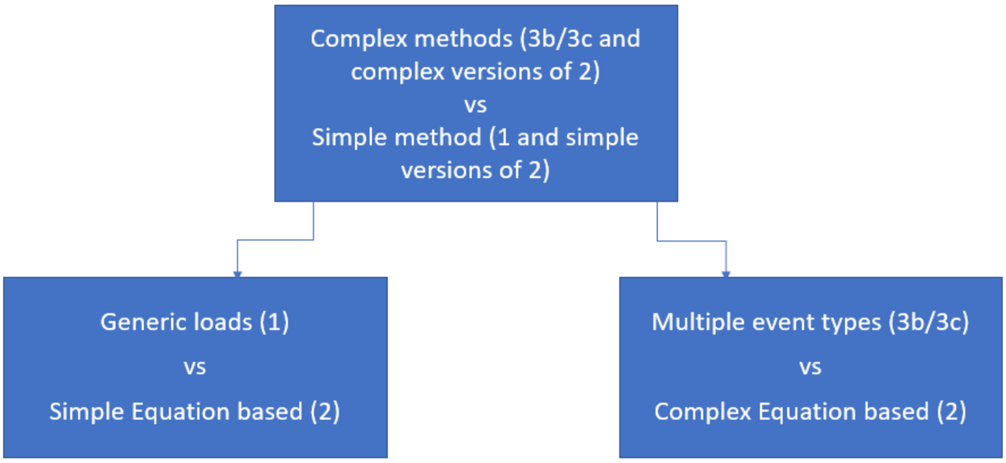
The key features that should be focused on in order to fulfil the criteria are

- 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

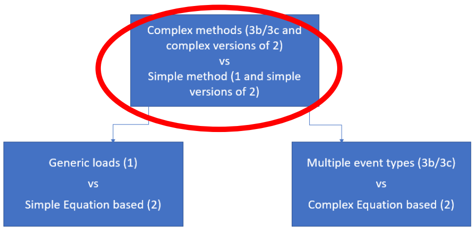
This section compares the different types of methods to give a summary on the differences with respect to fulfilling the requirements to the method. It is also focused on ability to solve challenges with current practice with explosion analysis (as well as generate new challenges). All methods listed 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):

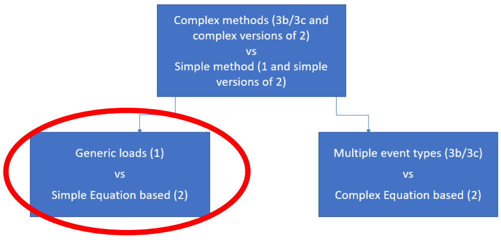
- There will be less subjective interpretations needed to perform modelling, which will ensure that inconsistent results for different companies/persons are avoided, which will reduce the risk of late changes (lower risk of change)
- The input will be available when needed, which will also reduce the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

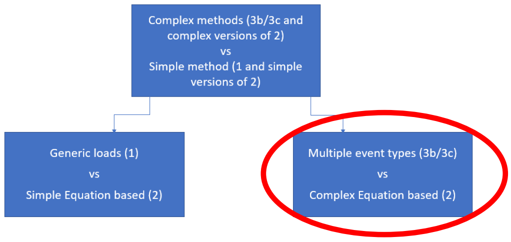
- The chain of events leading to and determining the outcome of an explosion is very complex and sensitive to small details. A simple method will not have the ability to reflect details that may be important in the context of an explosion event.
- A simplified method needs to be **conservative** as well 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)

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

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.

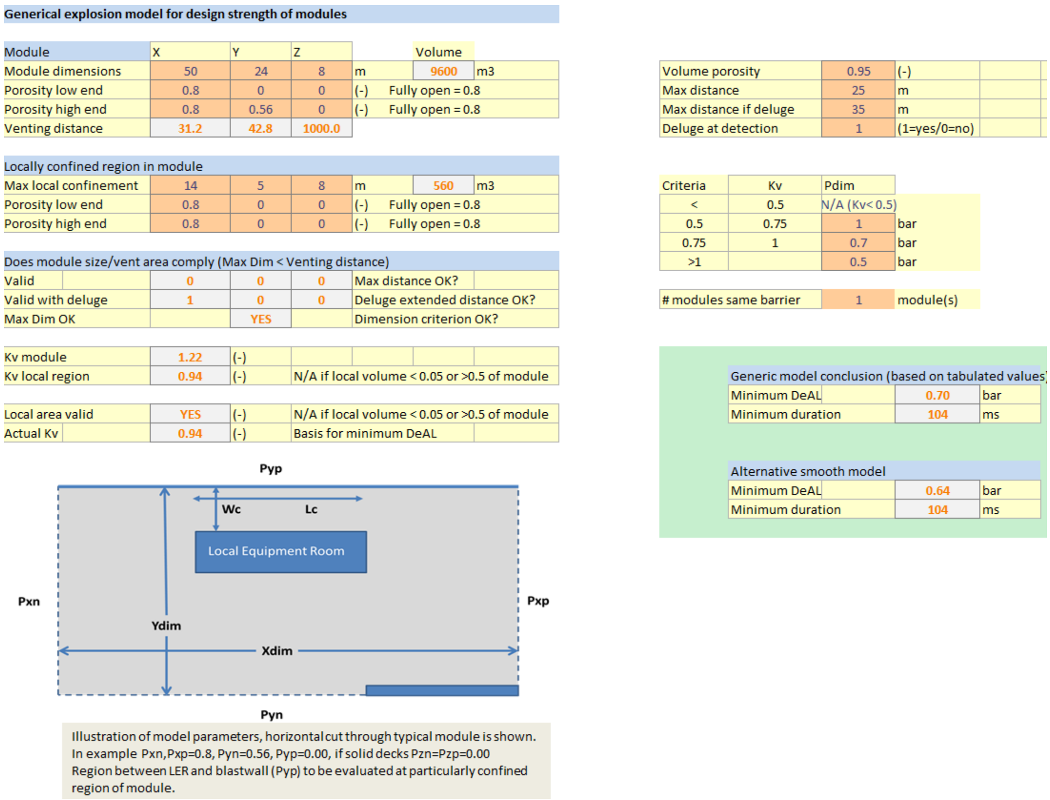


Figure 1 Draft worksheet for Generic Explosion Model Prototype. Input cells are in orange. Results are found in the green area, the upper result lines give either "Not Applicable", 0.5 bar, 0.7 bar or 1.0 bar, while the lower output gives an estimated design load above 0.5 bar according to a smooth model. 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.

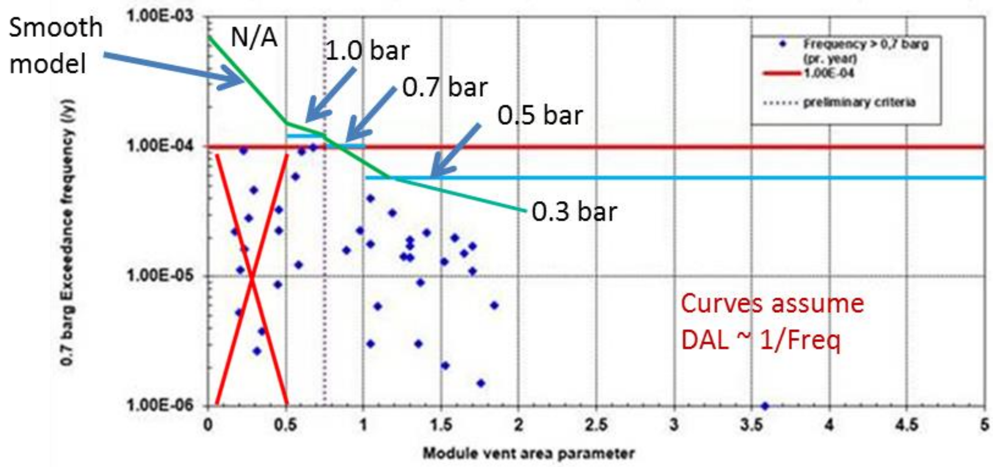


Figure 2 Generic Model is compared example platform design loads (blue dots). Plot shows frequency for exceeding 0.7 bar as function of vent parameter. Smooth model version is shown in the green line, while stepped version (0.5, 0.7, 1.0 bar) is shown with light blue horizontal lines. The goal of the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

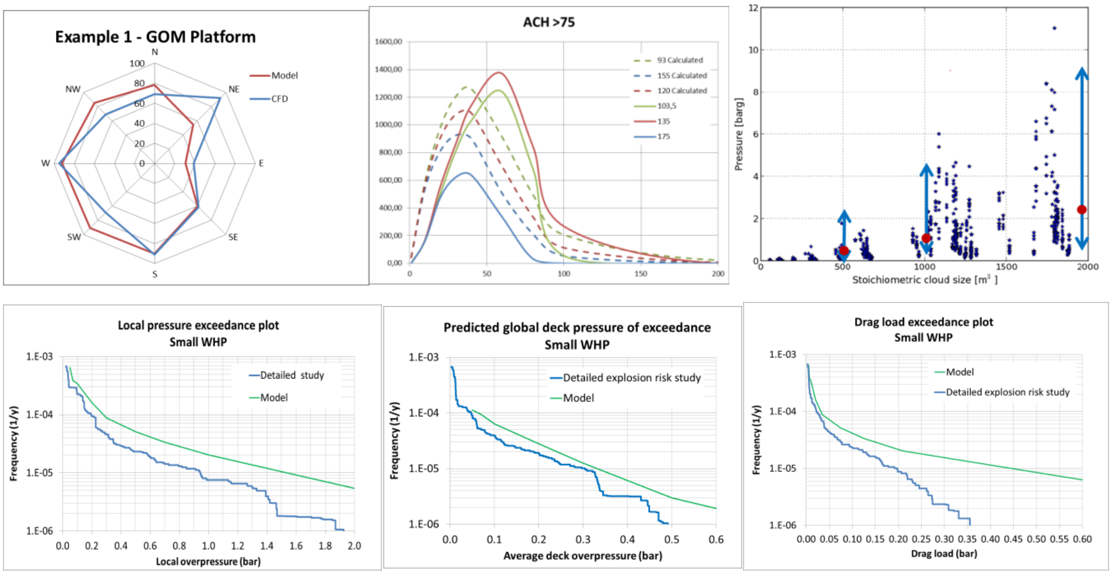


Figure 3 Example validation CFD versus Simplified NORSOK model LR, ventilation pattern (upper left), transient gas cloud sizes (upper centre), predicted explosion pressures (upper right), pressure exceedance curve for local panel, global panel and drag (lower left, centre and right).

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.

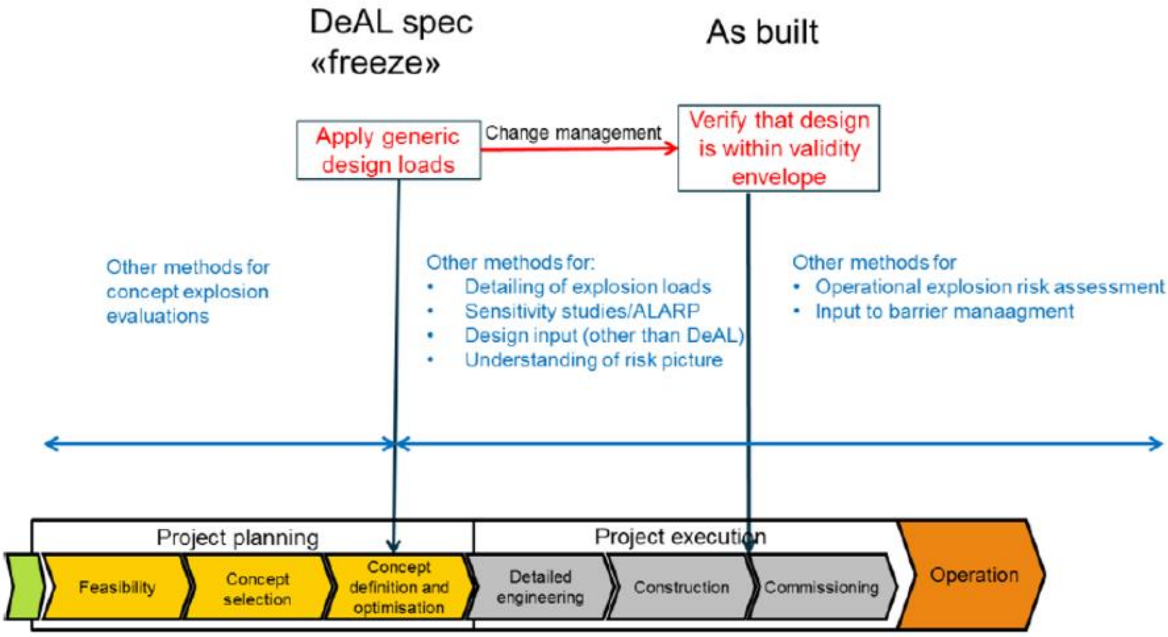


Figure 1 Ideal role and purpose of explosion risk analysis during development project sorted on a frame work suggested for RISP "generic explosion load" method

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.

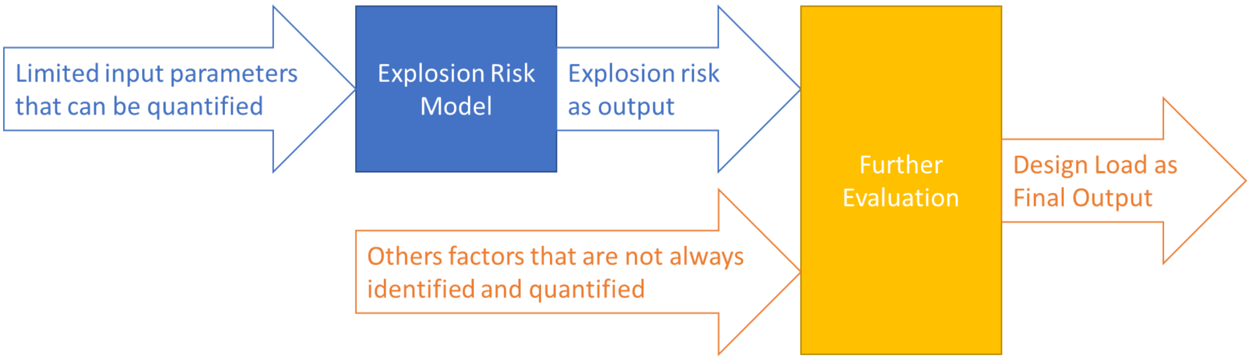
Could a simple model be feasible as basis for setting design explosion loads?
An emerging question is, considering the limitations and costs involved in a detailed ERA, could simple probabilistic analyses replace the complex NORSOK models for explosion risk quantification? The spontaneous answer to this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

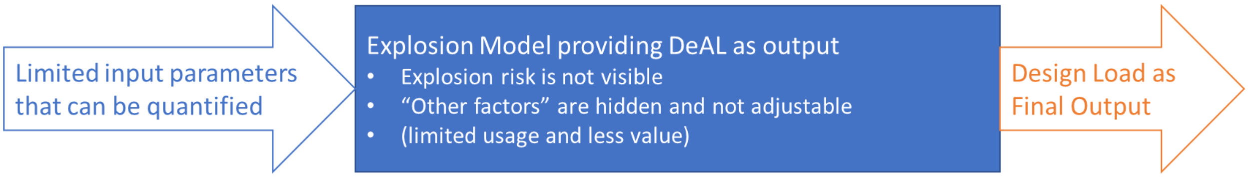
1.3 Proposed specification and a possible way forward

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))

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 $34/5363 = 6\cdot10^{-3}$ 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: $1.1\cdot10^{-3}$ per explosion area and year
- > 1 bar: $2.2\cdot10^{-4}$ per explosion area and year

The generic frequency for explosion barrier failure was estimated to $2.2\cdot10^{-4}$ 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 $4.3\cdot10^{-4}$ 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**

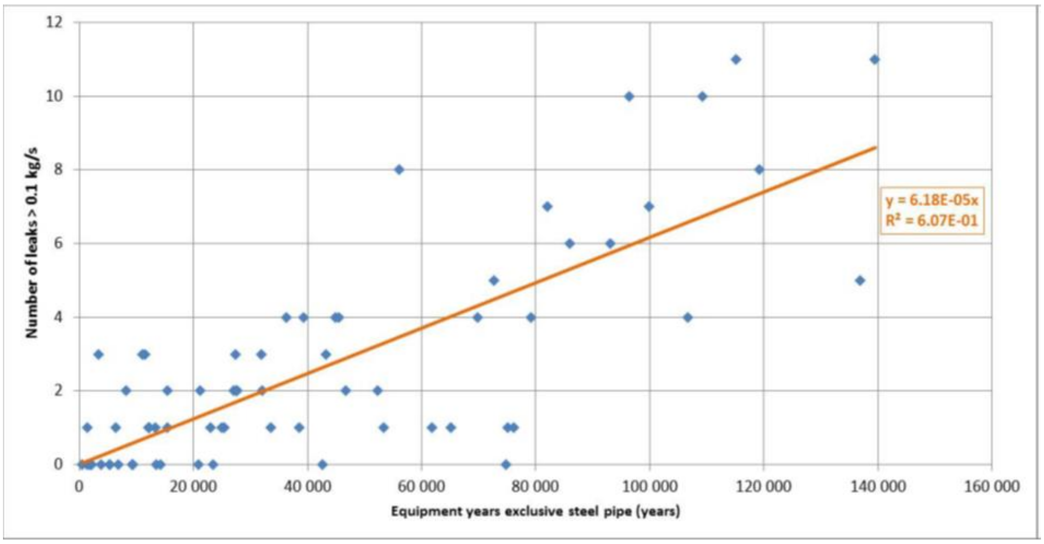

Figure B.1: Equipment years and observed number of process leaks > 0.1 kg/s [PLOFAM]

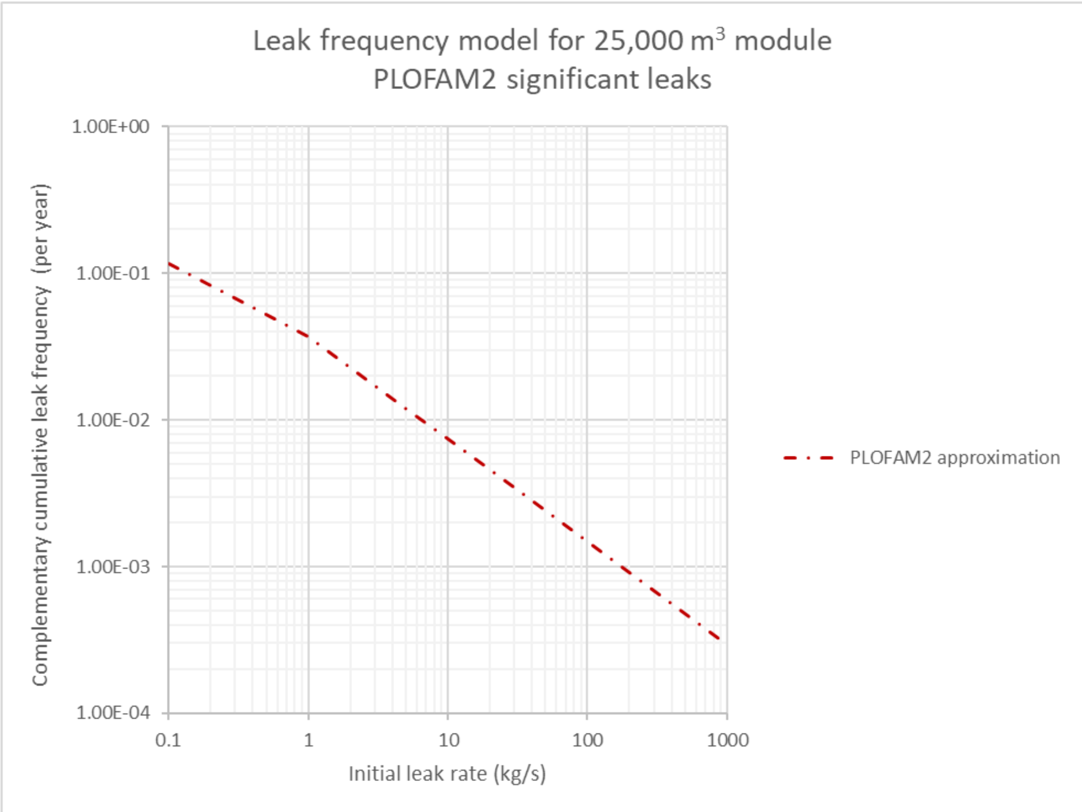

Figure B.2: Leak frequency for a 25000 m³ process module [PLOFAM]

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.

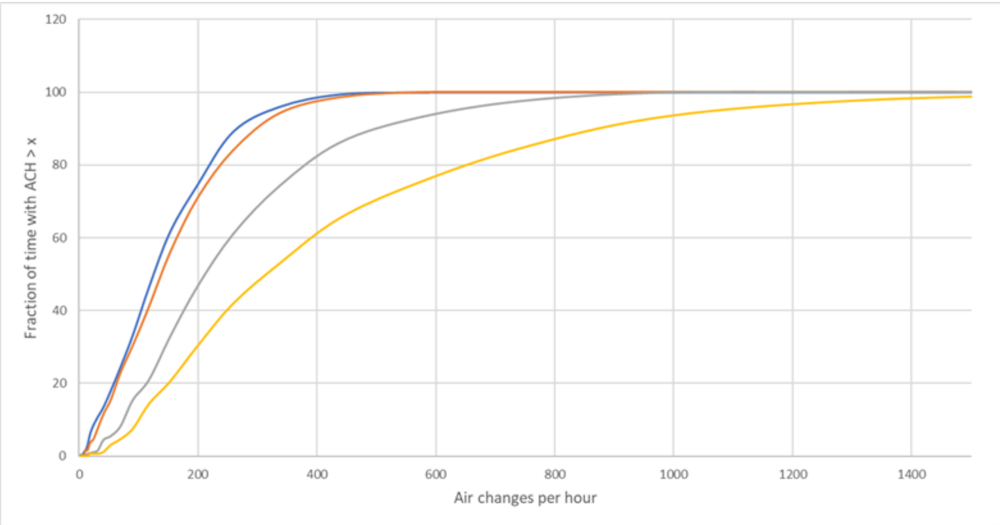

Figure B.3: Statistical analysis of natural ventilation expressed as ACH (examples)

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.

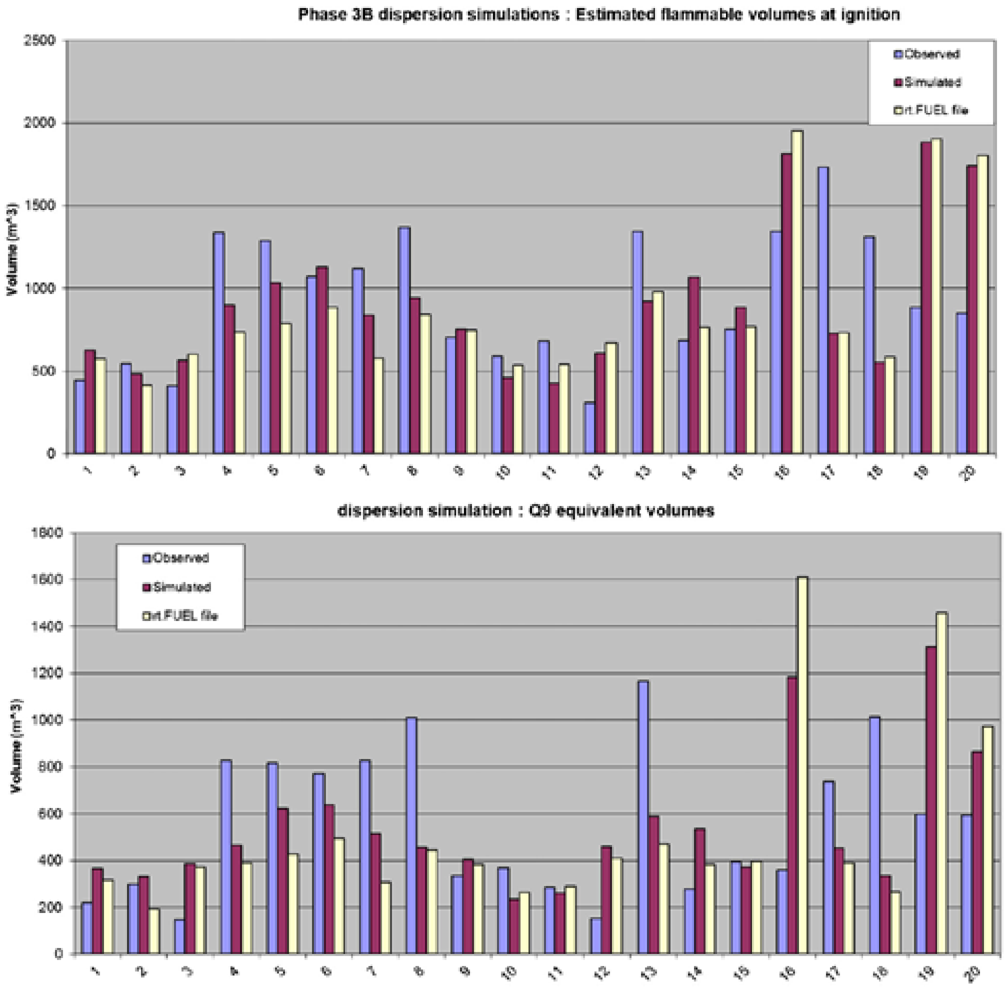

Figure B.4: Estimated flammable (top) and equivalent stoichiometric Q9 volumes at time of ignition from observed gas concentrations at sensors (blue), predicted gas concentrations at same sensors (red) and exact estimates from simulation (yellow) for the 20 ignited dispersion tests.

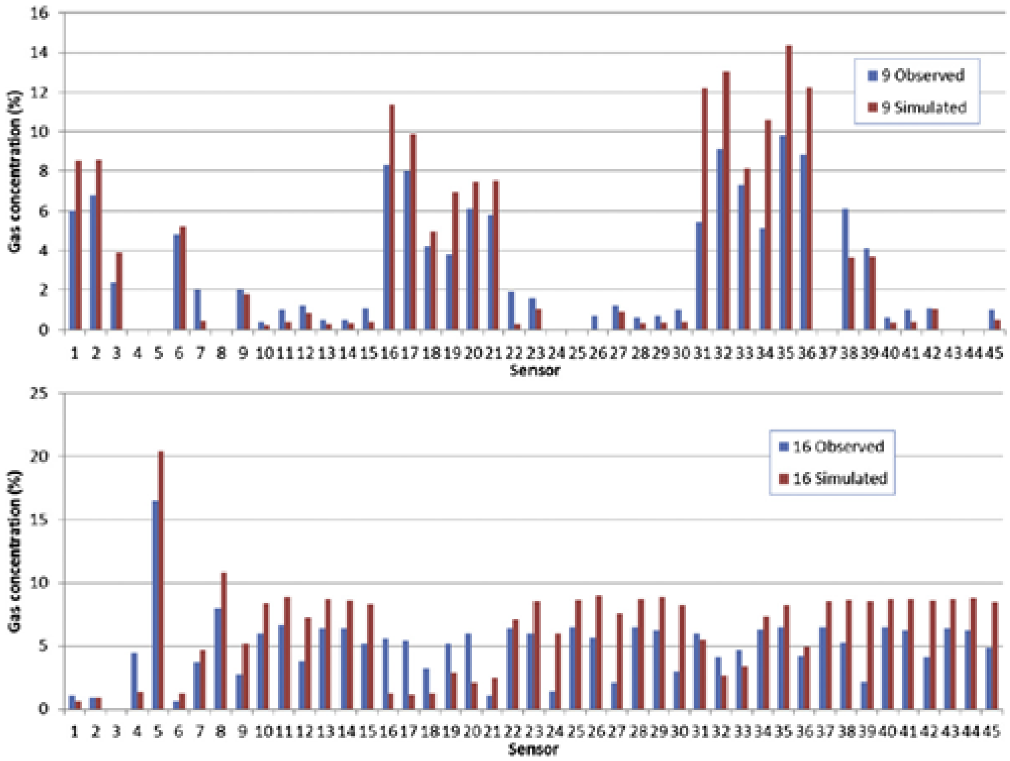

Figure B.5: Examples of sensor by sensor comparison of gas concentrations at ignition for Test 9 (top) and Test 16 (bottom). For Test 9 the simulated flammable volumes are very good, whereas for Test 16 there is a factor of three difference in estimated equivalent stoichiometric cloud.

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 ^{o}C for methane to 205 ^{o}C 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).

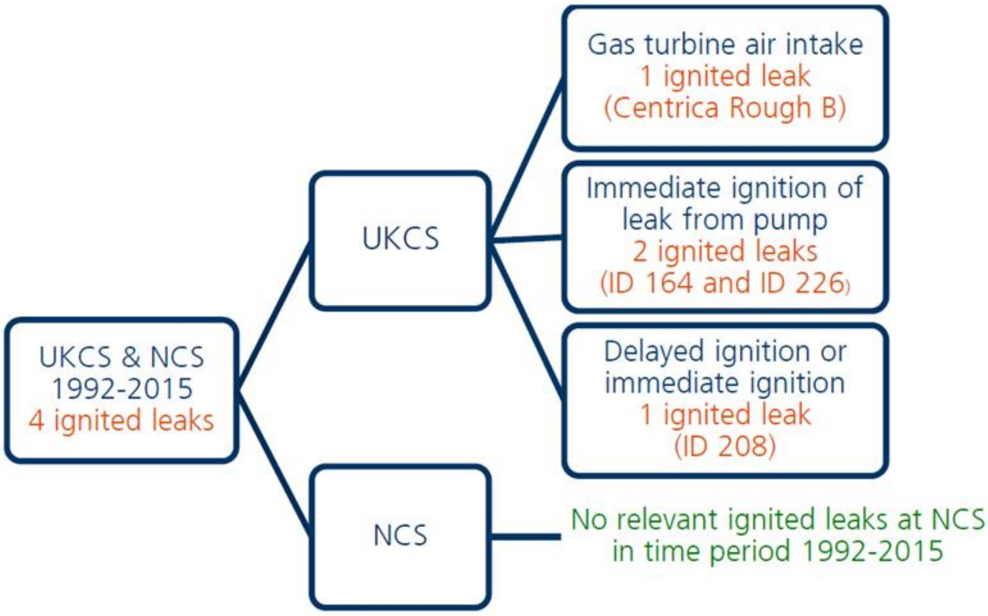

Figure B.6: Ignition of process leaks UKCS and NCS 1992-2015 [MISOF, Ref./3/]

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.

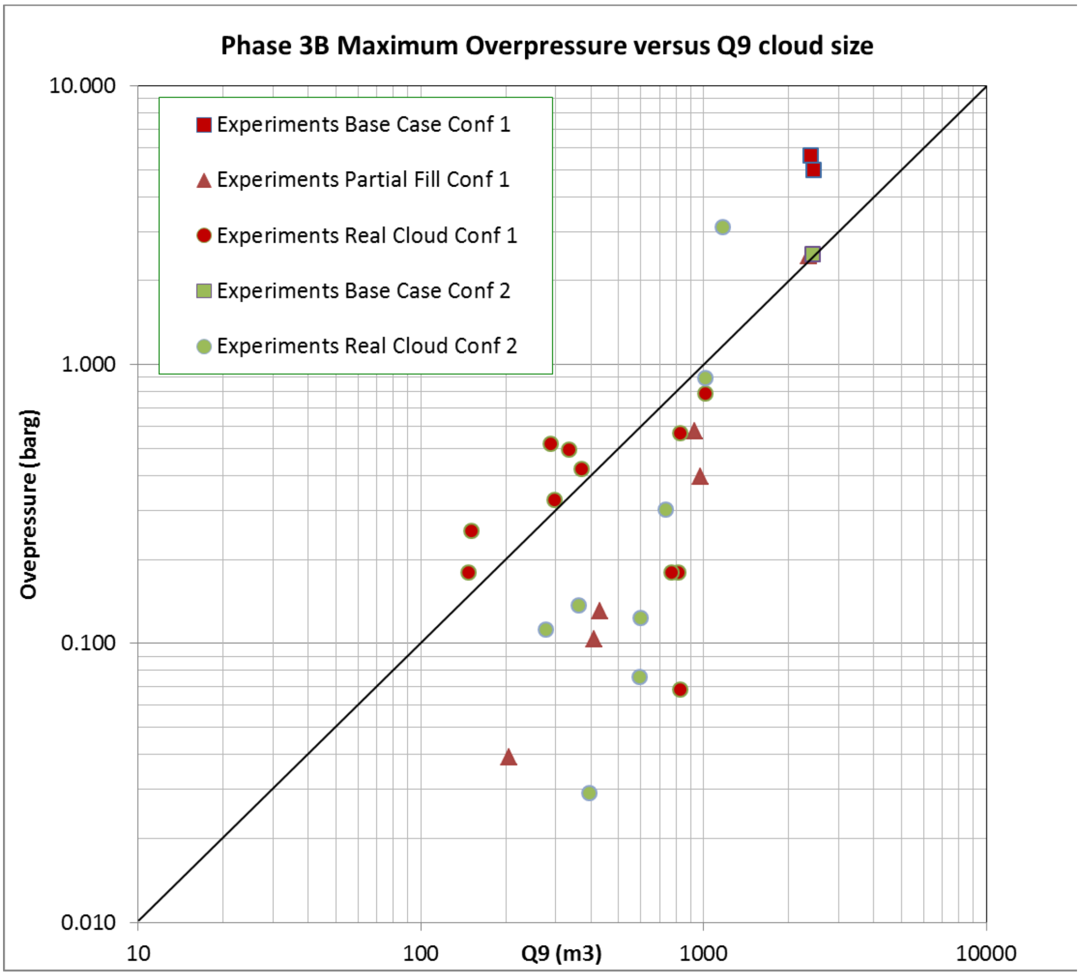

Figure B.7: Overview of BFETS Phase 3B experiments, overpressures plotted versus estimated Q9 equivalent stoichiometric cloud size [Ref./8/] for experiments in Confinement 1 (Red colour, 12m x 8m vent area on 3 sides) and Confinement 2 (Green colour, full venting 28m x 8m on one side wall). 100% worst-case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

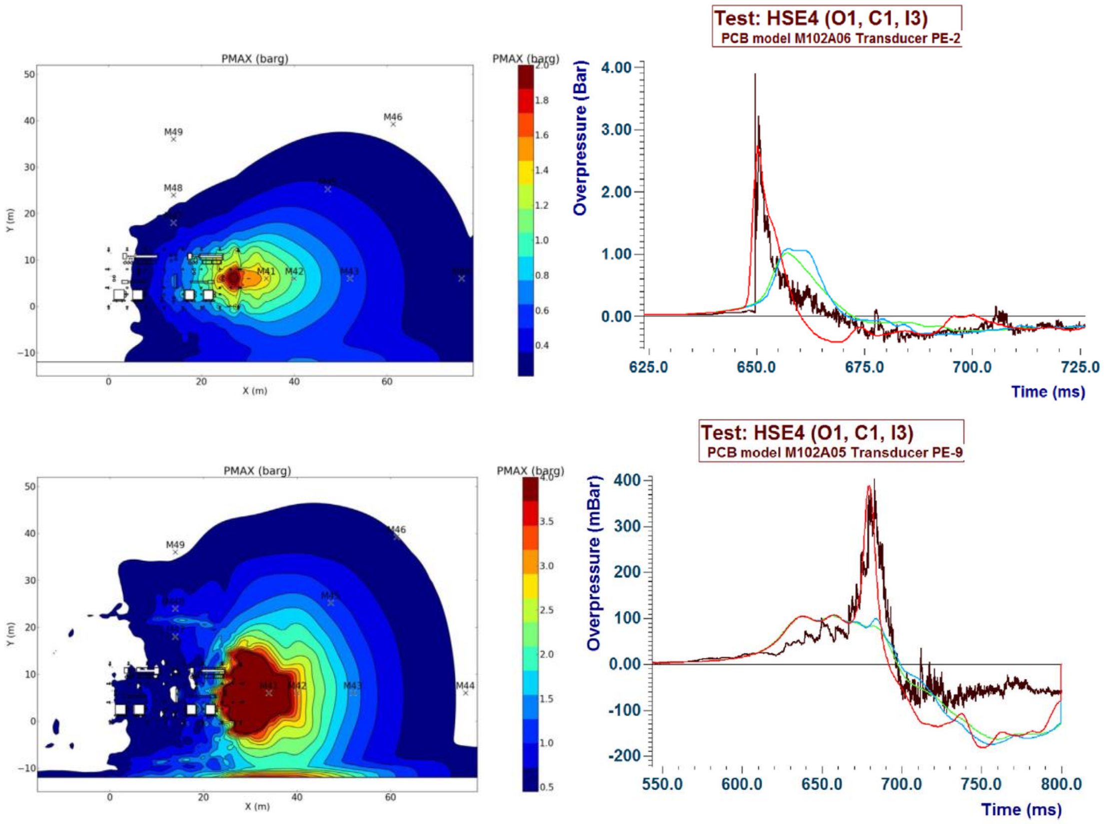

Figure B.8: Comparison blast patterns in Phase 3A Test 4 predicted as a deflagration (upper left-legend 0.25 bar – 2 bar) and a DDT towards end of module (lower left, legend is 0.5-4.0 bar), module with no walls extending from X=0-28m, Y=0-12m. In the plots to the right experimental pressures (black) 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.

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

Main report Workgroup 3 - Fires

Report for:
RISP Participants, att: Equinor Energy AS

Summary

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

Main report Workgroup 3 - Fires

Security classification of this report: Distribute only after client's acceptance

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Document history

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1. List of abbreviations and definitions

1.1 Abbreviations

AIS	Automatic Identification System
ALARP	As Low as Reasonably Practicable
ALS	Accidental Limit State
BAT	Best Available Technology
CAD	Computer-Aided Design
CAPEX	Capital Expenditure
CCR	Central Control Room
DDT	Deflagration to Detonation Transition
DeAE	Design Accidental Event(s)
DeAL	Design Accidental Load(s)
DiAL	Dimensioning Accidental Load(s)
DP	Dynamic Positioning
DP2	Dynamic Positioning – Redundancy Class 2
EERS	Escape Evacuation and Rescue Strategy
ESD	Emergency Shutdown
FEED	Front End Engineering and Design
FES	Fire and Explosion Strategy
FPSO	Floating, Production, Storage and Offloading
GBS	Gravity Based Structure
G-OMO	Guidelines for Offshore Marine Operations
HAZAN	Hazard Identification and Analysis
HAZID	Hazard Identification
HC	Hydrocarbon
HSE	Health, Safety and Environment
ISD	Inherent Safe Design
JIP	Joint Industry Project (In this case the RISP project)
LD	Lethal Dose
LEL	Lower Explosion Limit
MAH	Major Accident Hazard
MEG	Mono Ethylene Glycol
MeOH	Methanol
NCS	Norwegian Continental Shelf
NOROG	Norwegian Oil and Gas
PFP	Passive Fire Protection
PPE	Personal Protection Equipment
PRV	Pressure Relieve Valve
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Analysis
RISP	Risk Informed Decision Support in Development Projects
SC	Steering Committee
SPR	Sudden Pressure Relay
SSIV	Subsea Isolation Valve
TEG	Tri Ethylene Glycol
TRA	Total Risk Analysis
TSS	Traffic Separation Scheme
ULS	Ultimate Limit State
W2W	Walk to Work
WCPF	Worst Credible Process Fire
WG	Workgroup

1.2 Definitions

Terminology as used in the RISP project:

- Safety premises: Identified aspects presumed to be true and therefore used as a basis for the management of MAH. This can typically be presumption made in the HAZAN as a basis for concluding that the design is within the validity envelope of the RISP models. It can also cover other aspects such as operational restrictions. Safety premises typically needs to be verified at a later stage.
- Safety program: The safety program is a high-level plan describing the goals, means (resources), activities and analyses planned to manage MAH in a development project. Responsibilities, organisation and interaction arenas related to implementation of MAH design in the development project should be described.
- Safety strategy: The safety strategy is a high-level plan giving the link between the safety program and the design development w.r.t. MAH. The strategy describes how the end goals will be achieved. The safety strategy should also cover the needs related to fire and explosion strategy (FES) and escape, evacuation and rescue strategy (EERS). The safety strategy should outline applicable overall principles for design, layout, arrangements, philosophies and other high-level design and operational aspects related to barriers, e.g.:
  - Describing MAH relevant for the development (e.g. area by area) and describing key design measures and safety premises.
  - Describing how specific MAH are managed by the use of barrier functions, systems and elements. Typically, this should include a reference to standard requirements (e.g. Norsok S-001) and whether there are special solutions required not covered by the standards.
- Proven design: Design or concepts that are considered prequalified through operational experience and/or previous engineering documentation and analyses to such a degree that the RISP methodology and models can be applied.
- RISP methodology: The principles that has been used to establish methods and models in the JIP. The term is also applied as the totality of RISP methods and RISP models.
- RISP methods: The work steps and procedures proposed to be used for risk-based decision support in development projects.
- RISP models: The assessment tools proposed to be applied for risk-based decision support in development projects

2. Introduction

This report describes the work undertaken by WG (Workgroup) 3 as a part of the joint industry project RISP (Risk informed decision support in development projects). WG 3 has been constituted by representatives from Lilleaker Consulting, Lloyd's Register, DNV GL, Aker Solutions and Safetec.

A new methodology related to handling of MAH (Major Accident Hazards) in development projects has been established. The aim has been to allow for consistent use of industry experience rather than more analyses to support robust design of offshore facilities. The methodology is especially intended for use in project planning phase for projects.

This report is one of the workgroup reports constituting the basis for the overall RISP report, see also Figure 1. The methods and models established related to fires are documented in this report. Fires in this context are hydrocarbon fires feed by leaks originating from the well systems, risers or the process systems.

The report includes:

- Chapter 3: General premises for the methods and premises established
- Chapter 4: Proposed methods and models for process fires in process areas
- Chapter 5: Proposed methods and models for riser fires
- Chapter 6: Proposed methods and models for ignited blowouts
- Chapter 7: Recommendations for further work.

2.1 Overall RISP project

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project) with results and proposals for further work was presented in the Operations Committee meeting in NOROG and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The RISP joint industry project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is likely to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

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

The JIP consists of two Sub-Projects. Sub-Project 1 has been carried out in 2018 (includes WG 1 and WG 2). The RISP project organisation for Sub-Project 2 is illustrated in Figure 1. Sub-Project 2 includes WG 3, WG 4 and WG 5.

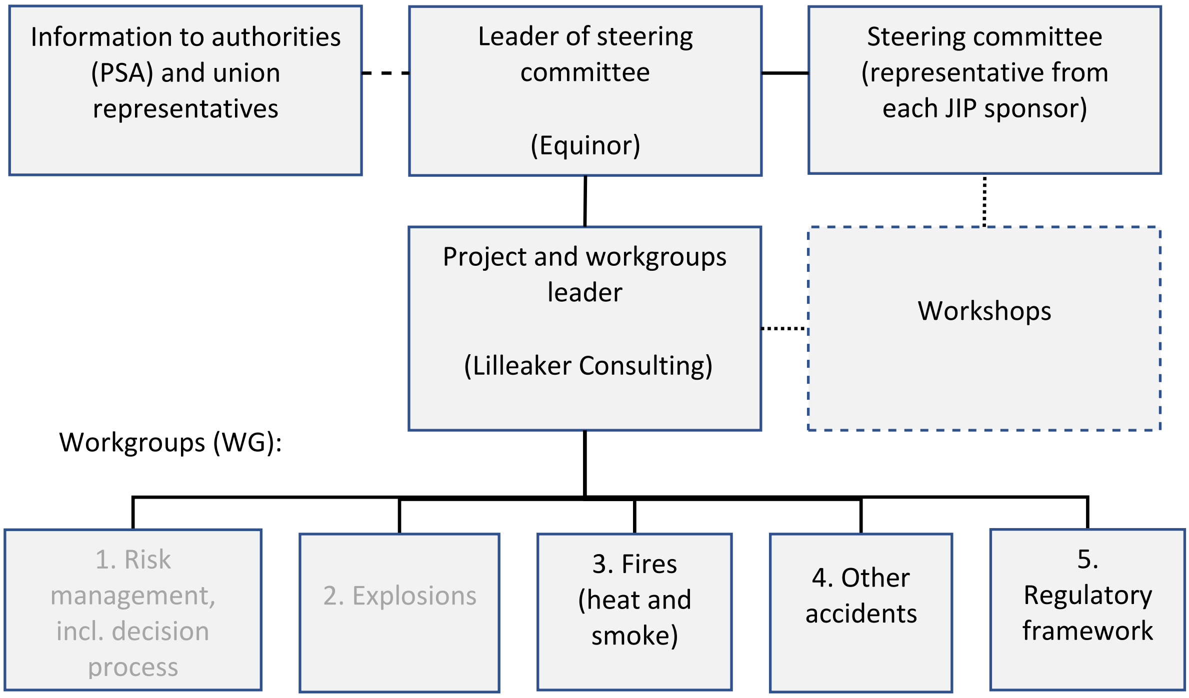

Figure 1 – The RISP project organisation overview

The five workgroups are undertaken by vendors nominated by the sponsors, and different work packages are defined for the different workgroups. The vendors are: Lilleaker Consulting, Gexcon, DNVGL, Lloyd's Register, Aker Solutions, Proactima and Safetec.

Both sponsors and vendors are participants in the JIP.

The PSA has been involved as observer in the RISP project.

2.1.1 Overall RISP context

Risk analyses have played, and still play, a key role in the safety work of the petroleum industry and have given the industry detailed and broad knowledge about risk factors and design principles. However, the present practice in use of models and tools often request input data on a very detailed level. 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. Consequently, the decision support often arrives too late.

Experience and insight gained throughout the years from making analyses have barely impacted the way analyses are made. In general, "everything" is looked at anew each time, the knowledge acquired from incidents that may occur and how plants can be optimally designed is not sufficiently utilised or reflected in the way the analyses are specified and performed.

A main recommendation from the NOROG project was that during a development project, traditional quantitative risk analyses should for proven designs as a main rule be replaced by simplified assessments. This should be done to provide the best possible support for decisions being taken on an on-going basis. Thus, the emphasis on detailed calculations of total risk, and measurement against risk acceptance criteria such as FAR and $1x10^{-4}$, should be changed. Rather than continuing to seek very detailed risk descriptions, the aim in the future should be to provide necessary decision support at the right time. This is also in line with the "new" definition of risk given in Norwegian regulations (see guidance to PSA Frame agreement §11), which is an important basis for the JIP.

The NOROG project drafted several principals and ideas for how to better deal with the above-mentioned factors. These ideas and principles have been further matured and specified in the RISP project. Proven and acceptable methods and tools can be developed for the industry's use based on the methodology outlined in this report. This will move risk management of proven designs away from total (quantitative) risk analysis as the governing element, and towards specific decision support related to each individual decision.

2.1.2 Overall RISP objective

The overall objective of the RISP project is to further develop the principles and ideas provided by the NOROG project into methods, models and guidelines, and establish a new common "industrial practice". This practice should describe how various decisions in a development project are to be based on general and specific knowledge about the incidents that the installation may be exposed to (such as leaks, fires and explosions).

Traditional quantitative risk analyses with considerable focus on detailed calculations of total risk and measurement against risk acceptance criteria such as FAR and frequencies of loss of main safety functions (1 x 10^{-4}) should, when technology and challenges are known, be replaced by input based on knowledge and experience acquired by past projects and analyses, providing a robust safety level. Instead of searching for detailed descriptions of what the risk level is, the objective should be to provide valid decision support at the right time.

All models to be developed as a part of the RISP methodology should, as far as possible, be based on the principles for risk-related decision support provided in ISO17776, see Figure 2.

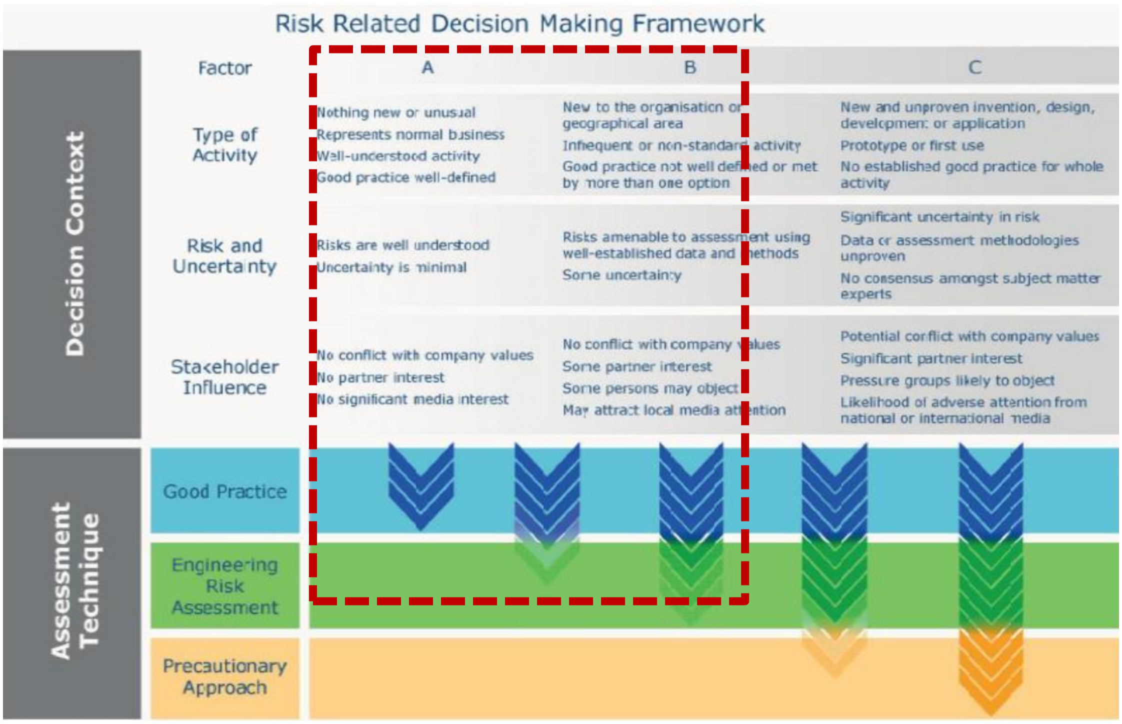

Figure 2 - Risk related decision-making framework from ISO17776 /2/). The validity envelope for the RISP methods and models is illustrated by the red dotted box, see also the WG 1 report

The new «industrial practice» developed aims to clarify:

a) if a potential type of hazard/incident is sufficiently covered by using systems and solutions indicated by requirements in standards, established good practice and results of former analyses (ref. left part of situation A in Figure 2), or

b) if the simplified RISP methods and models established can be used to provide the necessary decision support, if/when the requirements in standards, established good practice and results of former analyses (a) is not found suitable/sufficient (typically right part of situation A and major part of situation B in Figure 2), or

c) if there is a need for obtaining and using specific knowledge about the type of hazards associated to the facility/project of interest, by making various forms of analyses of the likely course of events and/or potential consequences, to be able to make sufficiently robust decisions (typically situation C in Figure 2).

When there is a need for additional knowledge compared to situation a), i.e. situation b) applies, the new "industrial practice" must specify the methods and models that should be applied, and give guidance on how results (and the conditions/assumptions they are based on) can/should be used in the decision-making process. In this way the decision maker should also be made aware of the importance of the decision and the impacts of the various decision options.

The methods and models included in the new «industrial practice» will be adapted to the knowledge and information typically available at the time when the specific decisions of interest are normally made. The decision support provided shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the input used and the restrictions related to further design development) has not been changed throughout the project. This will minimise the need for late design changes, when e.g. more detailed information is available. An as-built total risks analysis/quantitative risk analysis (TRA/QRA) will thus not be required within the new "industrial practice", but verification activities need to be developed. Verification shall ensure compliance with the validity envelope of the new approach, and that any changes in assumptions made during the development project are considered.

Barrier management, in its wide context, should found the basis for risk management in operations. A balanced description of the risk comprehensive enough for the operational phase, should be established also within the new "industrial practice".

2.2 Scope and objectives– workgroup 3

2.2.1 Scope of work workgroup 3

The work shall propose methods, and if needed models, for defining the fire scenarios and loads (heat and smoke) that needs to be accounted for/designed against throughout a development project. The methods shall be able to assess different input (changes) in a limited set of key design parameters without the need of doing extensive simulations or calculations, and/or requiring detailed information that is not available at the time of the assessment.

The fire types that shall be considered are:

- Process system fires in process areas
- Riser fires
- Ignited blowouts.

The starting point for the methods and/or criteria to be established shall be an ignited leak. The proposed method/criteria shall define the relevant fire scenarios and loads considering the outcomes of ignited leaks and their consequences, i.e. explicit assessment of leak frequencies, ignition probabilities, etc. shall not be included directly in the proposed methods/models. Definition of the validity envelope of the methods/criteria is however needed. The results and recommendations provided by the methods and models shall not be linked directly to probabilistic risk acceptance criteria (e.g. 10^{-4} per year), but the qualification / justification of the methods and models to be established can and should use such results as a reference, e.g. to show that the new methods and models will provide (at least) the same safety level as today. This is also necessary to fulfil the requirements and expectations by the regulator.

Only fires where the consequence models used in the NCS oil & gas industry today are found valid, shall be addressed, i.e. fires from fluids/gases at conditions that are within the validity envelope of the current methods and models (and the theory these are based on) shall be covered.

Design factors described by prescriptive requirements and practises in present standards and regulations shall be used as a basis for the work.

The scope for this work group shall include:

1. Develop guidelines for consistent use of WCPF in the industry, including treatment of oil vs. gas fires. Oil spray fires should also be discussed. Basis for the guidelines to be established should be definition of WCPF given in NORSOK S-001: 2018 edition and the mapping of present practise given in SINTEF report STF A27996 "Hvordan definers "worst credible process fire"?" (How is "worst credible process fire" defined?)
2. Evaluate applicability of WCPF and if needed establish other methods or criteria for how to design/protect escape routes, firewalls (size and extent), safe areas and evacuation means against fires and their loads. Develop guidance for use of the methods/criteria for decision support purposes when need for protection is considered. Possible tasks to include:
   a) Identify a small number of key risk driver parameters (design and process parameters) for fire risk, including smoke and heat, e.g. by a workshop with invited participants from relevant parties
   b) Establish a few generic fire risk pictures for situations reflecting different realistic sets of the key risk drivers, providing a set of design principles for e.g.:
      i. When an escape tunnel is needed
      ii. When a central escape route is needed
      iii. When to use grated vs. plated deck
      iv. When to implement SSIV
      v. When to use flexible risers and guide tubes
   c) Discuss the knowledge strength of the key parameters
3. Describe constraints and conditions for using the RISP methods and models (validity envelope). This should include premises for use of the methods both with respect to a standard design and relevant prescriptive requirements to be fulfilled.
4. Describe guidance related to meeting functional requirements in NORSOK S-001, 2018 edition.
5. Establish a guideline for use of the RISP methods and models. This should include a checklist to be used as a part of the HAZAN to ensure compliance with the validity envelope of the RISP methods throughout the project development process.
6. Identify possible challenges with existing regulations and standards.

The scope of work shall be updated initially in the execution of the work to reflect the preferred approach by the work group. The updated scope shall be issued for acceptance by the SC.

The work shall in an early phase include identification of professional subjects with conflicting considerations that needs to be raised for alignment / clarification / confirmation with the SC. Workshop(s) shall be proposed to present these subjects in a proper way at strategic timings

A workshop was held 15th May 2019 were priorities for the WG 3 scope was discussed. Important clarifications and priorities made during the workshop include:

- WG 3 shall prioritise to establish methods for definition of DeAL (Design Accidental Loads) and DeAE (Design Accidental Events) for process fires, riser fires and ignited blowouts. The work done by WG 3 shall be closely aligned with the SC to obtain the expected content and safety level. The methods to be established shall be based on the ideas and descriptions given in NOROG report, /1/. The parts to be further developed are:
  - Appendix 1, Chapter 2.2.1 – Process fires
  - Appendix 1, Chapter 2.2.2 – Riser and pipeline fires
  - Appendix 1, Chapter 2.2.3 – Ignited blowouts
- The further systematic review and screening of NORSOK S-001 from Chapter 7 and beyond, to be given lower priority and considered if time and budget allows. The topics in Norsok S-001 will still be reflected in the work mentioned above related to DeAL and DeAE.

The work in this JIP is a research activity and inherently entails uncertainty regarding the results to be achieved. The work performed focuses on the priorities given in the workshop 15th May. Recommendations for further work will also be considered.

3. Premises for the proposed methods and models for definition of DeAL and DeAE

3.1 Functional requirements to methods and models

When proposing methods and models to be used for defining recommended design accidental events (DeAE) and/or design accidental loads (DeAL) several aspects are considered and presented in the WG 1 report (Ref. /3/). Key aspects are repeated below:

- The models shall be transparent and traceable.
- The models shall ensure that (at least) the same level of safety is achieved by the current practice. Following discussions with the SC, reasonable robustness is included in the model based on:
    - Current practice on recent development projects.
    - Results from available data sources indicating typical risk level for the MAH (Major Accident Hazard).
    - Balancing degree/level of safety measures to be implemented to achieve similar robustness for different types of MAH's
    - Strength of knowledge for the MAH type. (ref. WG 1 report Chapter 2.2.4)
    - Cost level implied by use of the model, i.e. considering cost versus risk reduction. ALARP principles have hence been considered as basis for the models.
- Simple methods and models are proposed for use in the project planning phase:
    - The models are based on design parameters typically available in the early project planning phase.
    - Key design parameters affecting the risk level and robustness of the installation are identified as clearly as possible to make decision makers aware of the impact of decisions made and to influence maturing of the concept and layout.
    - Key aspects to be considered in the HAZAN and for defining the validity envelope models are captured as far as possible.
    - The intention for the models has been that decisions regarding DeAL and DeAE can be taken as part of project planning phase and do not need to be changed unless:
        - Changes are made that move the design outside the validity envelope or
        - a need for optimisation is requested.
    - Detailed models e.g. by use of CFD tools may be applicable if they can be used based on the information available in the project planning phase
- More advanced procedures (applying e.g. CFD) for implementation of requirements and optimisation in project execution phase:
    - During project execution phase more detailed design information is available and often a need for more detailed accidental loads are requested. This can be supported by models detailing the loads for DeAE defined in the project planning phase. Such detailing may be accomplished by detailed analysis e.g. by use of CFD.
    - Guidance for consistent use of such detailed models are given when relevant.
    - Detailed models may also be used for detailed optimisation of layout during execution phase by showing effect on accidental loads by design changes.
- The methods and models shall support the decisions typically made in development projects that should be influenced by risk-based information related to MAH.
- The validity envelope for the methods and models should be described as precisely as possible.

The above aspects are considered and discussed for the various fire hazards covered in this report (Chapter 4, 0 and 6). However, it is acknowledged that these aspects are not covered in a comprehensive and complete way in the present report.

3.2 Considerations related to present regulations and WCPF

A fundamental premise related to WCPF (Worst Credible Process Fire)is given by the requirement to prevent development of hazard and accident situations and limit the consequences of accidents as given by §33 in the Facilities regulations . The requirements related to WCPF are further elaborated in NORSOK S-001 (Ref. /4/):

> *"The worst credible process fire (WCPF) in a fire area is derived from an ignited leak in the ESD-segment including possible escalation that will give the worst exposure of main load bearing structures and fire divisions with regard to duration (not related to the time needed for safe evacuation) and heat load distribution. ESD valves and emergency depressurization valves limiting the supply of fuel can be assumed to function. With respect to liquid spills, consideration can be made to the open drain or grating in the area.*
>
> *The load from the WCPF shall be covered by the design accidental load for main load bearing structure and fire divisions. The identified WCPF shall not escalate to hydrocarbon pipeline risers or to wells (flow from reservoir) to avoid impairment of the load bearing structures"*

According to the requirements, the following safety systems can be accounted for when deriving the WCPF:

- ESD valves
- Emergency depressurization valves
- Open drain
- Grating

An important limitation of the WCPF scenario, is that it only applies to leaks originating from the process system. Hence, potential leaks stemming from utility systems, risers, pipelines and well are not included in the WCPF. However, the requirement given by §11 in the Facilities regulations gives minimum requirements to accidental loads related to main safety functions. This paragraph defines the maximum frequency for impairment of loss of main safety functions due to any fire scenario. Furthermore, the regulations include requirements stating that the fire safety design must be in accordance with the overarching ALARP- principle, which means that an even considerably lower maximum frequency for impairment of any safety barrier may be considered intolerable.

The requirements related to WCPF as given by NORSOK-S001 focus on long lasting fires that may impair the structural integrity of main load bearing structures. This often implies that medium sized leaks/fires (typically 5 to 30 kg/s) with sufficient durations will be the fires to design the fire protection for.

3.3 Workflow using RISP methods and models in development projects

The context for use of the RISP methodology in development projects, is described in the WG 1 report. As part of the WG 3 work, a further illustration of workflow using RISP methods and models in development projects has been established. The workflow is illustrated in Figure 3.

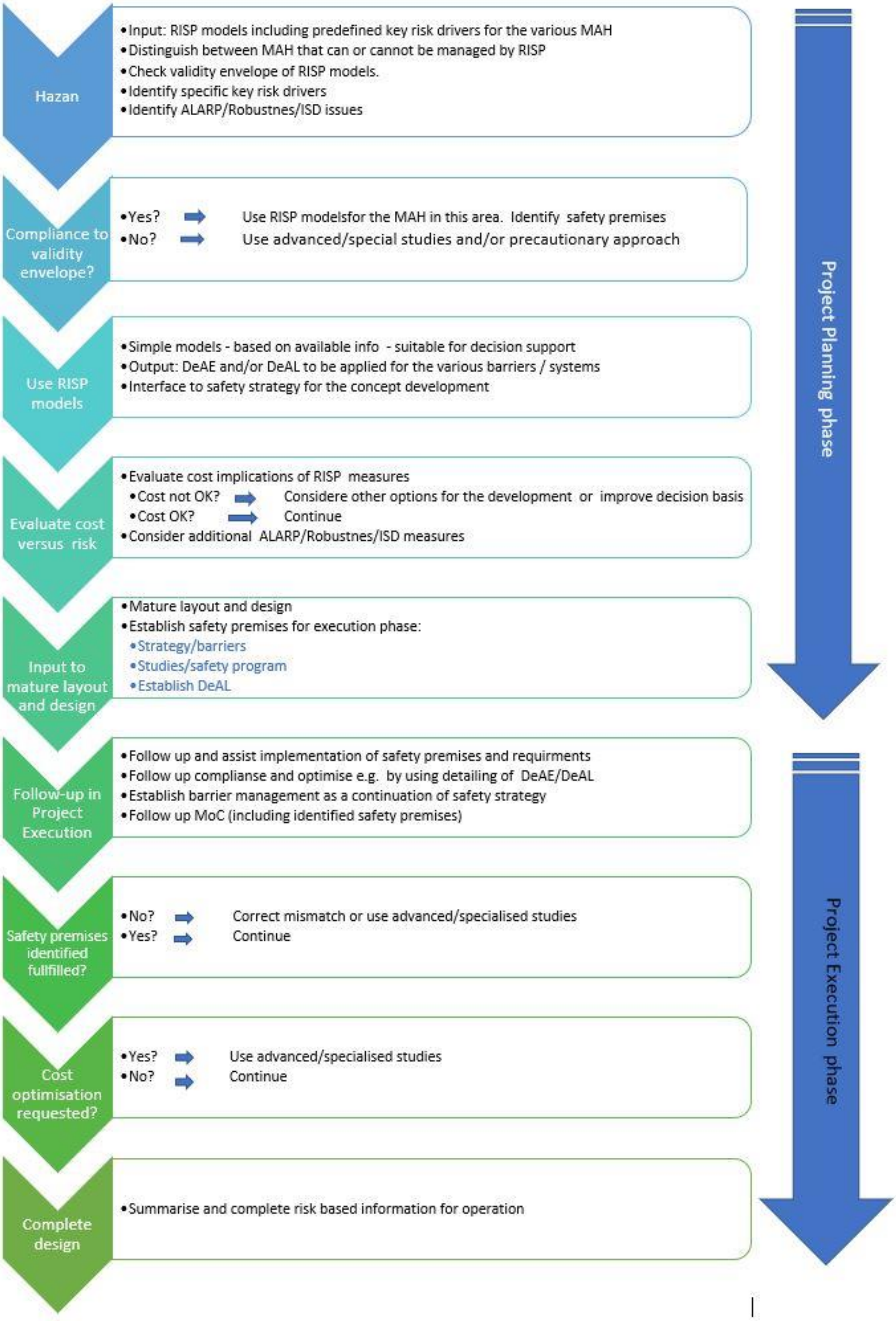

Figure 3 – Workflow using RISP methods and models - illustration

4. Proposed methods and models for process fires

4.1 Decisions to be made in development projects

Typical decisions impacting the fire hazards includes (the list is not exhaustive):

- Overall layout including segregation between main areas, size of process areas and degree of natural ventilation
- Escape route layout and location of safe area and location of evacuation means
- Type and location of power and combustion units (ignition sources)
- Location of process units (e.g. vessels, pumps, compressors, valves etc.), mass of hydrocarbons and related composition and pressure
- Size of isolatable process segments and location of ESD valves (to limit possible leak volume).
- Depressurization capacity (time requirement, sequential vs. simultaneous)
- Items that control process module ventilation during a fire; e.g. equipment density, local instrument rooms, number of walls, grated deck or grated ceiling
- Fire water system design
- "Bundings" and, open drain (it is suggested to consider development of emergency drain system that drain HC-liquid to safe area (e.g. sea) to reduce fire duration)
- Composition of HC fluid (gas, oil, water content). (The composition is not chosen but impacts the fire behaviour.)

Minimising the fire hazards is challenging because measures that can reduce the consequences of a fire, might have the opposite effect on other hazards. The heat load from a fire can be reduced and the fire can be extinguished by closing air ventilation. However, good ventilation of the process areas is an important measure against building up large explosive gas clouds. Moreover, it is more likely that a gas cloud finds an ignition source in a poorly ventilated area than in a well-ventilated area. Passive fire protection (PFP) is an efficient measure against fire heat loads on load bearing structures and process equipment. However, PFP introduces extra challenges with corrosion. Moreover, by adding to the diameter of pipes, and thickness of structures, application of PFP can increase explosion pressure loads.

According to "Guidelines for protection of pressurized systems exposed to fire" (Ref. /5/, the key parameters relevant for the fire protection of process equipment are:

- Depressurization
- Passive fire protection
- Deluge/water spray systems
- Pressure safety valves
- Selection of process equipment/materials
- Limitation of process inventories
- Fire scenarios
  - Layout
  - Ventilation
  - Drainage
  - Nature of combustible fluids
  - Nature of release (time dependent leaks/duration)

The main principles (barrier or measure) for achieving an optimum fire protection of the process system are:

- Maximum utilization of the flare system
- Selection of material quality

- Selection of material thickness/pressure classes
- Sizing of process segments/location of sectionalizing valves (inventory/volume)
- If necessary, application of passive fire protection
- Active fire protection.

4.2 Risk level and need for survivability requirements

In general, the fire frequency increase with increasing module size due to increasing number of leak sources as well as the number potential sources of ignition (e.g. electrical units, activity within the module and rotating machinery).

The resulting correlation between the process module size and fire frequency is presented in Figure 4. The results shown are based on three different modules naturally ventilated with two open walls solid roof and deck). The result is taken from the validation report of the recently validated PLOFAM and MISOF leak and ignition probability models considered to represent best industry practice at NCS for estimation of the risk related to leaks from process equipment. Hence, the figure only covers leaks from process systems according to the definition of process leaks in PLOFAM. The expected distribution with regards to initial leak rate is presented in Figure 5.

The total combined volume of all process modules at a typical installation in the North Sea, is in the interval 15 000 to 30 000 m3 This implies that the total fire frequency is expected to be about 5·10-4 per year for any given installation (strictly based on the figure, 5·10-4 per year corresponds to 30 000 m3). Most platforms consist of several modules, implying that the expected frequency per module is around 1·10-4 per year or less. The fire frequency is dominated by incidents where the initial leak rate is less than 1 kg/s.

For most platforms (i.e. the total of all modules) it is expected that the frequency for leaks with an initial leak rate greater than 10 kg/s is less than 1·10-4 per year.

This risk level is considered valid in most cases except situations where there are special sources of ignition that drive the ignition probability. The most common example is gas turbine air intakes, which currently believed to be a very potent ignition source (addressed specifically in a JIP project). Other examples are combustion engines introduced to power well intervention units. The effect of such sources of ignition is expected to be about a factor of two in unfavourable cases, mainly affecting the fire frequency for large leaks (i.e. initial leak rate > 10 kg/s).

Figure 6 shows the relative distribution of observed leaks at the Norwegian Continental Shelf in the period 2001-2017. The distribution shows that the number of leaks above 30 kg/s is few (4 leaks) and constitute only about 2.5% of the total number of leaks. In terms of fire frequency, the contribution from large leaks is more prominent, which follows from the fundamental premise in MISOF; a large leak is more likely to expose a potential live source of ignition than a small leak because it will in most cases generate a bigger combustible atmosphere. However, it may be stated that leaks having an initial leak rate larger than 30 kg/s is more remote ($0{,}7 \cdot 10^{-4}$ per year) and is less likely to take place within the lifetime of an installation.

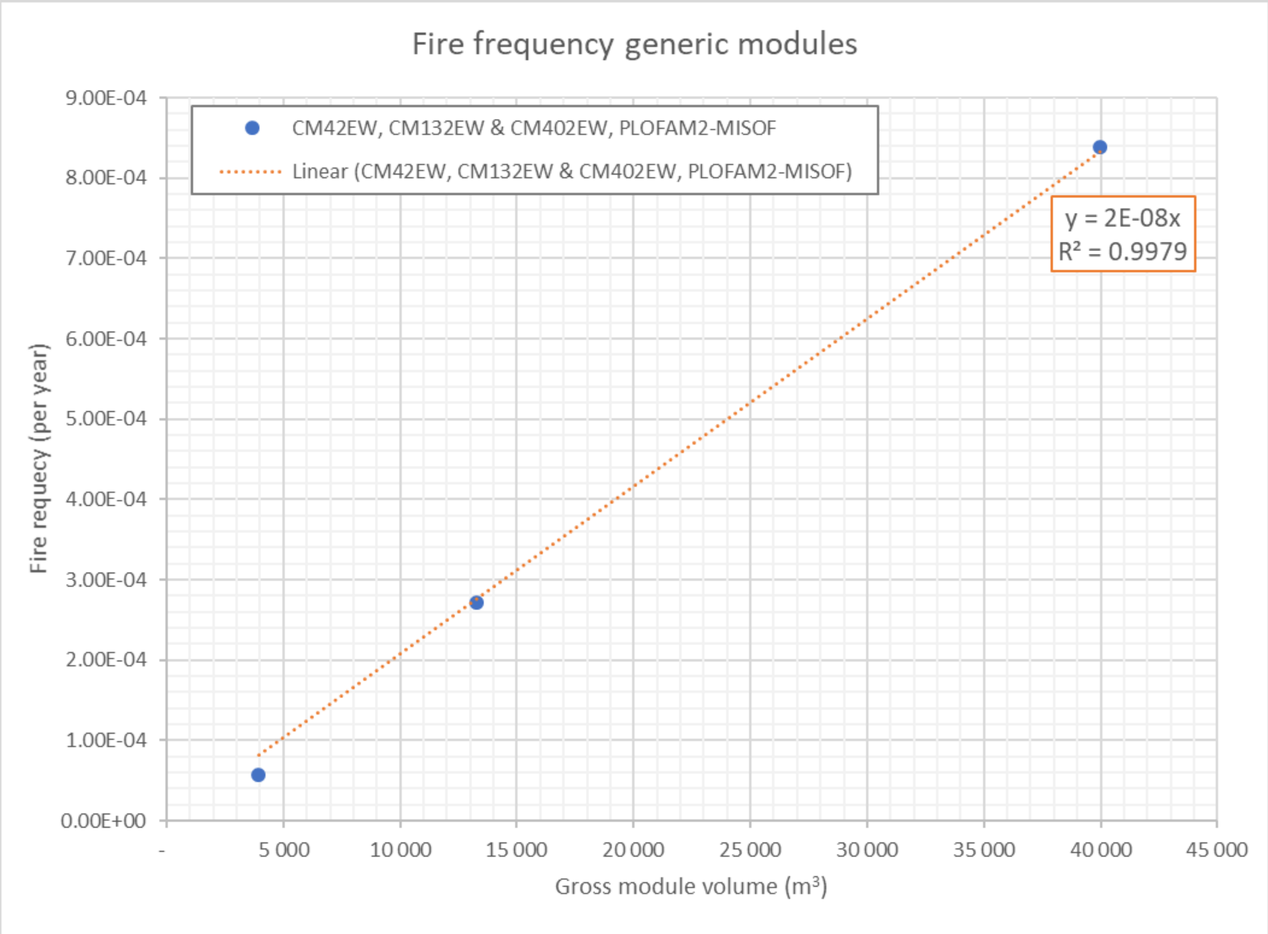

Figure 4 – Correlation between process module size and expected total fire frequency (initial leak rate > 0.1 kg/s). The estimate is taken from the test of the MISOF and PLOFAM models presented in the MISOF report (Ref. /6/).

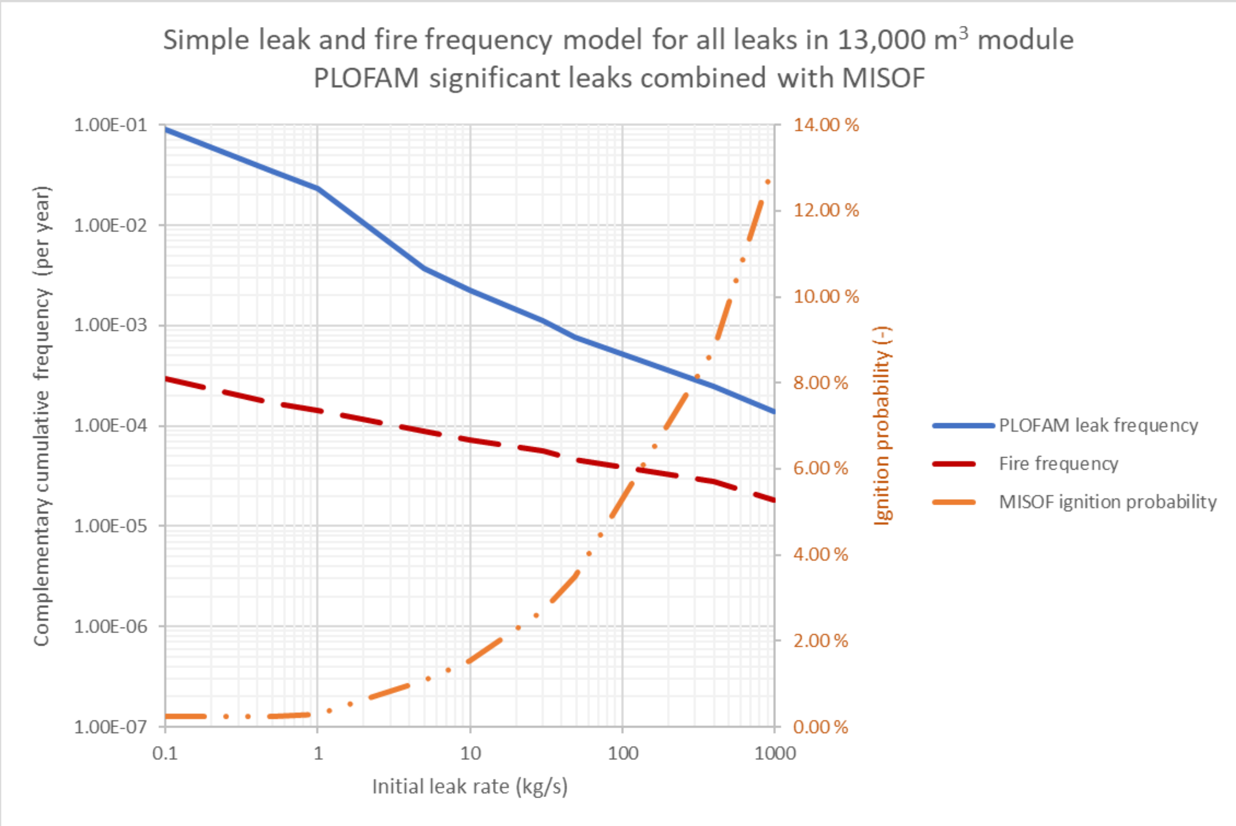

Figure 5 -Typical distribution of leak and fire frequency with respect to initial leak rate for a large process module at an offshore installation in the North Sea.

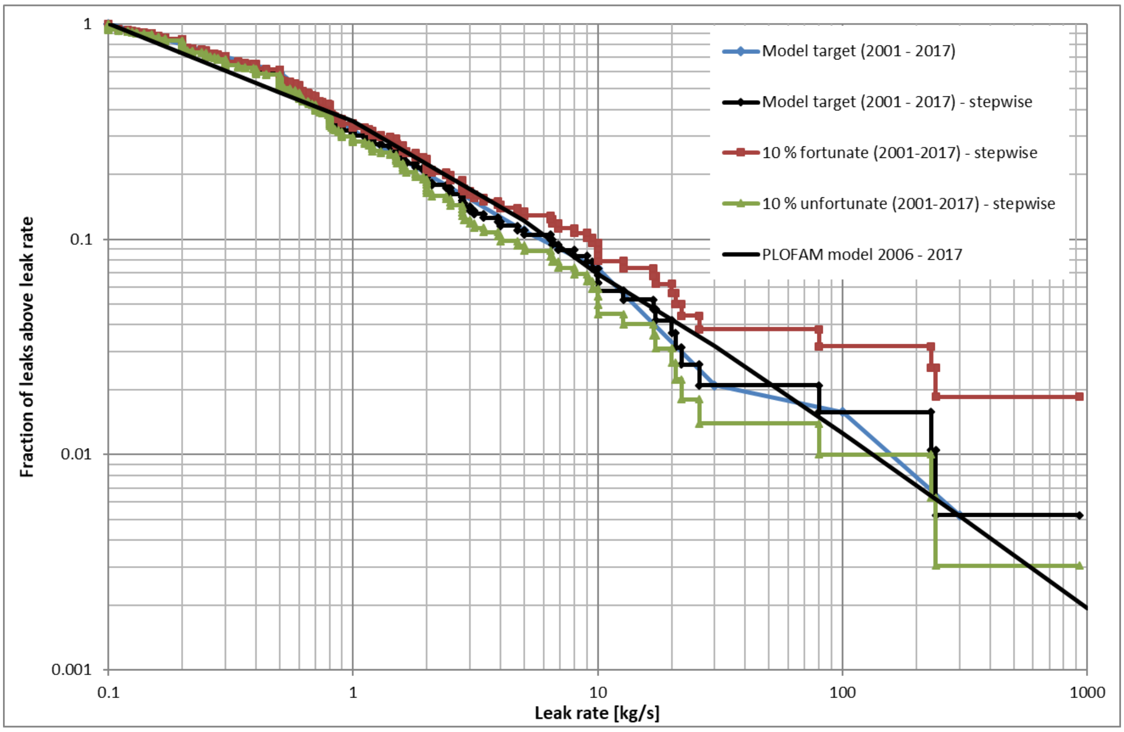

Figure 6 – Relative distribution of leaks observed at installations operating on the Norwegian Continental Shelf in the period 2001-2017.

4.3 Description of proposed methods and models

4.3.1 General

The main elements in the methodology proposed is illustrated in Figure 7. The methodology defines which accidental design scenarios that shall be used as basis for the design (DeAE) and the corresponding resulting loads (DeAL) to be applied for various systems that plays important roles in the scenarios.

The methodology consists of two steps. The first step, 'Source term modelling', covers how to represent the leak scenario feeding the fire (DeAE). The second step denoted 'Fire load modelling', describes how to estimate the fire load (DeAL).

The starting point for the methodology is the Worst Credible Process Fire as applied in present practice. The WCPF apply in all modules/areas with process equipment and is definition of the design accidental scenarios (DeAE) to be applied for "main load bearing structures and fire divisions". The resulting loads (DeAL) to be applied for structures and fire divisions can be established by a combination of fire exposure modelling and structural fire response modelling. The detailing level of this work implies that the work is normally performed during project execution phase to be able to do cost optimization of PFP required. Possibilities to simplify this work by extracting experiences obtained from performed analyses could be considered.

Fire DeAE and DeAL also needs to be defined as application for:

- escalation to process equipment
- secondary structures (e.g. supporting equipment)
- exposure to escape ways, evacuation means, mustering area, and personnel

It is considered too extensive to require that the WCPF shall be used also as a DeAE for these systems and functions. Instead predefined and suitable design scenarios are proposed that will assure a safety level equal or better than present practice and support decisions to be taken in the projects in a simple and robust manner.

An optional advanced approach reflecting the ALARP principle is recommended if the methodology result in cost-driving fire safety solutions that appear to be disproportional the achieved risk reduction.

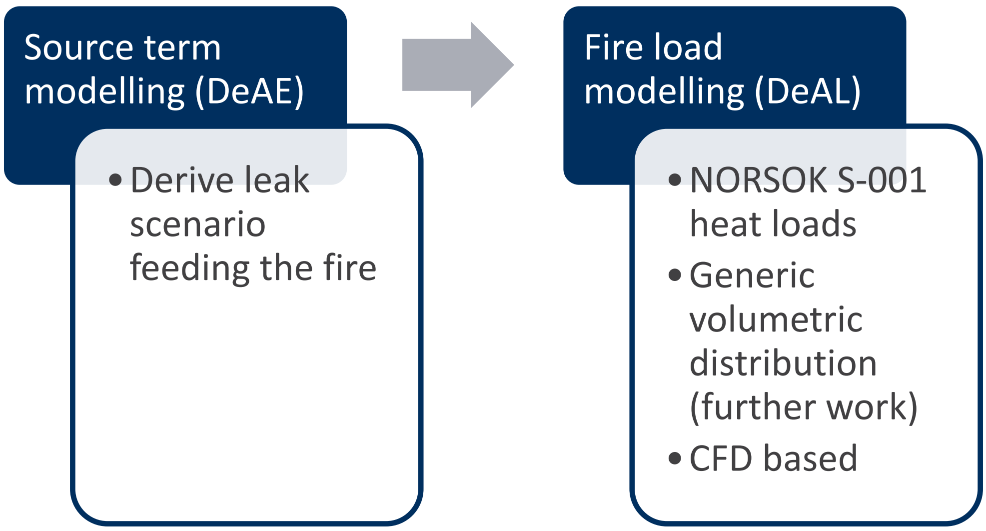

Figure 7 – Outline of models

4.3.2 Application in different project phases

The methodology is the same independent of the project phase, but the models used to estimate the source term and the fire load will typically be different. In the project planning phase, less information is available and the need for detailed calculations to provide decision support is less prominent. The requirements with regards to what models that should be used are to be discussed as part of the HAZAN. The typical situation is illustrated in the figure below.

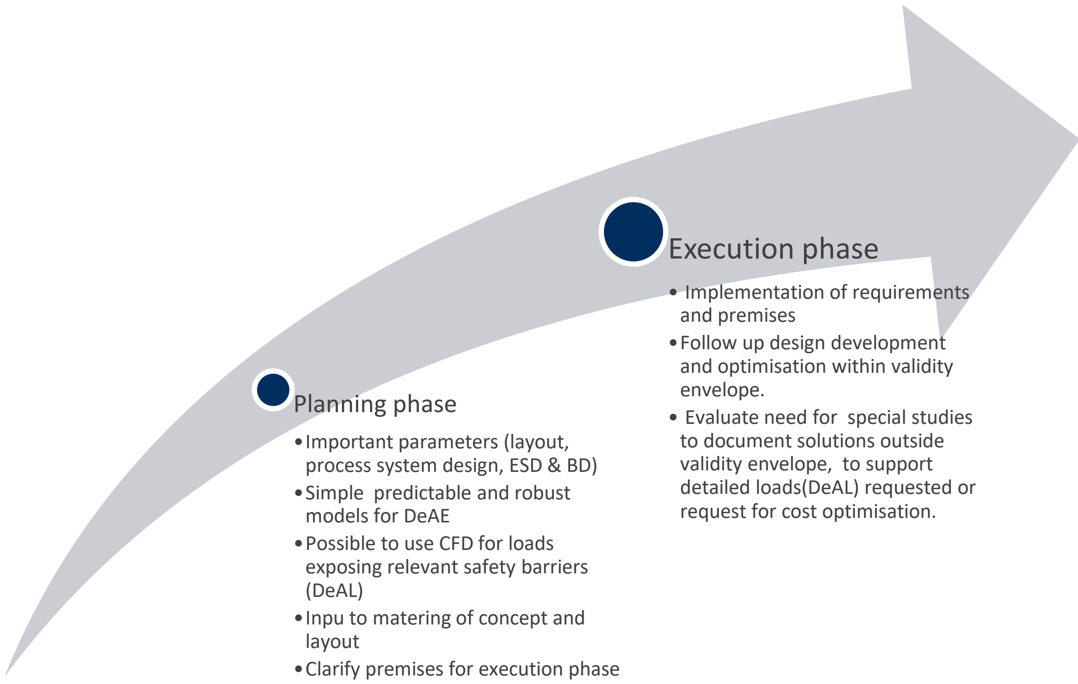

Figure 8 – Typical premise and use of models through a project.

4.3.3 Structural integrity and fire divisions

4.3.3.1 General

The basic principle is to define the inventories resulting in the most gradual slope of the time-dependent leak. The rational is that a more gradual slope will sustain critical fire loads over a longer period.

The output is one or several inventories with a set of properties that enable calculation of the resulting leak transient for any hole size.

Generally, one need to consider two type of inventories at offshore oil and gas installations:

- The ESD-segment feeding the most severe gas jet fire
- The ESD-segment feeding the most severe liquid leak (i.e. spray and/or pool fire).

The derived inventories constitute the basis for calculation of the duration of the fire exposure to both structures and equipment.

In many cases (e.g. for offshore installations with simultaneous depressurization of all segments), the ESD-segment with the largest gas inventory corresponds to the reservoir generating the leak with the most gradual slope. With regards to liquid leaks, one of the separator stages usually generates the leaks with the longest duration.

The following requirements applies when estimating the criticality of the segments according to above:

- Only ESD-valves can be accounted for when defining the inventory.
- The effect of the depressurization system can be included

- The time to closure of the ESD-valves and opening of the BD valves must be justified appropriately (e.g. do we have detection means in place that enable quick and reliable detection – item for clarification in HAZAN)
- For liquid/multiphase leaks generating pool fires, the effect of bunding and open drain can be included (preferably embedded in the calculation of the time-dependent fire load)
- In early project phase, the system parameters must be assessed such as:
    - Well pressure
    - Well composition
    - Depressurization
    - Passive fire protection
    - Deluge/water spray systems
    - Pressure safety valves
    - Selection of process equipment/materials
    - Limitation of process inventories

One single inventory might not be representative for all categories of objects in an area. This could typically be the case for large process areas (e.g. on a Floating Production Storage Offloading vessel). In large areas, the most severe gas leak scenario could for instance not generate significant heat loads in the part of the area where the most severe liquid leak scenario is relevant. In cases where various reservoirs are used as feed for the design fire scenario, the basis for the application for the different scenarios with respect to location must be described. The zone defining the boundary between the scenarios must be justified based on the expected exposure from the leak scenarios originating from various reservoirs.

The critical leak rate in term of heat flux distribution (i.e. exposed area, time variation and size) will vary with the characteristics of the module (e.g. size and ventilation conditions). This must be addressed specially in CFD studies and should also be reflected in any simple model used to set the fire loads (see below).

For naturally ventilated process areas with two- or three-way ventilation fulfilling the ventilation requirement given in NORSOK S-001, experience shows that the worst exposure of main load bearing structures and fire divisions typically is obtained for oil fire scenarios in the range 5-30 kg/s (DeAE). The potential duration of such a scenario can easily be estimated based on the total mass, the pressure and blow down capacity of the ESD segment (both leak in the gas phase and oil phase to be considered). In case the potential scenario has a duration longer than two hours, special considerations are needed, since certified PFP for fire duration longer than two hours are limited and costly. Possible solution is to limit the pool fire area by "bundings" and drain giving fire exposure handled by the structural redundancy.

The fire load modelling and corresponding volumetric distribution (DeAL) can be set based on the generic heat load given in NORSOK S-001 or advanced CFD simulations.

It is proposed by work group 3 to execute further work with the objective to develop a simple model for estimation of the heat load and corresponding volumetric distribution for exposure to various types of objects within the same module as the fire originates from. It is believed that a rather simple model can be derived based on recent work executed as part of e.g. the Johan Castberg development project (Ref. /7/ and /8/). This would enable quick and robust calculation of local fire loads at an early project phase accounting for the fire behavior, response of equipment and effect of safety systems (ESD and BD). Especially, the capacity of the blowdown system is important for the volumetric distribution. A high capacity depressurization system would reduce the volume generating the high peak heat loads (e.g. in general loads in the range 250 kW/m^2 to 350 kW/m^2). Such a method would also enhance harmonization between the various users of the RISP method. The principle is illustrated in Figure 9 below. A continuous curve displaying the full relationship is shown in Figure 10. The method can potentially be used for all types of objects; e.g. main load bearing structures, secondary structures and process equipment.

The loads can be presented as temperatures relevant for the object in question or as an equivalent heat load. The size of the sphere would vary with the inventory size, depressurisation capacity and the properties of the objects studied (e.g. material type, thickness).

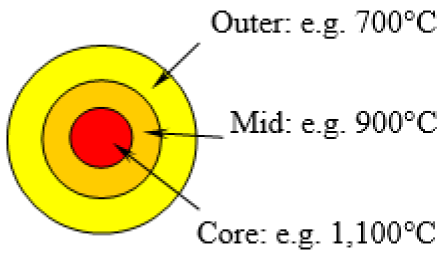

Figure 9 –Illustration of simplified fire load that can be developed. The extent of the various zones could be e.g.: core sphere diameter: 8 meters, mid sphere diameter: 12 meters: outer sphere diameter 20 meters

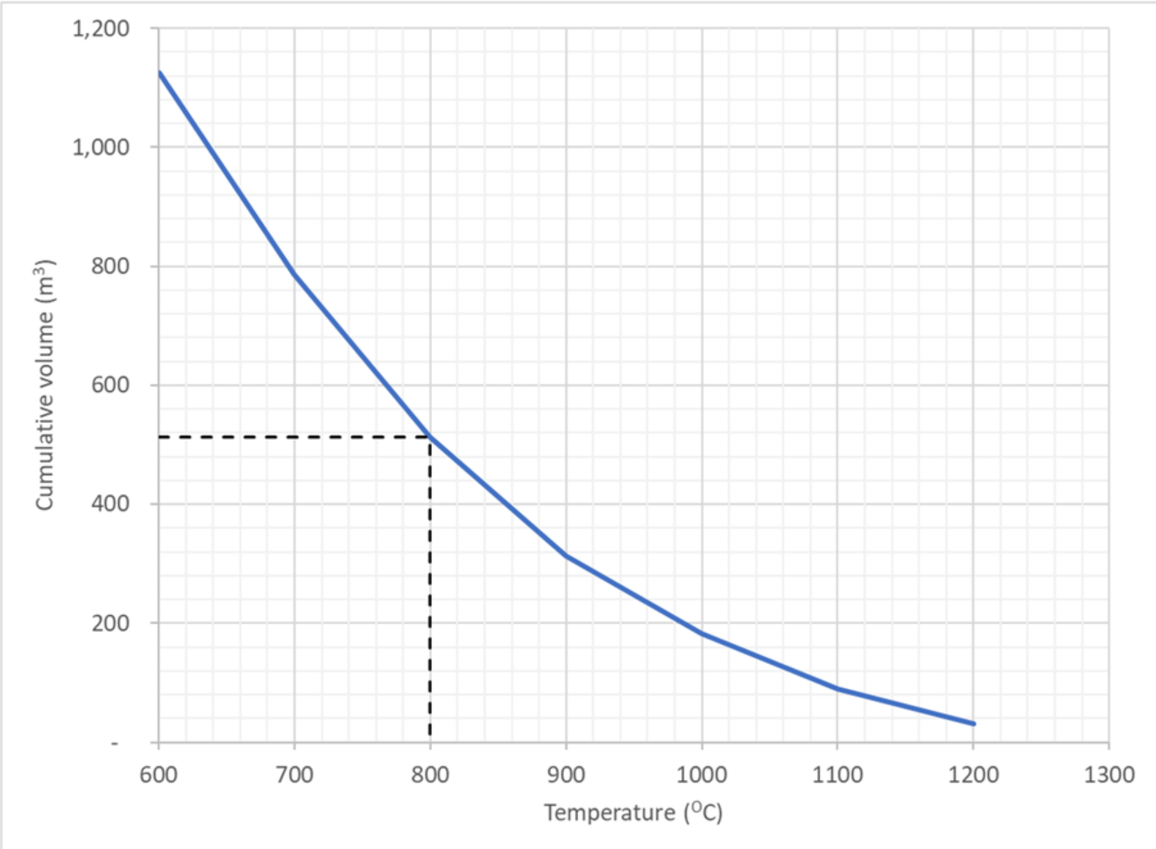

Figure 10 –Example volumetric distribution fire loads. The loads can be presented as temperatures relevant for the object in question or as an equivalent heat load. The size of the sphere would vary with the inventory size, depressurisation capacity and the properties of the objects studied (e.g. material type, thickness)

4.3.3.2 Details on source term modelling

A simple model for calculation of the transient behavior for all hole sizes associated with the system is acceptable but must be appropriately justified. It is proposed by work group 3 to execute further work with the objective to define a simple model for calculation of the transient behavior. It is believed that a rather simple mathematical model will suffice, which would enhance harmonization between the various users of the RISP method. For instance, to what extent the model reflects the thermodynamical properties may lead to variability between various users of the overall method. Moreover, it would be beneficial to agree on fixed values for certain parameters, such as the discharge coefficient, and even standardization of the composition (e.g. CH_4 for natural gas leak and $C_{10}H_{22}$ for liquid leaks).

The input to the source term model should be a table with the following typical content:

ESD segment	Liquid inventory	Gas inventory	Pressure	Temperature	Density	Flow into segment before closure of ESD valves	Depressurisation capacity	Fire detection and ESD system response
WCPI X_i GA	NA	1500 kg	30 barg	310 K	25 kg/m^3	10 kg/s	600 seconds to 6.9 barg Blow down valves fully open 5 seconds after start of fire	10 seconds from start of fire to fully closed ESD valves
WCPI X_i LA	11 000 kg	NA	10 barg	320 K	800 kg/m^3	20 kg/s	600 seconds to 5 barg	
...								
....								

The dimensioning duration to be set based the required survivability. For example, the time requirement is typically 1 hour for load carrying structure. The time requirement will vary for the type of object considered; (1) main load carrying structure, (2) escape ways, (3) evacuation means, (4) secondary structures, (5) process equipment and (6) integrity of Jack-up rig.

4.3.3.3 Details on Heat load modelling

A simplified approach based the heat loads provided in NORSOK S-001 can be used if appropriately justified. Further work is suggested to develop such a methodology.

For investigation of the response of load bearing structures subjected to the WCPF scenario, CFD simulations coupled with a structural response tool (such as USFOS) is recommended.

In order to define the leak sources, the module/area is divided in 9 equally sized areas based on splitting the length and width of the module in 3. The leak location is set to the center point of each the resulting 9 areas.

The combinations of leak points, leak directions and wind conditions that must be covered are shown in the figure below (16 leak scenarios x 2 wind conditions (8 m/s for prevailing adjusted to 45 degrees relative installation and 180 degrees relative to prevailing). Each scenario is to be simulated for the following initial leak rates:

- 5 kg/s
- 10 kg/s
- 20 kg/s
- 30 kg/s.

This result in that 128 fire scenarios (16 leak scenarios x 2 wind conditions x 4 leak rates) should be investigated.

Transient mass flow from the leak points can be simulated by combining heat loads from a list of steady state flow rate simulations in transient heat response calculations. Each steady state load is then assigned a duration to make a stepwise approximation of the transient mass flow rate that depends on hole size, ESD, depressurization and the reservoir conditions. The heat load from a fire depends on the fire itself and on radiation feedback from heated solid surfaces. Unless the calculations are setup to calculate the transient solid heat response from all solid surfaces in the domain, the solid surface temperature response should be modelled as adiabatic surfaces (i.e. surfaces with perfect insulation).

The analysis should evaluate whether a smaller leak rate than 5 kg/s and a larger leak rate than 30 kg/s should be investigated. However, based on the historical data, it is judged that 30 kg/s is a reasonable upper estimate for a credible worst-case scenario.

The following generic situation describes the scenarios to be simulated:

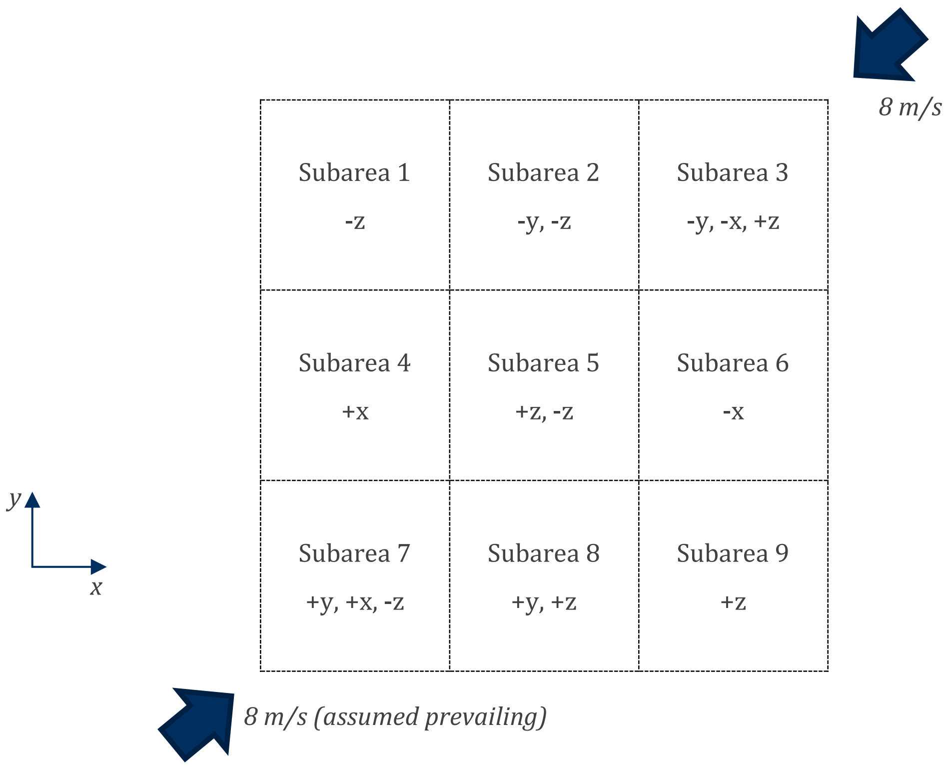

Figure 11 –Illustration leak scenarios to be simulated with CFD to analyse exposure to load bearing structure

Transient behaviour of the fire load can be represented by steady state simulations.

4.3.4 Escalation to process equipment

The requirements for fire escalation to process equipment affects the scenarios to design the structural integrity as well as global safety functions on the installation. Stringent requirement would imply a lot of PFP on process equipment which is both considered costly and a risk potential since corrosion is a known problem related to insulation. The following loads and corresponding requirements are proposed to achieve a robust safety level.

- No escalation to process systems within 2 minutes when exposed heat to a local heat load of 250 KW/m². This requirement is established to avoid a small initial fire to escalate before personnel close by can escape. It is considered that this requirement can be achieved generally without the use of PFP but rather considering credit of ESD and blow down combined with selection of piping class.
- No escalation to process systems causing escalated fire of 30 kg/s or more when exposed to a local heat load of 350 KW/m² for 15 minutes. The 30 kg/s value is linked to the corresponding requirement for global safety functions such as escape routes in neighboring

areas. The 15 minutes stipulated is linked to a default value for escape time from neighboring area (e.g. drilling area). Specific studies may be performed to validate shorter time frame.

For corresponding global heat loads, the values stipulated in Norsok S-001 can be applied.

4.3.5 Secondary structures (e.g. supporting equipment)

Secondary structures (equipment support, all structures that are not main load bearing structures) necessary to ensure integrity of safety barriers for the time frame for the barrier to perform its function in the fire scenario. One important barrier is the avoidance of escalation to process equipment. Secondary structures required for the integrity of process equipment needs to maintain its structural strength to avoid escalation. The fire scenarios will be the same as defined for in Chapter 4.3.4. A simple model is to apply the same fire loads and extent as given in Figure 9. However, the heat load modeling needs to be further considered.

4.3.6 Exposure to escape ways, evacuation means, mustering area, and personnel

4.3.6.1 General

The critical leak rate in terms of exposure to main safety functions outside the module of which the fire originates, such as escape ways from neighboring areas, mustering area, air intakes and evacuation means is proposed to be fixed to 30 kg/s steady state.

Using 30 kg/s as fixed rate for assessment of the performance of main safety functions simplifies the traditional risk-based approach to a large degree and harmonizes the design scenario for the various installations. The rational is in line with the rational for the WCPF incorporating a margin towards the overarching 10^{-4} per year criterion without performing detailed probabilistic calculations. The historical data (see Figure 6) demonstrates that leaks with a rate beyond 30 kg/s is quite remote. Any installation designed for the fire loads generated by an initial leak rate of 30 kg/s will be able to demonstrate robust performance of its main safety functions covering evacuation and escape (even large installations). The only design cases where a more thorough assessment is required before a leak rate of 30 kg/s is confirmed to be the design basis, is when gas turbine(s) is/are used for direct drive (*i.e.* gas turbines are sources of ignition of particular concern) or any other source of ignition are identified (i.e. frequent use of combustion engines (not equipped with flame arrestors) for powering of well intervention units). In situations where the 30 kg/s leak rate drives CAPEX, an advanced probabilistic approach according to the 10^{-4} per year criterion and the ALARP-principle could be used to optimize the design scenario.

The 30 kg/s rate also defines the maximum tolerable leak rate with respect to local escalation to process equipment in the same main area. This means that escalation to process equipment resulting in a leak rate less than 30 kg/s is in general considered acceptable after the specified time frame allowing for local evacuation. An advanced study deriving specific critical escalated leak rates can be executed to deviate from the 30 kg/s as the general design scenario. This must be based on a special study (*e.g.* by use of detailed CFD simulations in accordance with the rule set for definition of fire scenarios as described below).

4.3.6.2 Heat load modelling

General

Fire water influence the fire loads, however it cannot be accounted for within the NCS regulative regime.

An initial assessment as part of the HAZAN to clarify whether a CFD analysis is required or whether a simplified model is sufficient.

CFD modelling is preferred if geometrical model available at the project stage where decisions can be affected. It is expected that at a CAD model fit for purpose is available even at early project stages. Even a coarse geometrical model will be able to capture the important effects in most cases.

The rule sets for modeling and assessment of the two main categories of fire loads and corresponding objects is described in the following sections.

Far field loads exposing main safety functions

The study should demonstrate that each of the relevant main safety function maintain integrity for 90% of the sample space of possible WCPF EE30 scenarios in each module/area. A module/area is considered to be an area separated from the other modules/areas on the installation by use of fire partitions rated for hydrocarbon fires (e.g. H0 firewall). This is most effectively achieved by simulating the following 100 fire scenarios and demonstrating that each main safety functions can survive at least 90 of them.

Liquid leaks are to be modelled as spray leaks in most cases unless the pressure is very low (less than 2 barg)

In order to define the leak sources, the module/area is divided in 9 equally sized areas based on splitting the length and width of the module in 3. The leak location is set to the center point of each the resulting 9 areas. A set of leak directions to be simulated (4) is defined for 5 leak locations, resulting in 20 leak scenarios in terms of leak location and leak direction.

These leak scenarios should be combined with the following wind conditions:

- 8 m/s wind from each direction angled 45 degrees relative to the x- and y-axis
- 16 m/s wind from the most likely direction out of the 4 defined directions above
- The rationale behind the rule set for defining the simulation matrix is to capture
- scenarios that generate effective combustion inside the module
- fire scenarios where the leak is directed outwards resulting in combustion of most of the released gas on the outside of the module, which is believed to be critical for main safety functions
- wind conditions reflecting various wind conditions as the wind direction is in general important for critical exposure of main safety functions
- the most likely wind speeds

The following generic situation appear (assuming a prevailing wind direction):

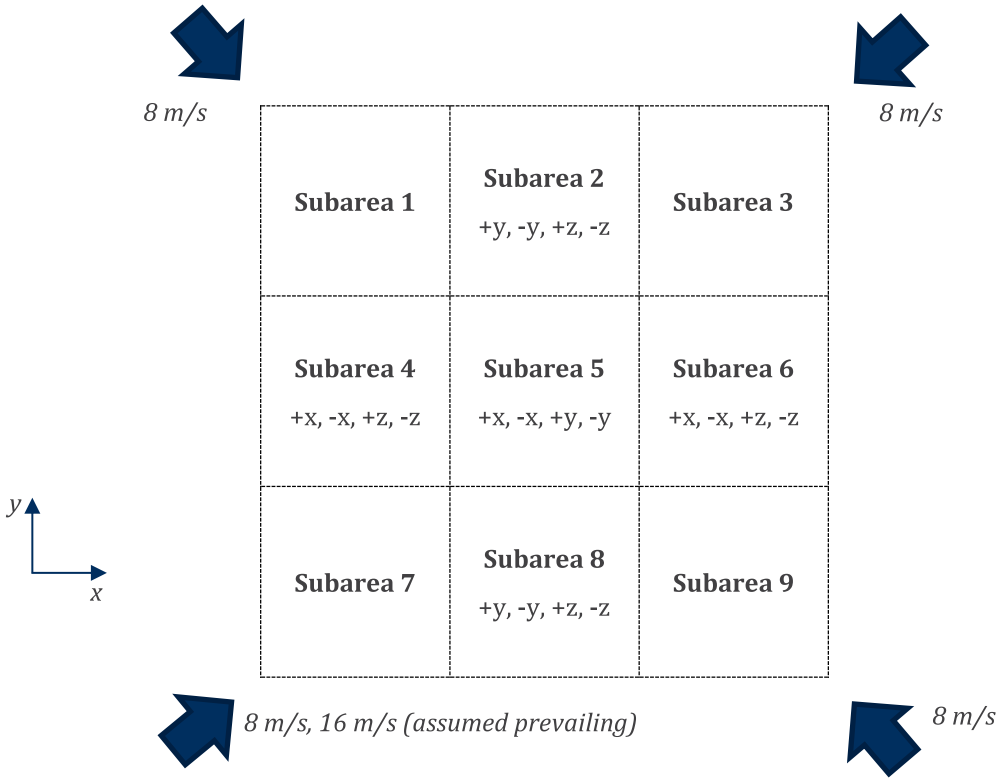

Figure 12 –Illustration leak scenarios to be simulated with CFD to analyse exposure to main safety functions (except load bearing structure)

If there are no relevant leak sources in the area, the most unfavorable (based on an engineering judgement) neighboring subarea should be used as basis instead. For example, if there is only water treatment equipment in Subarea 8, then the simulations to be executed in Subarea 7 if a fire in that area is judged to be more critical with respect to exposure to main safety functions than leaks in Subarea 9.

If CFD simulations are run according to the simulation matrix described in the following section to calculate response of load bearing structures, the additional 30 kg/s simulations should preferably be added to the sample space for calculation of the performance of the respective main safety functions relative to the stated 90% criterion (90% of the total number of scenarios, and not 90 out of the 100 scenarios specified above).

5. Proposed methods and models for riser fires

5.1 Decisions to be made in development projects

Typical decisions made in the project planning phases, were the risks related to riser fires are important:

- Optimisation of riser design
  - Type of risers
  - Location
  - Guide tubes
  - SSIV
- Protection of riser against external impact
  - Dropped objects / lifting restrictions
  - Collision
  - Fire escalation
- Need for protection against riser fire/leak loads (DeAE/DeAL)
  - Passive fire protection (PFP) of riser
  - Structural fire integrity (e.g. water filled jacket legs), or PFP on the underside of the topside
  - Exposure of ignition sources and/or gas ingress to mechanically ventilated rooms
  - Exposure of escape and evacuation means (main safety functions).

5.2 Risk level and need for survivability requirements

5.2.1 Risk level for riser fires

This section contains a simple calculation example for typical rise fire frequency. The purpose is to illustrate typical riser fire frequencies for different types of risers.

A recommended and commonly used source for failure data on pipelines and risers is the DNV GL "Recommended Failure Rates for Pipelines", ref /9/. The data given is applicable for vertical steel risers as well as flexible risers. Steel catenary risers are considered outside the validity envelope of RISP methods. Further the data in ref /9/presumes external loads e.g. due to ship collisions or dropped objects are considered separately, as historical frequencies for external loads are not used due to few events and large uncertainty.

The failure data are differentiated between:

- Flexible and steel risers
- Steel risers above and below 16"
- Hole sizes: Small (< 20 mm), medium (20-80 mm), large (>80 mm) and rupture
- Leak location: Above splash zone, splash zone and subsea

The frequency of a riser fire also depends on the ignition probability in case of a leakage. The ignition probability depends on several parameters that can be investigated for each specific case. This typically includes:

- Release composition, rate and duration.
- Release location (inside J-tube, topside, airgap, subsea etc.)
- Weather conditions (wind, waves and sea currents)
- Exposure of ignition sources topside or by nearby installations and vessels operating at the installation (JU-rig, supply vessels, flotel, etc.)

A rough estimate of generic ignition probability is shown in Table 1. It should be noted that the actual ignition probabilities will be affected by installation-specific circumstances (type of installation, location of nearby drilling rigs and vessels, type of riser and their content, topside ignition sources etc.). A brief review of the estimated ignition probability for riser leaks in TRAs on recent installations shows that it is typically in the range of 0.01% to 15 %.

Table 1: Typical conditional ignition probabilities for riser leaks.

Installation	Small hole (<20 mm)	Medium hole (20-80 mm)	Large hole (>80 mm)	Rupture
Ignition probability (given leak)	0.2 %	2 %	10 %	10 %

By combining leak frequencies with the ignition probability, it is possible to obtain an indication of the risk level associated with riser fires. Table 2 shows the number of risers on an installation that could give an estimated frequency of riser fires equal to a fire frequency og 1E-5 and 1E-4 fires per year.

Table 2: Coarse riser evaluation for various riser types.

Riser type	Number of risers needed to add up to the target fire frequency		
Target fire frequency	**1E-5 fires per year**	**1E-4 fires per year**	**Comments**
Steel risers (> 16”)	3 risers	30 risers	Based on generic ignition probabilities as shown in Table 1. Not including contribution from flanges, valves or external loads /dropped objects, ship collision, etc)
Steel risers (< 16”)	0,3 risers	3 risers	Based on generic ignition probabilities as shown in Table 1. Not including contribution from flanges, valves or external loads /dropped objects, ship collision, etc)
Flexible risers	0,05 risers	0.5 risers	Based on generic ignition probabilities as shown in Table 1. Not including contribution from flanges, valves or external loads /dropped objects, ship collision, etc)

This implies that for a normal riser configuration on an installation it is required to define ignited riser fires as a design event to comply with regulations (ref. e.g. Management regulations Chapter III and V and Facilities regulation section 11) even with a low number of risers on the installation. It can also be argued that the risk numbers established in ref /9/ are based on few incidents and hence has a large statistical uncertainty compared to e.g. topside leak data. This uncertainty should be considered in the usage of the failure frequencies.

Further it can be argued that a large riser fire is equally or more likely to be experienced than a small riser fire. A large riser fire will generally last shorter than a smaller fire unless it causes escalation. For fires related to steel risers it can be argued that the risk level is so low that it is reasonable to optimise safety measures versus cost of the safety measures. This means that the severity of a design fire and which safety functions that needs to be intact can be considered partly from an ALARP perspective.

5.2.2 Brief “review” of riser fires on installations on the NCS

Table 3 shows an overview of the most resent newly built oil and gas installations on the Norwegian Continental Shelf (NCS). All installations are jacket leg platforms. Table 4 summarizes the riser fire contribution to the estimated risk level and if riser fires are mentioned in the DeAL spec as a design fire event.

Some observations:

- 5-12 % of all riser fires are estimated to result in loss of main load bearing structures – even after taking into account passive barriers like PFP on connection points and cellar deck structures, and water-filled jacket legs.
- Approximately 30 % of all riser fires are estimated to result in loss of escape from topside areas. This numbers seems to be consistent for all the installations
- 1-45 % of all riser fires are estimated to result in loss of evacuation means or mustering area. This number figures varies a lot from installation to installation.
- The contribution to loss of main load bearing structure is likely to be higher if no passive barriers are in place (or taken into account in the risk analysis)
- If riser fires are not a dimensioning scenario and no fire load is defined in the DeAL-specification, why is PFP applied and jacket legs water filled?
    - The risk is acceptable/low partly because of the passive barriers. It is therefore misleading (wrong?) to state that riser fires are not design events.
    - This is an indication that the decision of having several barriers are not taken based on the risk analysis, but rather based on normal practice.

Table 3: Overview of some recent installations on the NCS.

Installation	Brief description of installation	Brief description of risers
Installation 1	Jacket riser platform. No LQ. Bridge to neighbour platform Water-filled jacket legs without topping up system Connection points towards between jacket and topside have PFP Underside of cellar deck is protected with PFP to withstand riser design fires	19 risers - 2 x oil export risers (20” and 36”, 274 km, steel riser) - 1 gas export riser (18”, 157 km, with SSIV, steel riser) - 8 x production risers (16”, 10 km, steel riser, J-tube) - 2 x production risers (16”, 10 km, steel riser) - 3 x future gas lift risers (10”, 7 km, steel riser, J-tube) - 3 x future WAG/gas injection risers (10”, 7 km, steel riser, J-tube)
Installation 2	Jacket platform Wellhead and production With LQ and utility Drilling via JU-rig Water-filled jacket legs without topping up system Underside of cellar deck and connection points towards between jacket and topside have PFP	4 risers - 1 gas export riser (20” and 27 km, with SSIV, steel riser) - 1 oil export riser (10¾” and 2.3 km, steel riser) - 1 gas Zeepipe IIA (16” and 26 km to hot tap, steel riser) - 1 future production riser (10¾ and 9 km, steel riser)
Installation 3	Jacket platform Wellhead and production With LQ and utility Drilling via JU-rig Water-filled jacket legs with topping up system	12 risers - 1 gas export riser (14” and 145 km, with SSIV) - 1 oil export riser (27”) - 3 gas lift risers (4” and 5 km, 4” and 5 km inside J-tube, 8” and 9 km)

Installation	Brief description of installation	Brief description of risers
	Underside of cellar deck has PFP	- 7 production risers (2 x 10" and 9 km, 8" and 5 km, 4 x 8" and 5 km inside J-tube
Installation 4	Jacket platform Wellhead and production With LQ and utility Drilling via JU-rig Water-filled jacket legs	4 risers - 1 gas export 30", steel riser - 1 oil export 24", steel riser - 1 import from Embla 14", steel riser - 1 future import riser 20", steel riser No SSIV. Riser EVs are welded and located on mezzanine deck in lower process rea

Table 4: Summary of riser contribution to risk and DeAL on some recent installations on the NCS.

Installation	Fire DeAL specified for jacket structure / underside of installation	Riser fire contribution to loss of Main Safety Functions (MSF)	Comments
Installation 1	Yes (worst credible fire on sea scenario defined in DeAL spec)	Loss of escape: < 5.5E-5 per year Loss of main loading bearing structure: 2.7E-5 per year Loss of evacuation means/muster area (bridge to DP): 1.5E-6 per year	Total riser leak frequency: 1.6E-2 leaks per year (not including topside leaks). Total riser fire frequency: 1.8E-4 fires per year (1.3 % of all leaks will ignite). 94 % of fire frequency comes from subsea leaks. It is assumed that the J-tubes have a gas tight top flange. 99 % of leaks inside J-tubes will be terminated subsea. Hence, J-tubes have a significant impact on the risk numbers.
Installation 2	No	Loss of escape: < 3.7E-5 per year Loss of main loading bearing structure: 2.1E-5 per year Loss of evacuation means/muster area: < 4.5E-5 per year	Total riser leak frequency: 2.9E-3 leaks per year. Total riser fire frequency: 1.0E-4 fires per year (combined drilling and production phase - 3 % of all leaks will ignite). The water filled jacket legs and PFP on the underside of cellar deck are given credit in the loss of MSF calculations. The JU-rig also contributes to loss of MSF. From the TRA it shows that there is no dimensioning fires underside of the platform. But the riser fire frequencies in ALARP region with respect to the accidental fire design situation.
Installation 3	No	Loss of escape: < 7E-6 per year Loss of main loading bearing structure: 2.2E-6 per year Loss of evacuation means/muster area: 3.6E-6 per year	Total riser fire frequency: 2.8E-5 fires per year. The water filled jacket legs and PFP on the underside of cellar deck are given credit in the loss of MSF calculations. The probability of occurrence for fire at sea is low and hence not a dimensioning scenario in the DeAL spec.
Installation 4	No	Loss of escape: < 1E-5 per year	Riser fires in the area below cellar deck and fires on sea surface are not dimensioning for the jacket structure,

Installation	Fire DeAL specified for jacket structure / underside of installation	Riser fire contribution to loss of Main Safety Functions (MSF)	Comments
		Loss of main load bearing structure: 2.5E-7 per year	i.e. due to the combined fire frequency for such scenarios being low.

5.2.3 Typical measures implemented to handle riser fires

Table 5 lists some typical barriers found on offshore installations, that can reduce the risk associated with riser fires.

Table 5: Typical barriers and measures implemented to handle riser fires, and their effect.

Barrier or measure	Description
PFP	PFP can be applied on load bearing structures, risers, process equipment and more, to improve their survivability when exposed to fires (it takes longer time to heat up the structure or the content in the process).
SSIV	A subsea isolation valve will limit the inventory in a riser that will be released in an accidental leak/rupture of a riser. As a result, the riser fire duration is reduced. In general, it is advised to install the SSIV as close as possible to the facility, but as far away as needed in order to avoid exposure of the facility in case of a leak from SSIV location. Where pipeline leak caused by dropped objects is a relevant scenario, the SSIV location should be outside the probable dropped object zone.
Water filled jacket legs	Water filled jacket legs will increase the survivability of a jacket structure when exposed to fire (heat from the fire heats up and evaporates the water). The water-filling is only effective if the inside of the structure is filled with water. As water evaporates the water level in the legs is reduced, so the upper parts of the water filled jacket structure will be dried out relatively fast in a riser fire. To get full effect of the water filling, the upper part of the water filled structure typically needs to be protected with PFP, or an automated system for refilling water during the fire event needs to be installed.
J-tube	J-tubes are typically installed to make the installation and the support of riser easier. But it also provides some added protection of the risers to external loads (impact loads, fire loads). If design to maintain an internal pressure it will also partly contain a riser leak that occurs inside the J-tube. If the upper part of the J-tube is gas tight, a riser leak inside the J-tube will be forced to find its way down to the bottom of the J-tube (subsea). This can be an effective barrier to reduce the likelihood of a riser fire in the air gap.
Escape tunnel	A pressurized escape tunnel will increase the likelihood of personnel located topside to successfully escape to safe area, in case a riser fire event. Some riser fire events will make it impossible to use the life boats unless carefully located and protected. But not all. An escape tunnel will improve the ability to escape in the riser fires events where the life boats are not impaired/unavailable due to the riser fire (meaning that personnel actually have a chance to escape and evacuate the platform).

5.3 Project planning phase methods and models

5.3.1 Validity envelope for RISP riser fire model

Table 6 shows a description of the validity envelope for the RISP riser fire model.

The most important aspect of the model is that it states that if an offshore installation has one or more riser containing flammable fluids, the RISP riser fire applies. Because of this there are very few design variations that are outside the validity envelope.

Table 6: Validity envelope for RISP riser fire model

Design parameter	Inside envelope	Outside envelope	Comments
Type of riser	All riser types		As long as there are one or more risers with flammable content, the model is considered relevant for all riser types.
Installation type	Jacket platforms, Gravity Based Concrete (GBS) platforms, Semi, FPSO, Tension-leg platforms		The model is considered relevant for all known platform concepts that fulfill the requirements stated in NORSOK S-001
Manning	Normally manned, normally unmanned and unmanned installations		The model is considered relevant for all known platform concepts that fulfill the requirements stated in NORSOK S-001
Design standards	NORSOK S-001	Installations not designed according S-001	
Number of risers	One or more riser containing flammable fluids	No riser containing flammable fluids	

5.3.2 RISP riser fire model

Chapter 5.2 shows that Riser fires should be considered design accidental events (DeAE), and that several design measures are typically implemented to reduce the risk associated with riser fires.

The main point of the RISP riser fire model is that riser fires are DeAE and therefore need to be designed for.

The RISP riser fire model is further inspired by WCPF, where some barriers and effects are credited, while others are not.

A DeAE is derived from an ignited leak in any of the riser segments that will give the worst fire exposure of the main load bearing structures, safe area and evacuation means. The following requirements are given for the protection against the DeAE:

- ESD valves and SSIVs can be credited as segregation for the riser segments. The closure time needs to be reflected w.r.t heat loads and duration. This presumes the valves are treated as safety systems with testing and performance requirement (typical reliability level of 98 % or higher). This presumes that the valves have requirements for closing time and internal leak that are verified through testing.

- The assessment shall include possible escalations (to other risers, wells, and/or process equipment).
- Main load bearing structure intact to ensure escape to safe area and time for evacuation. Default time for evacuation is set to 60 minutes but should preferably be based on installation specific considerations.
- Safe area/mustering area intact and functional to allow time for evacuation. Default time for evacuation is set to 60 minutes but should preferably be based on installation specific evaluations.
- Evacuation means for minimum 100 % of maximum manning onboard at any time available for evacuation. Requirements for availability of an extra lifeboat for redundancy, shall also be included. The evacuation means shall be available from 15 minutes after onset of the DeAE until evacuation can be considered complete. For bridge connected installations the requirement can be fulfilled by availability of the bridge.
- The applicable fire loads can be established by CFD tools or conservatively applying simpler methods (e.g. NORSOK S-001).
- The DeAL shall reflect/cover loads from at least 90 % of representative scenarios (DeAE) within each leak size category (see Table 1) for each riser segment. The 90 % requirement is stated to cover variations in weather conditions, leak location, leak direction etc.

It is considered that the required design input needed to perform the RISP riser fire modelling will be available with a sufficient accuracy in the project planning phase. Commercial tools are available to perform leak rate and duration assessment as well as representative fire load calculation for use with limited effort and providing predictable results.

The potential for recommending a fixed leak rate (e.g. 100 kg/s) as definition of riser fire design accidental event, has been discussed. However, it is judged that key design parameters driving the risk should be applied in the modelling when available and easy to reflect as is the case with the presented model

Cases which may be arguments for less stringent requirements are:

- Few risers, especially with few steel risers
- Only few large size risers since failure frequency is proven to be significantly lower. However, release potential is significantly larger.
- Low gas release potential due to composition or pressure
- Use of guide tubes leading a leakage well away from ignition sources
- Very few ignition sources such as supply vessel visits, air intakes to combustion engines etc.
- Unmanned installations
- Risers with very high water-cut (above 80-90%)

5.3.3 Key risk drivers

- Type of installation (fixed, FPSO, semi, tension leg platform, etc)
- Type of riser
    - Flexible, steel riser, J-tube/pull-tube
    - Riser inventory (composition, phase, pressure and temperature)
    - Length and diameter (=volume) and location of SSIV, down hole valve, etc.
- Number of risers
- Riser dimensions
- Location of topside ESDV
- SSIV or no SSIV
- Composition and water cut in risers

Special cases

- Fixed installations with bridge connections, W2W, jack-up drilling rig: distance to nearby installation
- Fixed installations with drilling performed with jack-up drilling rig
- GBS with risers in shaft
- FPSO with risers in turret

5.4 Project execution phase methods

During project execution phase more detailed and possibly less conservative design loads may be obtained using gas, fire and smoke simulation with use of CFD tools. Gas dispersion and fire simulations can be successfully applied with the design information available. 3D models established in the development project may be applied or a sufficient detailed purpose made 3D models may be established with low effort. For multiphase risers connected to long pipelines the release models often will benefit from applying advanced tools to estimate release rate, duration and composition. The industry has also established applicable models to evaluate dispersion of gas and oil through the water column.

If fire simulations are performed to detailed assess loss of main structural integrity, loss of escape and loss of safe haven including evacuation means, a minimum of 50 different representative riser fire scenarios should be modelled and evaluated in terms of their impact.. The selection of fires scenarios shall consider leak location, leak direction (for air gap leaks), wind conditions, leak rate and leak duration.

6. Proposed methods and models for ignited blowouts

6.1 Decisions to be made in development projects

Typical decisions that are made in development projects that can have impact on or be impacted by fire loads from ignited blowouts are:

- Need for protection against ignited blowout loads (DeAE/DeAL)
    - Passive fire protection (PFP) of risers
    - Structural fire integrity, e.g.:
        - water filled jacket legs
        - PFP on the underside of the topside
        - PFP on derrick
        - PFP on topside load bearing structures
- Exposure of ignition sources and/or gas ingress to mechanically ventilated rooms
- Exposure of escape and evacuation means (main safety functions).

6.2 Risk level and need for survivability requirements

The risk level related to blowouts is thoroughly discussed in Ref. /10/. In general, the fire frequency increase with increasing activity level (well operations and well interventions) and increasing number of producing wells.

The resulting expected range in fire frequency for typical installations is presented in Table 7.

For most platforms (i.e. the total of blowouts at possible leak locations) it is expected that the frequency for blowouts (unignited) is much higher than $1{\cdot}10^{-4}$ per year. The only leak location where the resulting expected fire frequency is significantly below 10^{-4} per year is subsea blowouts and mud module/shaker room.

It is concluded that blowouts are a dimensioning scenario in all areas. The frequency for ignited subsea blowouts are expected to be low, but due to that subsea blowouts may impair the load carrying structure of the installation, it is judged that also subsea blowouts must be considered if that is a relevant leak scenario for the installation. The frequency is expected to be low in mud module/shaker room and can in most cases be disregarded, which is to be verified as part of the HAZAN. Unless there are special circumstances (criticality with respect to exposure to main load carrying structure, novelty of design or special reservoir conditions) pointing towards that the observed historical risk picture is not representative, release points in the mud module/shaker room can be disregarded.

Based on this, ignited blowout is as a starting point considered to be a design fire scenario in all areas where there is a possible flow paths between equipment in the area and the reservoir. Equipment in this context are either equipment used in well operations (e.g. drilling, coiled tubing or wire line) or under normal production (e.g. wellhead and X-tree).

Table 7: Typical range of blowout frequency and fire frequency for the most important leak locations based on Ref. /10/.

Leak location	Expected blow out frequency rang (per year)	Ignition probability	Expected ignited blow out frequency range (per year)
Subsea	$<< 1.0{\cdot}10^{-4}$	0.5 - 2%	$< 1.0{\cdot}10^{-5}$
Wellhead	$1.0{\cdot}10^{-4}$ - $1.0{\cdot}10^{-3}$	5 - 15%	$1.0{\cdot}10^{-5}$ - $1.0{\cdot}10^{-4}$

Leak location	Expected blow out frequency rang (per year)	Ignition probability	Expected ignited blow out frequency range (per year)
Well intervention	$1.0 \cdot 10^{-4}$ - $1.0 \cdot 10^{-3}$	5 - 15%	$1.0 \cdot 10^{-5}$ - $1.0 \cdot 10^{-4}$
Mud module/ Shaker room	$1.0 \cdot 10^{-5}$ - $1.0 \cdot 10^{-4}$	5 - 15%	$1.0 \cdot 10^{-6}$ - $1.0 \cdot 10^{-5}$
Drill floor	$1.0 \cdot 10^{-4}$ - $1.0 \cdot 10^{-3}$	5 - 15%	$1.0 \cdot 10^{-5}$ - $1.0 \cdot 10^{-4}$
Diverter line (shallow gas)	$1.0 \cdot 10^{-4}$ - $1.0 \cdot 10^{-3}$	5 - 15%	$1.0 \cdot 10^{-5}$ - $1.0 \cdot 10^{-4}$

6.3 Methods and models

The leak scenario, or rather an interval for leak rates with corresponding duration, to be set according to the following:

The first step is to derive the largest possible release rate based on an analysis of the flow paths (e.g. pressure drop and cross section) and reservoir conditions (e.g. pressure, composition (GOR)). The largest possible release rate to be set based on evaluation of potential scenarios under normal operation and under well operations. The highest release rate to be selected as the upper boundary for the analysis.

Since the worst response of the critical objects may materialize for smaller leak rates than the largest possible leak rate (dependent of module design; typically, the ventilation conditions and module size), also leak rates less than largest leak rate must be evaluated. Hence, the method results in an interval of leak rates to be investigated limited by the maximum blow out rate. At least 4 leak rates should be covered by the consequence analysis.

If the information required to estimate the largest possible leak rate is not available, the maximum release rate to be covered is set to 100 kg/s. This is based on

- the Macondo /Deep Water Horizon incident, see Ref. /10/, demonstrating that a leak rate in this order of magnitude is credible .
- the dimensioning blowout rate is typically found to be in the range 50 – 100 kg/s for an installation at NCS

Based on above, the following leak rates must be considered in the consequence analysis with respect to exposure of the load bearing structure:

- 5 kg/s
- 10 kg/s
- 30 kg/s
- 100 kg/s or estimated maximum leak rate

For evaluation of exposure to the other main safety functions, only the 100 kg/s leak rate must be covered by the study as it expected that 100 kg/s will result in the worst exposure to main safety functions. For load bearing structure, the most severe exposure will in many cases result for much smaller leak rates (which would be more in balance with the ventilation conditions of the module, see also Chapter 4).

For environmental risk analysis, higher blowout rates should be considered based on a specific study of the reservoir conditions.

The duration of a blowout is typically >> 2 hours. The dimensioning duration to be set based the required survivability. For example, the time requirement is typically 1 hour for load carrying structure. The time requirement will vary for the type of object considered; (1) main load carrying structure, (2) escape ways, (3) evacuation means, (4) secondary structures, (5) process equipment and (6) integrity of Jack-up rig.

The method for determination of fire load should follow the procedure outlined for process fires.

A simplified method is acceptable if appropriately justified. This should be clarified as part of the HAZAN.

If CFD simulations are run, the following is recommended:

- in general, it considered adequate to reflect one leak location per area, but this must be justified (typical cases that must be addressed are leak sin the BOP area (if BOP located topside) and subsea blowouts)
- at least 4 leak directions should be run per leak location, and upwards must be one of them
- the five wind conditions illustrated in Figure 12 should be executed to analyse exposure to main safety functions (except load bearing structure).
- The two wind conditions illustrated in Figure 11 should be executed to analyse exposure to load bearing structure

The report should evaluate whether the selected scenarios reflects exposure to main load carrying structure and exposure to adjacent structures (such as the sub structure or the cantilevered derrick of a Jack-up rig). In principle, the design should maintain the integrity of the main structure through the worst possible blow out fire scenario (worst in terms of all mentioned fire scenario parameters including the response). An argumentation based on that impairment is only possible in extreme cases (meaning a small fraction of the sample cases within a leak rate category e.g.: < 10% of scenarios within the 30 kg/s category) is acceptable if appropriately justified.

7. Recommendations for further work

A new methodology for replacing traditional quantitative risk analysis with simplified experience-based methods for improved decision support in development projects has been outlined and substantiated in this report. Based on the work in WG 3, the following recommendation for further work is given:

- There is a potential to further improve and standardize fire loads from process fires to be used for survivability requirements for main load bearing structures, secondary structure and process equipment. It is recommended to establish improved methods and models e.g. by utilizing the experience obtained in recent projects such as the Johan Castberg FPSO development.

8. References

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/8/ ComputIT report: "Guidelines for design fire loads", ComputIT report no. R1806, project no. 100486, dated 30.11.2018.

/9/ DNV GL report: "Recommended Failure Rates for Pipelines", Report no. 2017-0547, Rev. 2, dated 08.12.2017

/10/ SINTEF report: "Blowout and well release frequencies based on SINTEF Offshore blowout database 2017", Report no. 19101001-8/2018/R3, Final, 20. April 2018

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

Main report Workgroup 4 - Other accidents

Report for:
RISP Participants, att: Equinor Energy AS

Summary

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

Main report Workgroup 4 - Other accidents

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1 List of abbreviations

1.1 Abbreviations

AIS	Automatic Identification System
ALARP	As Low as Reasonably Practicable
ALS	Accidental Limit State
BAT	Best Available Technology
CAD	Computer-Aided Design
CAPEX	Capital Expenditure
CCR	Central Control Room
DDT	Deflagration to Detonation Transition
DeAE	Design Accidental Event(s)
DeAL	Design Accidental Load(s)
DiAL	Dimensioning Accidental Load(s)
DP	Dynamic Positioning
DP2	Dynamic Positioning – Redundancy Class 2
EERS	Escape Evacuation and Rescue Strategy
ESD	Emergency Shutdown
FEED	Front End Engineering and Design
FES	Fire and Explosion Strategy
FPSO	Floating, Production, Storage and Offloading
GBS	Gravity Based Structure
G-OMO	Guidelines for Offshore Marine Operations
HAZAN	Hazard Identification and Analysis
HAZID	Hazard Identification
HC	Hydrocarbon
HSE	Health, Safety and Environment
ISD	Inherent Safe Design
JIP	Joint Industry Project (In this case the RISP project)
LD	Lethal Dose
LEL	Lower Explosion Limit
MAH	Major Accident Hazard
MEG	Mono Ethylene Glycol
MeOH	Methanol
NCS	Norwegian Continental Shelf
NOROG	Norwegian Oil and Gas
PFP	Passive Fire Protection
PPE	Personal Protection Equipment
PRV	Pressure Relieve Valve
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Analysis
RISP	Risk Informed Decision Support in Development Projects
SC	Steering Committee
SPR	Sudden Pressure Relay
SSIV	Subsea Isolation Valve
TEG	Tri Ethylene Glycol
TRA	Total Risk Analysis
TSS	Traffic Separation Scheme
ULS	Ultimate Limit State
W2W	Walk to Work
WCPF	Worst Credible Process Fire
WG	Workgroup

1.2 Definitions

Terminology as used in the RISP project:

- Safety premises: Identified aspects presumed to be true and therefore used as a basis for the management of MAH. This can typically be presumption made in the HAZAN as a basis for concluding that the design is within the validity envelope of the RISP models. It can also cover other aspects such as operational restrictions. Safety premises typically needs to be verified at a later stage.
- Safety program: The safety program is a high-level plan describing the goals, means (resources), activities and analyses planned to manage MAH in a development project. Responsibilities, organisation and interaction arenas related to implementation of MAH design in the development project should be described.
- Safety strategy: The safety strategy is a high-level plan giving the link between the safety program and the design development with respect to MAH. The strategy describes how the end goals will be achieved. The safety strategy should also cover the needs related to fire and explosion strategy (FES) and escape, evacuation and rescue strategy (EERS). The safety strategy should outline applicable overall principles for design, layout, arrangements, philosophies and other high-level design and operational aspects related to barriers, e.g.:
    - Describing MAH relevant for the development (e.g. area by area) and describing key design measures and safety premises.
    - Describing how specific MAH are managed by the use of barrier functions, systems and elements. Typically, this should include a reference to standard requirements (e.g. NORSOK S-001) and whether there are special solutions required not covered by the standards.
- Proven design: Design or concepts that are considered prequalified through operational experience and/or previous engineering documentation and analyses to such a degree that the RISP methodology and models can be applied.
- RISP methodology: The principles that has been used to establish methods and models in the JIP. The term is also applied as the totality of RISP methods and RISP models.
- RISP methods: The work steps and procedures proposed to be used for risk-based decision support in development projects
- RISP models: The assessment tools proposed to be applied for risk-based decision support in development projects

2 Introduction

This report describes the work undertaken by WG (Workgroup) 4 as a part of the joint industry project RISP (Risk informed decision support in development projects). WG 4 has been constituted by representatives from Lilleaker Consulting, Lloyd's Register and Safetec.

A new methodology related to handling of MAH (Major Accident Hazards) in development projects has been established. The basis has been to allow for consistent use of industry experience rather than more analyses to support robust design of offshore facilities. The methodology is especially intended for use in project planning phase for projects.

This report is one of the workgroup reports constituting the basis for the overall RISP report, see also Figure 1 The report covers methods and models related to "other loads".

2.1 Overall RISP project

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project) with results and proposals for further work was presented in the Operations Committee meeting in NOROG and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The RISP joint industry project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is likely to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

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

The JIP consists of two Sub-Projects. Sub-Project 1 has been carried out in 2018 (includes WG 1 and WG 2). The RISP project organisation for Sub-Project 2 is illustrated in Figure 1. Sub-Project 2 includes WG 3, WG 4 and WG 5.

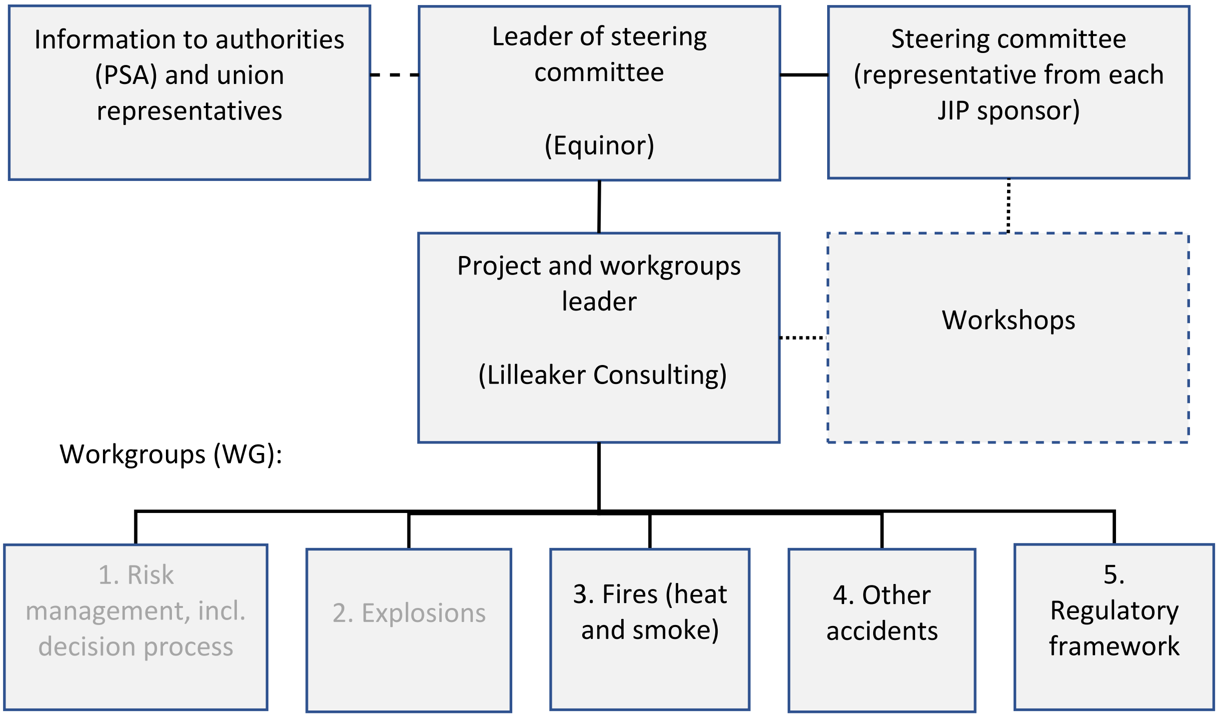

Figure 1– The RISP project organisation overview

The five workgroups are undertaken by vendors nominated by the sponsors, and different work packages are defined for the different workgroups. The vendors are: Lilleaker Consulting, Gexcon, DNVGL, Lloyd's Register, Aker Solutions, Proactima and Safetec.

Both sponsors and vendors are participants in the JIP.

The PSA has been involved as observer in the RISP project.

2.1.1 Overall RISP context

Risk analyses have played, and still play, a key role in the safety work of the petroleum industry and have given the industry detailed and broad knowledge about risk factors and design principles. However, the present practice in use of models and tools often request input data on a very detailed level. 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. Consequently, the decision support often arrives too late.

Experience and insight gained throughout the years from making analyses have barely impacted the way analyses are made. In general, "everything" is looked at anew each time, the knowledge acquired from incidents that may occur and how plants can be optimally designed is not sufficiently utilised or reflected in the way the analyses are specified and performed.

A main recommendation from the NOROG project was that during a development project, traditional quantitative risk analyses should for proven designs as a main rule be replaced by simplified assessments. This should be done to provide the best possible support for decisions being taken on an on-going basis. Thus, the emphasis on detailed calculations of total risk, and measurement against risk acceptance criteria such as FAR and $1x10^{-4}$, should be changed. Rather than continuing to seek very detailed risk descriptions, the aim in the future should be to provide necessary decision support at the right time. This is also in line with the "new" definition of risk given in Norwegian regulations (see guidance to PSA Frame agreement §11), which is an important basis for the JIP.

The NOROG project drafted several principals and ideas for how to better deal with the above-mentioned factors. These ideas and principles have been further matured and specified in the RISP project. Proven and acceptable methods and tools can be developed for the industry's use based on the methodology outlined in this report. This will move risk management of proven designs away from total (quantitative) risk analysis as the governing element, and towards specific decision support related to each individual decision.

2.1.2 Overall RISP objective

The overall objective of the RISP project is to further develop the principles and ideas provided by the NOROG project into methods, models and guidelines, and establish a new common "industrial practice". This practice should describe how various decisions in a development project are to be based on general and specific knowledge about the incidents that the installation may be exposed to (such as leaks, fires and explosions).

Traditional quantitative risk analyses with considerable focus on detailed calculations of total risk and measurement against risk acceptance criteria such as FAR and frequencies of loss of main safety functions (1×10^{-4}) should, when technology and challenges are known, be replaced by input based on knowledge and experience acquired by past projects and analyses, providing a robust safety level. Instead of searching for detailed descriptions of what the risk level is, the objective should be to provide valid decision support at the right time.

All models to be developed as a part of the RISP methodology should, as far as possible, be based on the principles for risk-related decision support provided in ISO17776, se Figure 2.

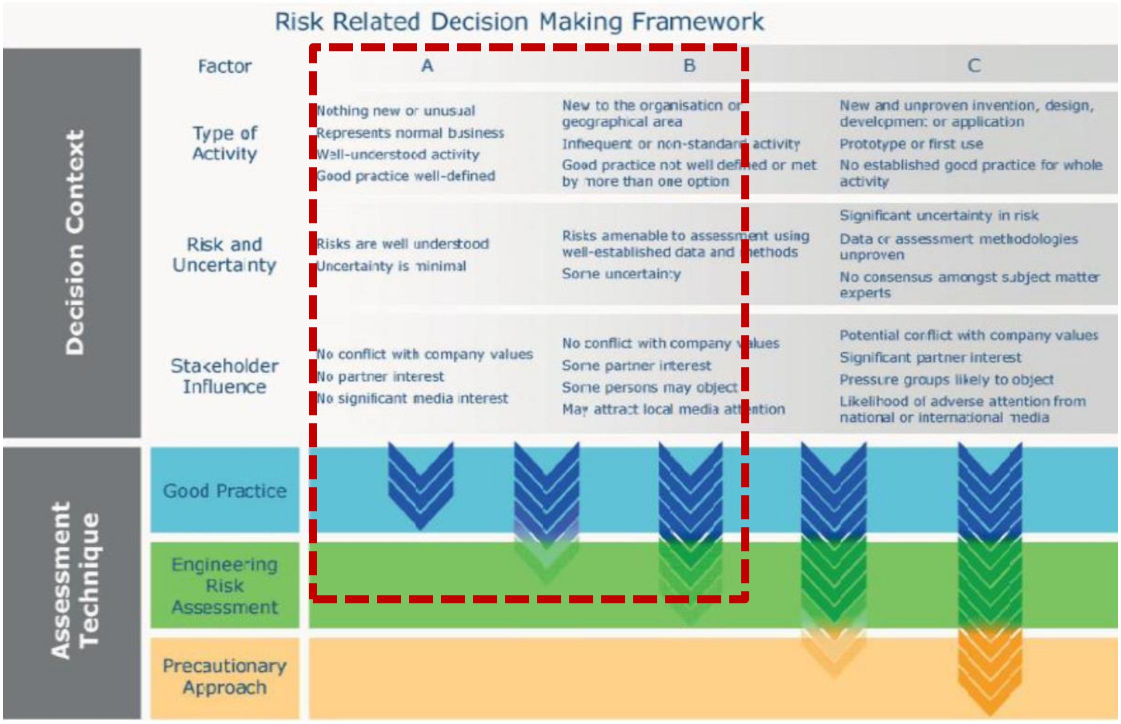

Figure 2 - Risk related decision-making framework from ISO17776 (ref./2/). The validity envelope for the RISP methods and models is illustrated by the red dotted box, see also the WG 1 report

The new «industrial practice» developed aims to clarify:

a) if a potential type of hazard/incident is sufficiently covered by using systems and solutions indicated by requirements in standards, established good practice and results of former analyses (ref. left part of situation A in Figure 2), or

b) if the simplified RISP methods and models established can be used to provide the necessary decision support, if/when the requirements in standards, established good practice and results of former analyses (a) is not found suitable/sufficient (typically right part of situation A and major part of situation B in Figure 2), or

c) if there is a need for obtaining and using specific knowledge about the type of hazards associated to the facility/project of interest, by making various forms of analyses of the likely course of events and/or potential consequences, to be able to make sufficiently robust decisions (typically situation C in Figure 2).

When there is a need for additional knowledge compared to situation a), i.e. situation b) applies, the new "industrial practice" must specify the methods and models that should be applied, and give guidance on how results (and the conditions/assumptions they are based on) can/should be used in the decision-making process. In this way the decision maker should also be made aware of the importance of the decision and the impact of the various decision options.

The methods and models included in the new «industrial practice» will be adapted to the knowledge and information typically available at the time when the specific decisions of interest are normally made. The decision support provided shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the input used and the restrictions related to further design development) has not been changed throughout the project. This will minimise the need for late design changes, when e.g. more detailed information is available. An as-built total risks analysis/quantitative risk analysis (TRA/QRA) will thus not be required within the new "industrial practice", but verification activities need to be developed. Verification shall ensure compliance with the validity envelope of the new approach, and that any changes in assumptions made during the development project are considered.

Barrier management, in its wide context, should found the basis for risk management in operations. A balanced description of the risk comprehensive enough for the operational phase, should be established also within the new "industrial practice".

2.2 Scope and objectives– workgroup 4

The objective is to establish decision support for the handling of accidental loads generated by other accidents than fires and explosions in the project planning phase of a development project. The scope is limited to accidents (MAHs) typically covered in a QRA today.

The proposed method/criteria shall define the relevant scenarios and loads considering only the outcomes of relevant accidental events, i.e. explicit assessment of frequencies, branch probabilities, etc. shall thus not be included directly in the proposed methods/models. Definition of the validity envelope of the methods/criteria is however needed. The results and recommendations provided by the methods and models established shall not be linked directly to probabilistic risk acceptance criteria (e.g. 10-4 per year), but the qualification/justification of the methods to be established can and should however use such results as a reference, when relevant, e.g. to show that the new methods will provide (at least) the same safety level as today. This may also be necessary to fulfil the requirements and expectations by the regulator.

Only accidental loads where the consequence models typically used in the NCS oil & gas industry today are found valid, shall be addressed, i.e. design, layouts, etc. that are within the validity envelope of the current methods (and the theory these are based on) shall be covered.

Design factors described by prescriptive requirements and practices in present standards and regulations shall as far as possible and when relevant, be used as a basis for the work.

The hazards that shall be considered are:

a) Ship collisions

b) Falling and swinging loads

c) Toxic and suffocating loads

d) High voltage transformer fires and explosions

e) Utility fires (MEG, TEG, MeOH, diesel)

f) Helicopter accidents

g) Extreme weather

h) Earthquakes

i) Engine compartment fires

j) Stability and ballasting failures

k) Structural failures and gross errors

The scope shall be updated initially in the execution of the work to reflect the preferred approach by the work group. The updated scope shall be issued for acceptance by the SC. For this workgroup, it is expected that tasks may be performed relatively independent for each hazard type. The need for discussions and coordination will thus be less than for the other workgroups.

The work shall in an early phase include identification of professional subjects with conflicting considerations that needs to be raised for alignment / clarification / confirmation with the SC. Workshop(s) shall be proposed to present these subjects in a proper way at strategic timings.

The scope shall include:

1. Collect up-to-date risk assessment methods and relevant prescriptive design requirements given in regulation and standards for the various hazards above.
2. Review and screen methods and requirements identified in item 1. The purpose is to categorize the hazards into two groups:
    a) Hazards that should be treated in design by use of prescriptive requirements in standards combined with good engineering practice. The recommended requirements and the validity envelope for the use of this practice should be described. The last part of the above list (e-k) is most likely to be in this group.

b) Hazards that need further method development to support risk-based decision support. For these hazards' further refinement of RISP methods as outlined in item 3 to 7 below should be established. The first part of the above list is more likely to be in this group (e.g. a-d).

3. Establish RISP methods to provide recommended design scenarios and/or loads unless handling of the hazard is sufficiently covered by prescriptive requirements.
4. Identify key (most important or critical) design parameters and their importance that can be used to optimize and/or evaluate development concepts and layout with respect to the hazards. Design factors described by prescriptive requirements and practices in present standards and regulations should be a basis for the work.
5. Discuss competence strength of factors influencing the hazards and related need for robustness in design
6. Describe constrains and conditions for using the RISP methods (validity envelope). This should include premises for use of the methods both with respect to a standard design and relevant prescriptive requirements to be fulfilled.
7. Establish a guideline for use of the RISP methods. This should include a checklist to be used as a part of the HAZAN to ensure compliance with the validity envelope of the RISP methods throughout the project development process.
8. Identify, if relevant, challenges with existing regulations and standards

Chapter 4 in Attachment 1 of the NOROG report is relevant input to the work regarding ship collisions.

3 Ship collision

3.1 Introduction

This section covers the assessment of accidental loads related to ship collisions. The main focus is to set realistic design loads for the offshore facility related to vessel traffic in the area and field vessel activity. The intention is to give good input to identify relevant scenarios and set a validity envelope for assessing realistic impact loads using RISP. The work is to a large extent based on the results from a recent JIP related to vessel collision risk, Ref. /3/

3.2 Context

The applicability for RISP will be assessed in the HAZAN (see Section 3.3.1). During the HAZAN the following should be assessed to verify applicability for RISP:

- Regulatory requirements
- GOMO guidelines
- Overall layout and plans.

The RISP method is developed for oil and gas operations on the Norwegian Continental Shelf, and comply with Norwegian regulations for petroleum activities, and based on procedures and operating practices which are considered industry practice on the Norwegian Continental Shelf.

3.2.1 Regulatory requirements

For the ship collision loads assessment to be considered within the RISP validity envelope, it must as a minimum document compliance with the following regulatory and standard requirements:

- PSA Management regulations
    - Section 9: Acceptance criteria for major accident risk and environmental risk
- PSA Facility regulations
    - Section 11 Loads/actions, load/action effects and resistance
- NORSOK S-001 (2018)
- NORSOK N-003 (2017)
- Section 9.3 Impact actions.

In addition, it must be assumed that all standards for design and construction of ships and its parts are adhered to.

3.2.2 G-OMO - Guidelines for Offshore Marine Operations

G-OMO is a standard global approach to encourage good practice and safe vessel operations in the offshore oil and gas industry.

The guideline covers all relevant aspects form vessel procurement, voyage planning, mobilisation, loading, outward voyage, approach to location, working at location, departure from location and inward voyage. However, a specific guide is prepared related to collision risk management within G-OMO. This guide includes recommendations related to:

- Safety Zones
- Bridge Team Organisation and Management
- Approaching Location
- Selection of Station Keeping Method
- Pre-Entry Check Lists
- Setting Up Before Moving Alongside
- Use of Dynamic Positioning

- In Operating Position and Change of Operating Location
- Weather Side Working
- Departure and Commencement of Passage
- Field Transits.

The RISP method apply for facilities applying these recommendations.

3.2.3 Overall layout and plans for the marine operations

When the supply and lifting strategy are established, a coarse description of procedure and restrictions should be developed. Procedures need to be developed to ensure safe vessel operations including considerations of:

- Material handling
  - location of laydown area(s)
  - crane location
  - supply vessel loading position
- Riser
  - location relative to vessel operating position
  - protection of risers
- Offloading location
- W2W vessel
  - Bridge landing area
- Weather restrictions.

All this to define safe loading position and to set operational restrictions. Normally lifting from supply vessels and shuttle tanker offloading is preferred in downwind position of the facility and away from unprotected risers.

Based on these layout considerations, the design loads application areas (for impact loads) are known.

3.2.4 Framework for design of topside arrangements protection

All topside arrangements that according to the plans may be exposed to collision impact loads should be designed to withstand the loads with enough robustness to render unlikely a release of hazardous material or loss of main safety function.

3.2.5 Strength of knowledge

Assessment of the risk associated with collision risk has been performed over many years and is well understood in the petroleum industry. The RISP method for collision impact loads/energies has therefore no additional conservatism due to lack of knowledge about the phenomenon. However, the risk modelling of consequences of impacts is still under further development.

Conservatism in the RISP method is therefore linked to the simplified approach.

3.3 Proposed RISP Method

Main steps of the recommended method are as follows:

1. Establish context of analysis
   a. Identify operational phases and operations covered
2. Define the representative collision scenarios i.e. vessel types and phases (HAZAN)
   a. An appropriate set of representative operating scenarios must be established. Each representative scenario will have a unique set of initial conditions

b. Identify visiting vessel types and size (displacement)

c. Identify relevant barriers in place and discuss whether the RISP methodology is applicable within a validity envelope.

3. Set the relevant design loads for the relevant scenarios

4. Assess and describe uncertainty – Evaluate and demonstrate strength of knowledge

These steps are set up to sort out which design scenarios that are relevant for the concept in question and which of those design scenarios that are within the RISP envelope and those design scenarios that requires additional assessments.

3.3.1 HAZAN and validity envelope

Based on experience from operations in the NCS, the following identified hazards (collision scenarios) should be considered, but not limited to:

- Passing vessels – vessel traffic with no relation to the specific facility
- Supply vessel
- Standby vessel
- Shuttle tanker – field specific
    - DP operation
    - Conventional
- W2W- vessel – for the facility
- Flotel
- Field-related
    - Installation vessel
    - Heavy-lift vessel
    - Pipe-laying vessel
    - Anchor handling vessel
    - Multi-purpose vessel
- Other – area and site-specific activities with floating vessels or barges

Scenario phases

For visiting vessel visit three phases should be addressed;

- on arrival,
- manoeuvring from standby position to operating position, and when in
- operating position.

In addition to the three phases, there is normally a phase where the vessel will be positioned in standby position, possibly for an extended duration, between on arrival and manoeuvring from Standby position to Operating position. It is however expected that the selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) and based on a careful consideration of the current weather conditions and with respect to the field layout and nearby installations. In this case it is assessed that the probability of collision can be efficiently mitigated by selecting this position such that the vessel is not exposing any nearby installations in case of a black out scenario. Being at a safe distance/location it is also assessed that the probability of not being able to respond to and correct a drive-off event (or other failure situations) is negligible.

Facility layout considerations (input to design)– to be discussed in HAZAN:

- Material handling - Laydown area – crane location – supply vessel loading position –> preferred downwind
- Riser location and protection – away from loading position (supply vessel)
- Offloading – location -> preferred downwind

- W2W – bridge landing area.

The RISP methodology is applicable within a validity envelope. This is relevant to address in the HAZAN i.e. separate validity envelopes are assessed per RISP model (hazard and area). In the table below a set of parameters to be discussed in the HAZAN is listed for the different collision scenarios.

Other vessel operations with other collision impact loads, which it is considered and decided not to be designed for, should be specifically addressed with respect to assessment of operational risks and compensating measures. The HAZAN shall document the reasoning not using the relevant scenarios for design input.

Table 1 - Typical collision scenarios to be considered

Collision Hazard	Barriers and RISP envelope	Input to design load	RISP method
All passing vessels	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) Location away from traffic separation scheme (TSS), at least half of the width of TSS.	No	Vessel traffic survey (AIS data) Degree of operational barriers
All visiting and attending vessels in waiting position	Selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) Weather conditions - vessel is not exposing any nearby installations in case of a black out scenario. Drive-off event fully recoverable	No	
Supply-vessel – on arrival	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure	No	
Supply-vessel – Manoeuvring from standby position to operating position	G-OMO-procedure Waiting position downwind facility	Yes	See section 3.3.2.1
Supply-vessel – Operating position	G-OMO-procedure Loading position down-wind	Yes	See section 3.3.2.2
Shuttle tanker Conventional (No DP) – visiting	NA	Yes	Detailed assessment required. Outside RISP envelope.
Shuttle tanker – on arrival	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure	No	
Shuttle tanker vessel – Manoeuvring from standby position to operating position	G-OMO-procedure	Yes	See section 3.3.2.3

Collision Hazard	Barriers and RISP envelope	Input to design load	RISP method
Shuttle tanker - Operating position	GOMO-procedure Weather vaning FPSO 80-100 m offloading distance DP-operation	Yes	See section 3.3.2.3
W2W vessel	Minimum DP2 Preferred connected downwind Speed requirements Heading and hold time requirements	Yes	See section 3.3.2.2
Standby vessel	In downwind position	No	
Field-related	Separate risk evaluation	No	
Flotel	Separate risk evaluation	Yes	Use JIP model (Ref. /3/), outside RISP

3.3.2 Design loads – collision – impact energy

The collision energy (E_s) can be calculated by the equation, by using the vessel mass (displacement in kg) (m_s), the vessel added mass (a_s) and its impact velocity (V_s):

$$E_s = \frac{1}{2}(m_s + a_s)V_s^2$$

The added mass accounts for the hydrodynamic forces that act on the ship during a collision. There are a number of factors that need to be considered when assessing the added mass for a vessel, such as the shape of the vessel, its draught and the duration of the impact. Frequently used added masses are 10% for stern/bow on collisions and 40% for broadside collisions.

With respect to the consequence modelling, the following factors are taken into consideration:

- Energy dissipation between the vessel and platform, i.e. not all initial kinetic energy will be transferred to the platform structure and lead to plastic deformation. In direct hits, all energy is absorbed by the vessel and the platform structures. Typically, in low energy impacts most of the energy will be taken up by the facility. For high energy impacts, most of the energy will be taken up by the vessel. Smaller vessels absorb more of the energy than large vessels.
- It is important to note that the energy distribution between vessel and facility depends on several factors such as type of bow, size of vessel, collision angle, point of contact(s) etc. Without a detailed structural analysis of the specific platform and relevant vessel it is challenging to conclude with certainty about the energy distribution.

In view of the above-mentioned uncertainties, it is difficult to obtain exact numbers for how much of the energy that is distributed between the platform and vessel. A guideline for establishing the energy distribution between vessel and installation has been developed. This guideline is outlined in Section 3.3.3.

3.3.2.1 Supply-vessel – Manoeuvring from standby position to operating position

There may be a wide variation in impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact, dissipation of energy between installation and vessel. The corresponding speed in head-on collisions varies and can be up to 4 m/s. Considerations of procedures for field traffic surveillance, speed limitations, and improvements in the design of vessel control systems also play an important role in giving realistic impact scenarios.

3.3.2.2 Supply-vessel and W2W vessel – Operating position

Due to the limited distance between the vessel and the installation during loading/offloading, the speed at impact given a drive-off is assessed to be low. If there are specific vulnerable collision targets, such as risers or living quarter, it might be necessary to apply a more detailed speed distribution. For a conservative approach, the speed distribution given in NORSOK N-003 (2017) should be used. There may be a wide variation in impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact. From operating position, it is likely that in addition to head-on collision, the vessel may move sideways, in the aft direction, or even rotating when colliding with the installation. The corresponding speed in head-on collisions shall be 0.5 m/s and 3.0 m/s for ULS and ALS checks respectively. A hydrodynamic (added) mass of 40% for sideways and 10% for bow and stern impact can be used.

3.3.2.3 Shuttle tanker vessel – Manoeuvring from standby position to operating position and operating position

NORSOK N-003 (2017) suggest using a minimum collision energy of 100 MJ for collision scenario involving shuttle tanker hitting the stern of a FPSO. This is assessed valid both design scenarios i.e. for the manoeuvring from standby position to operating position, and when in operating position.

3.3.3 Application of collision load energy

Application of load energy need to take into consideration several factors. Depending upon the impact conditions (speed and type of hit), a part of the kinetic energy may remain as kinetic energy also after the impact, while the rest of the kinetic energy has to be dissipated as strain energy in the installation and the vessel. A method was developed in the JIP project (Ref. /3/). The method was developed as a guidance to us of DNVGL-RP-C204 “Design Against Accidental Loads” (Ref. /4/) and DNVGL-RP-C208 “Determination of structural capacity by non-linear finite element analysis methods” (Ref. /5/

3.4 Application of methods in design

No specific input.

4 Falling and swinging loads

4.1 Introduction

Falling and swinging loads covers lifts performed with the platform cranes, monorails, runway beams, pad eyes, pipe handling cranes on the drill floor and so on. However, the focus is on lifting hazards that have major accident potential. The supply vessel is usually outside the scope of the early facility development phase, hence dropped objects that land on the vessel is not covered by this document.

A dropped object is defined as a load that is unintentionally released from a lifting device, or that is swinging and unintentionally impacts some part of the installation structure. An object can be any item lifted on the installation, including containers, baskets, drilling equipment, crane boom and so forth. Accidental drops of objects can result in:

- Injuries and fatalities among personnel working on the installation
- Damage to equipment (anchor lines, flare, lifeboats, etc.). If hydrocarbon carrying equipment is hit, leaks or, in extreme cases, blowouts can result
- Damage to the platform main structure

Dropped objects can initiate major accident events. If a dropped object hits hydrocarbon carrying equipment causing loss of containment, ignition can cause a major fire or an explosion. Dropped loads with impact energies above the platform's structural design limits can result in major structural damage to the installation.

Lifts that are partially taken over sea, such as those between the platform and supply vessels, can result in objects dropped to sea. Objects falling overboard may hit and damage the structure of the installation, or they may sink towards the seabed and be a hazard for any subsea equipment installed in the proximity of the facility.

The RISP methodology on falling and swinging loads is intended to provide decision support during the early development phase to ensure safe design according to the RISP framework (see RISP WG 1 report), but the methodology also allows for instant consequence assessment whenever the decision is made. This includes providing good principles for design and operation and appropriate design loads for the selected design and lifting plans.

4.2 Strength of knowledge

4.2.1 General

Assessment of the risk associated with falling and swinging loads has been performed over many years and is well understood in the petroleum industry. The RISP method for falling and swinging loads should therefore have no additional conservatism due to lack of knowledge about the phenomenon. Conservatism in the RISP method is therefore linked to the simplified approach with less detailed analyses than what is normally done in a traditional risk analysis.

However, the simplified RISP approach has disclosed that the current industry practice with a risk based approach to protection of subsea arrangements (see section 4.2.3) has a potential weakness in that it provides the least protection in the area where the consequence of a release is most severe; directly under and near the platform. This is due to an established cost-benefit trade-off allowing for less protection than perhaps needed in the near vicinity of the platform (while still meeting the frequency requirement).

4.2.2 Protection of topside arrangements

On average, a drop of the load can be estimated in the order of one time per 1E-06 lifts. An average platform can typically have in the order of 8000 lifts per year[1], rendering a dropped object to occur in the order of 1E-02 times per year on an average facility. Even though that only a

1 This is a Lloyd's Register best estimate based on experience and is not consolidated by a detailed review of platforms. However, the context of which the estimate is used in RISP does not depend significantly on having a more accurate number.

fraction of the dropped objects (in the order of 75%) are dropped over the platform, the drop frequency is so high that this must be considered a dimensioning event that need to be managed by the design or by lifting procedures (or a combination of the two).

The RISP model will require knowledge of which object (measured in weight class) that will be lifted where and with which height to be able to assess the need for protection. However, the frequency of lifting is not required.

4.2.3 Protection of subsea arrangements

The frequency for drop over sea can be estimated to be in the order of 1E-02 times per year (see also section 4.2.2), and this must therefore be considered as a dimensioning event.

Note that for dropped object protection on subsea equipment the proposed RISP method is more robust than traditional probabilistic methods.

Traditional methods for seabed protection are normally based on a frequency assessment. The frequency assessment can be done either by following DNV-RP-107 with a acceptance criteria of resulting pipeline releases below 1.0E-04 times per year, or the frequency assessment it is based on an assessment of how much the pipelines has to be protected to ensure that all identified risk numbers (impairment of main safety functions) are below the acceptable limits. When using traditional methods, one need to know exactly what is going to be lifted, and which frequency it is going to be lifted with (or at least have an upper limit of these). This means that a change in the lifting programme may in theory change the need for protection of pipelines. Note that according to the RISP framework (see section 1.3.3. in the WG 1 report) one can use RISP models for parts of the facility design. E.g. when using RISP models for, say, explosion one may still choose to use the traditional DNV-RP-107 frequency approach for protection of subsea arrangements. Note, however, that the traditional approach of basing seabed protection on contribution to total risk numbers cannot be used when parts of the development is based on RISP models since the total quantification of risk numbers will not be available as a part of a RISP development.

The proposed RISP method for protection of subsea arrangements is independent of lifting frequency and lifting programme since it is de-coupled from frequency and only presumes that all weight categories of DNV-RP-107 can be lifted. This means that the RISP method can be more readily applied earlier in a project development than traditional methods.

However, the RISP method will lead to more robust design of pipeline protection than what is normally seen from traditional studies. Particularly, the RISP method will result in more robust seabed protection near the drop points. While this may sometimes be a challenge to achieve from a cost point of view, it is also a robustness that provides better protection in the area where the consequence of a release is highest (near the platform where a long duration fire on sea has the most severe consequences). Using traditional methods for seabed protection may reduce the cost, but at the same time it will often result in less protection in the areas where the consequences of a leak is highest (compensated with additional robustness in the areas further away for the drop point where the consequence is less severe).

The proposed RISP model is based on an assumption of survivability, i.e. given any drop at any possible location the pipeline must survive without a major release with a given probability. To identify an expedient survivability for the RISP model, one can establish two outer boundaries for survivability; 90% given drop and 99% given drop. Given that the likelihood of a drop over sea is in the order of 1E-02 per year, a 90% survivability will result in an order of 1E-03 times per year subsea release and the 99% survivability will result in an order of 1E-04 times per year subsea release. Assuming an ignition probability in the order of 10%, the 90% survivability will result in a fire on sea in the order of 1E-04 times per year while the 99% survivability will result in subsea fires in the order of 1E-05 times per year.

Based on the above frequency assessment, the proposed RISP model for protection of seabed arrangements is based on a 95% survivability given drop. This will ensure that designing with the new RISP model is at least as safe as designing with traditional approaches.

The RISP model presented gives new and useful awareness about the need for more robust seabed protection near the drop point than what is traditionally used today.

4.2.4 Crane boom fall

The frequency for crane boom fall can be estimated to be in the order of less than 5E-05 times per year (see also section 4.3.7), and this can therefore be considered as a not dimensioning event. However, if there are especially critical or hazardous areas directly under the crane boom (on the upper deck), protection of these targets can be considered as part of the ALARP process.

4.3 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for falling and swinging loads:

4.3.1 Regulatory requirements

For the falling and swinging loads assessment to be considered within the RISP validity envelope it must as a minimum document compliance with the following regulatory and standard requirements:

- PSA (Management regulations & Facility regulations)
- NORSOK S-001
- NORSOK N-003
- NORSOK R-002
- NORSOK R-003

In addition, it must be assumed that all standards and codes for design and construction of cranes and its parts is adhered to.

NORSOK S-001: "Equipment and piping containing hydrocarbons shall be located or protected to minimize consequences from dropped objects, crane boom fall and swinging loads etc".

4.3.2 Lifting strategy

In alignment with the requirements of PSA Framework regulations §4 and NORSOK S-001 the facility must be designed to minimise the consequences of dropped objects.

To develop a robust design against falling and swinging loads it is necessary that a lifting strategy is already established. The lifting strategy must define what needs to be lifted, how high it needs to be lifted and where it needs to be landed. This includes defining whether objects will be moved internally on the platform with trucks or if they will be lifted over the platform.

The inherent safe design principle should be applied when developing the lifting strategy, i.e. one should seek to avoid lifting over or near hazardous equipment, and if this is not possible all hazardous equipment should be protected to withstand the potential loads from falling and swinging objects.

If a lifting strategy is not developed, then the design against falling and swinging loads cannot be performed.

4.3.3 Lifting procedures and lifting plans

A coarse plan of what needs to be lifted where must be developed. Procedures need to be developed to ensure safe lifting. The procedures must be aligned with the design of the platform.

Deck cranes shall not perform routine lifting operations over the living quarters or any other restricted lift zones and shall not be used in conditions where operational limits are exceeded, nor shall the cranes be used during helicopter operations.

Lifting procedures should prohibit lifting over pressurized hydrocarbon carrying equipment.

A fatality on the NCS occurred in year 2000 due to cargo handling on a pipe deck. In the accident investigation following the incident, The Norwegian Petroleum Directorate expressed concern that "a culture has developed over time where breaches of fundamental principles for safe lifting operations are accepted". Based on this, and the remarks made above, the importance of adhering to lifting procedures cannot be overestimated.

Ideally all the information listed below should be available for a lifting activity study for all offshore installations:

Lifting activity

- What objects are lifted (pipes, containers, tanks, etc.) and how heavy are they?
- Lifting distribution between the platform cranes
- Lifts from supply vessels
- Internal lifts

Lifting pattern

- Typical lifting heights to different laydown areas
- What objects typically go to each laydown area
- Are internal lifts lifted over sea, or over the installation only?

Lifting restrictions

- Are there any areas where there are lifting restrictions?
- Are there weather or other restrictions to lifting?

Dropped object protection

- Need for dropped object protection topside?
- Need for dropped object protection on risers?
- Need for dropped object protection on pipelines?
- Need for dropped object protection on structure (jacket, installation legs, floating devices)?

In reality it is rather rare that all this information is made available in the early development phase and more general assumptions must therefore be made based on experience. The lifting activity information should be collected for all relevant operations (normal operation, drilling operation, revision stops, etc).

4.3.4 Structural design of crane

When the lifting strategy and lifting plans are established, a structural design of cranes must be selected in a way that allows for safe operation of the lifting plans.

This includes coverage, capacities, line of sight, lifting radius, rotational speed, etc. allowing to operate safely.

The selected crane design must be well known and provide robustness in main support (pedestal) and crane boom arrangement to render structural collapse unlikely.

Best available technology must be applied, and conventional crane design standards and codes must be followed in the global and local use of capacities, safety factors and other elements that constitute a part of the robustness of the cranes.

4.3.5 Design of topside arrangements protection

All topside arrangements that according to the lifting plans may be exposed to falling and swinging loads should be designed to withstand the loads with enough robustness to render unlikely a release of hazardous material or loss of main safety function.

The RISP method for robust protection of topside arrangements is presented in section 4.4.1.

4.3.6 Protection of subsea arrangements

When objects are lifted over sea, either between a supply vessel and the installation or internal lifts over sea, they can be dropped from the crane boom and fall to sea. A dropped object to sea can potentially damage subsea structures such as pontoons, jacket, anchor lines, risers, pipelines, subsea wellheads, subsea BOPs, etc. The impact energy to these structures must be calculated and compared with the impact capacity of the same structures.

All subsea arrangements with major accident potential must be protected to withstand loads from dropped objects with enough robustness to render unlikely a release of hazardous material.

The RISP method for robust protection of subsea arrangements is presented in section 4.4.2.

4.3.7 Crane boom fall

Crane boom fall must also be considered as part of the ALARP process (see Section 4.2.4). A crane boom can fall at any time during its lifting route. A falling crane boom can strike areas that are protected by lifting restrictions. The lifted objects (container, pipes) will not be lifted above the areas with lifting restrictions, but the crane boom can still expose the restricted area.

A recent review of all reported crane boom falls on NCS and UKCS (ref. /6/) has indicated that crane boom falls can be expected with a return frequency of no more than 5E-05 times per platform year. While none of the reported crane boom falls has resulted in release of hydrocarbons, this cannot be disregarded, and design and operational measures should be considered to limit the risk according to the ALARP principle.

In addition to material failure and fatigue the dominating main causes of reported crane boom fall was failure of the boom hoisting cable system, hydraulic system and main power system. Providing the crane with sheave guards that prevents the boom hoisting cable to disengage from the sheaves will therefore reduce the likelihood of crane boom falls. Designing fail safe hydraulic and power systems will also contribute to reduced boom fall likelihood.

A significant part of the reported incidents was linked to failures that could have been prevented by a more rigorous inspection programme. In particular, maintaining the integrity of the boom hoisting cable system is a key factor for preventing crane boom fall. Preventing crane boom fall is therefore as much an operational factor as a design factor.

Crane boom falls are normally not contributing significantly to the overall risk (typically less than 1-2% of the total loss of main safety function) due to both low likelihood of occurrence and moderate consequences given a fall. The crane boom impact is likely to be on the top deck of the facility, and the consequences of an impact will be depending on what is stored in the area. The upper deck is usually the least hazardous place to have an explosion (since area is usually open and low-congested) and a fire (since heat and smoke loads are highest at some distance above the leak point and is less likely to cause escalation or loss of escape when the fire is on the top deck). If the top deck is highly congested or if there are large quantities of hazardous liquids stored, one should consider protecting the critical equipment from crane boom fall from an ALARP point of view.

Deck plates are not reported to be impaired from crane boom falls and need no additional protection from crane boom fall.

4.4 Proposed RISP method

If the HAZAN has concluded that the development project is within the validity envelope of RISP the methodology in section 4.4.1 through section 4.4.3 can be applied to determine the protection against falling and swinging loads.

4.4.1 Protection of topside arrangements

The consequence of a dropped load depends on several factors including:

- Mass of object;
- Fall height (governing object impact energy);
- Object orientation at impact;
- Component of horizontal velocity and degree of potential energy converted into kinetic energy; and

- Hazard potential and vulnerability of impacted object.

It is assumed that all the potential energy will be converted into kinetic energy and transferred to the laydown area upon impact; hence deformation of the dropped object is not considered. This is a conservative assumption as in reality a portion of the kinetic energy will be applied to deform the dropped object.

The impact energy, E, can then be calculated by the following equation:

$$E = m \times g \times h$$

Where:

m = mass of object in kg

g = 9.81 m/s^2

h = drop height in meter

The potential drop height of an object will depend on the path where the object is lifted. All hazardous material and all landing areas must be protected to withstand the potential energies from all objects lifted above them with masses and heights according to the lifting plan.

Protection against swinging loads must be provided to protect important equipment located closer than 3 meters from the landing areas.

For fixed installations the swinging load protection should be able to withstand swinging impact with energies, Es, corresponding to horizontal velocities of 1 m/s for all lifted objects, i.e.

$$E\text{s} = ½ \times m \times \text{v}^2$$

Where:

m = mass of object in kg

v = horizontal velocity in m/s

For floating installations, the swinging load protection should be able to withstand swinging impact with energies, Es, corresponding to horizontal velocities of 2 m/s.

4.4.2 Protection of subsea arrangements

As a main principle, designing by the RISP methodology is going to provide enough robustness to deem unlikely that a dropped object over sea is going to lead to a hydrocarbon release with potential major consequences for personnel or environmental. Unlikely in this context means in the order of less than 5%. This implies a 95% survivability for the pipeline given a drop over sea.

A 95% survivability corresponds to a fire on sea with an average frequency in the order of 5E-05 times per year, see section 4.2.3.

When an object hits the sea and starts to sink, it will after some time reach a constant vertical velocity given by its weight and shape. It will, however, to a lesser or larger degree also be subjected to horizontal forces that will move the object away from the drop point. The objects will thus tend to move within a cone with a top angle depending on object shape, mass, impact angle when hitting surface, etc. The actual trajectory will depend on several parameters as the impact angle, the impact velocity, the water current, the waves, the shape of the object etc. Common to most of the possible trajectories is a velocity along the trajectory varying between 3m/s and 20 m/s, while the vertical velocity after a certain distance will become more constant.

For tubular shaped objects the angular spreading will not increase below 180 meters, while compact objects will continue spreading within the cone shape down to the sea bed, but the spread is assumed not to exceed the corresponding spread of pipes at 180 m. Pipes may be lifted as a bundle.

The description of objects falling within a cone with an angle depending on the object is a simplification but illustrates the overall behaviour. The excursion of different objects should be considered as a stochastic event. The spread of objects on the sea bottom can be described by a normal distribution as given by the following equation from DNV-RP-107, ref. /7/:

$$p(x) = \frac{1}{2\pi\delta} e^{-\frac{1}{2}\left(\frac{x}{\delta}\right)^2}$$

where

$p(x)$ = Conditional probability of a dropped object hitting the sea bottom at a distance x from the vertical line through the drop point given a drop

x = Horizontal distance at the sea bottom

δ = Standard lateral deviation. For practical purposes the standard deviation δ is given as the corresponding half top angle through the relation. Different standard deviations will be used for each of the object categories. δ = d*tan(α), where d is the water depth and α is the angular deviation

An important parameter in the calculation of hit probabilities is the applied angular deviation for each dropped object. This is particularly important for tubular objects as these potentially have a large angular deviation. Angular deviations are presented in Table 2.

Table 2 - Angular deviations for different dropped object categories, Ref. /7/

Type	Categories	Typical objects	Weight [tons]	Angular deviation [deg]
1	Flat/long shaped	Drill collar/casing, scaffolding	<2	15
2		Drill collar/casing	2 - 8	9
3		Drill riser, crane boom	>8	5
4	Box/round shaped	Container, basket, crane block	<2	10
5		Container, basket, crane test block	2 - 8	5
6		Container, basket	>8	3
7	Box/round shaped	Massive objects	>>8	2

Impact energy from a dropped object will depend on terminal velocity at the point of impact. The impact velocity will vary significantly, particularly for pipes or slender objects. Due to variation in terminal velocities one can expect conditional probabilities for various energy bands as shown in Table 3. The conditional probabilities are proposed for a close to horizontal pipeline with normal protection requirement, and a normal distribution of the impact energies.

Table 3 - Impact energy distribution for different loads, Ref. /7/

Description	Weight [tons]	Typical objects	Energy band (kJ)					
			<50	50-100	100-200	200-400	400-800	>800
Flat/long shaped	<2	Drill collar/casing, scaffolding	30%	18%	14%	12%	11%	15%
	2-8	Drill collar/casing	5%	8%	15%	19%	25%	28%
	>8	Drill riser, crane boom	-	-	10%	15%	30%	45%
Box/round shaped	<2	Container, basket, crane block	50%	30%	20%	-	-	-
	2-8	Container, basket, crane test block	-	20%	30%	40%	10%	-
	>8	Container, basket	-	-	-	-	70%	30%
Box/round shaped	>>8	Massive objects	-	-	-	-	30%	70%

According to the main RISP principle for protection of subsea equipment described above all pipelines must be protected to withstand credible impact energies from the identified drop point to the horizontal distances where it is less than 5% likelihood of being hit. Horizontal distance on seabed that needs to be protected can be found by solving the horizontal spread equation with cumulative likelihood $P(X_D)$ = 0.95 (i.e. 95% survivability):

$$P(X_D) = \int_0^{x_D} 2\pi\, x\, p(x) dx = 0.95$$

In the RISP model the seabed drop area is divided into three drop zones with 1/3 likelihood of being hit in the case of a drop over sea:

Inner zone: $P(X_{INNER}) = \int_0^{x_{INNER}} 2\pi\, x\, p(x) dx = 0.33$

Middle zone: $P(X_{MIDDLE}) = \int_{INNER}^{x_{MIDDLE}} 2\pi\, x\, p(x) dx = 0.33$

Outer zone: $P(X_{OUTER}) = \int_{MIDDLE}^{x_{OUTER}} 2\pi\, x\, p(x) dx = 0.33$

The above equations indicate that the radial distance of the inner zone X_{INNER}, middle zone X_{MIDDLE} and outer zone X_{OUTER} are selected so that the conditional probability of hitting within each zone given a drop is 33%. The drop zones are illustrated in Figure 3.

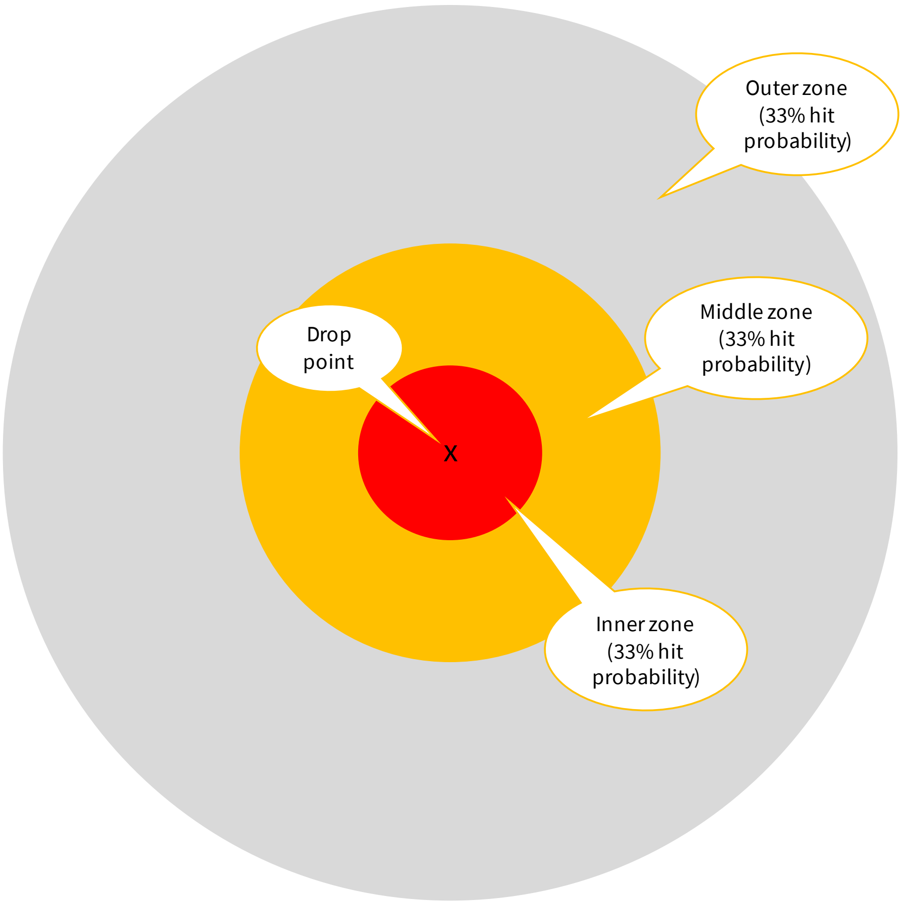

Figure 3 – Drop zones applied in RISP model for each object that can be dropped

Three drop zones (inner, middle and outer) are defined for all object types defined in Table 2 (with their given Angular deviation). The three drop zones for each object type will be different due to the different Angular deviation.

The average likelihood of hitting one pipeline within each drop zone is estimated by assuming that the pipeline is hit if the dropped objects lands closer than 2,5 m from the pipeline on each side (i.e. critical drop width of 5 m). The likelihood of hitting a pipeline in each drop zone can hence be found by

$$Hit\ probability = \frac{5m}{2\pi X_{MEAN}}$$

Where X_{MEAN} is the mean radial distance from the drop point for each drop zone.

The total energy that the dropped object protection must be able to absorb without resulting in a rupture to the pipeline can then be found by assuming that given a drop in one drop zone, the pipeline must have 95% probability of surviving. Consequently. if the hit probability is less than 5% in a drop zone, then there is no need for additional protection. If the hit probability is above 5% the pipeline must be protected with sufficient strength to provide total survivability of 95%

E.g. if the hit probability is 50% then the pipe must be protected to survive 90% of the hits to have a total survivability of 95%:

$$\frac{(0.95-(1-0.5))}{0.5} = 0.90$$

From Table 3 the cumulative collision energy for each object type can be estimated. Combining the hit energy with the hit rate and the target total survivability of 95% the required protection energy can be estimated for all dropped object types in all drop zones.

In the RISP model it is assumed that all object types of Table 2 will be lifted, and by following the process described above for all objects and applying the highest calculated protection energy for each radial distance, the dimensioning protection energy can be produced for all radial distances from the drop point. The capacity of the pipeline (typically 20 kJ) can be subtracted from the protection energy to define a dimensioning dropped object protection energy in addition to the robustness of the pipeline (i.e. if the dimensioning protection energy is 20 kJ, then there is no need for additional protection than what is provided by the pipeline itself).

If the pipeline is shielded from direct hit (see section 4.5 for details on shielding) then the hit probability can be further reduced, leading to a reduced need for additional protection of the pipeline. The RISP requirements for protection of pipelines for different shielding factors and water depths are presented in Figure 4 through Figure 6.

The same numbers are tabulated in Table 4 through Table 6.

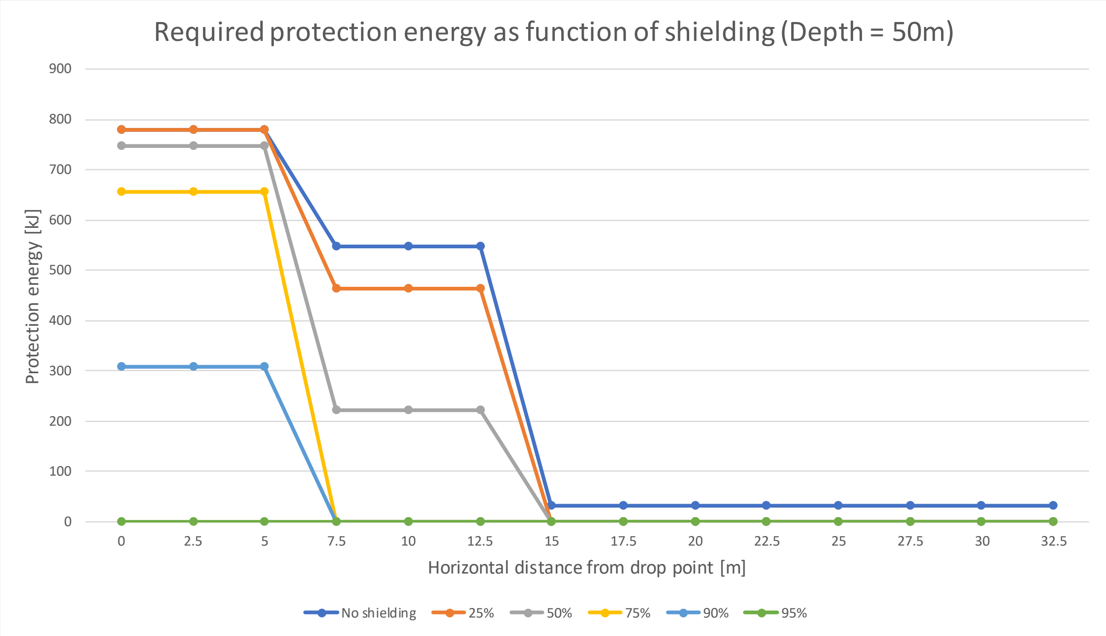

Figure 4 – Required protection energy – water depth 50m (95% survivability)

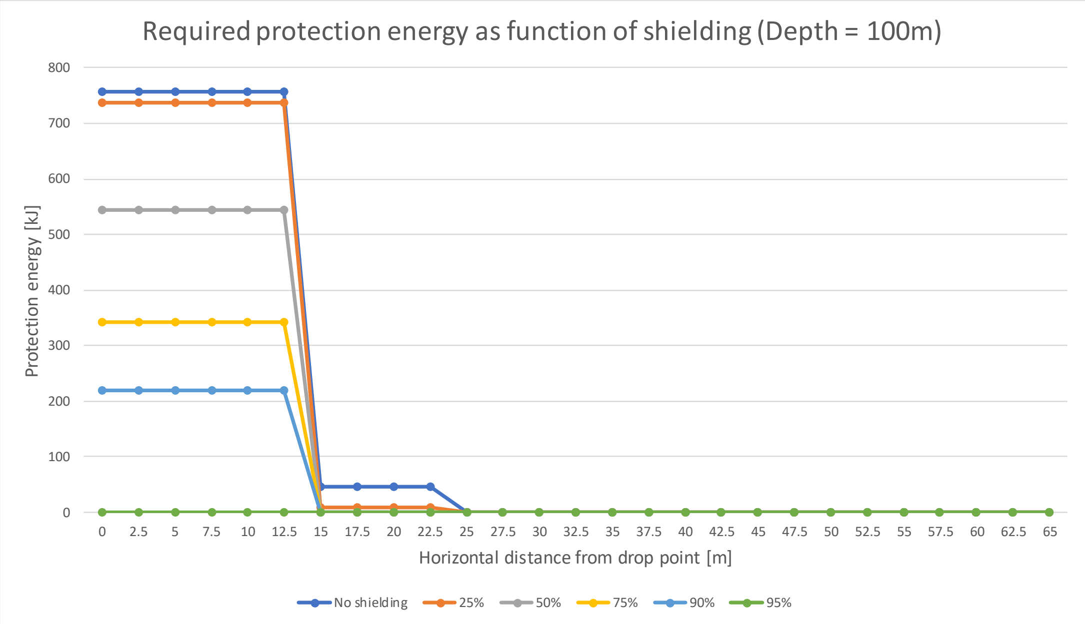

Figure 5 – Required protection energy – water depth 100m (95% survivability)

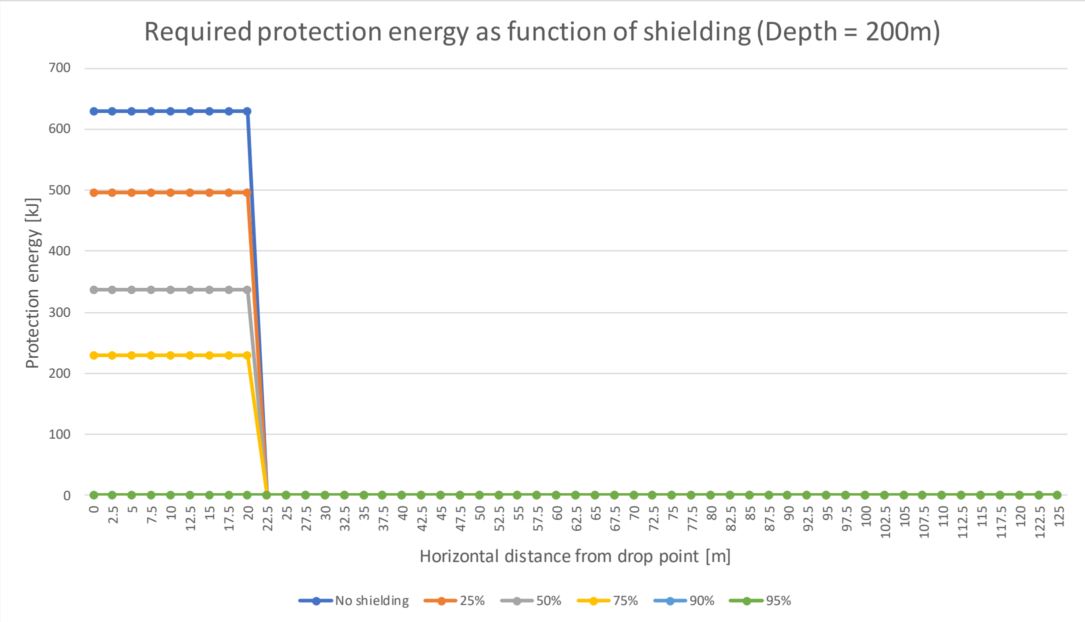

Figure 6 – Required protection energy – water depth 200m or more (95% survivability)

Table 4 – Tabulated protection energies – water depth 50m (95% survivability)

Shielding	Protection Energy Inner zone (radial distance)	Protection Energy Middle zone (radial distance)	Protection Energy Outer zone (radial distance)
0%	780 kJ (0-10m)	547 kJ (11-20m)	30 kJ (21-33m)
25%	780 kJ (0-10m)	463 kJ (11-20m)	0 kJ (21-33m)
50%	747 kJ (0-10m)	220 kJ (11-20m)	0 kJ (21-33m)
75%	657 kJ (0-10m)	0 kJ (11-20m)	0 kJ (21-33m)
90%	307 kJ (0-10m)	0 kJ (11-20m)	0 kJ (21-33m)
95%	0 kJ (0-10m)	0 kJ (11-20m)	0 kJ (21-33m)

Table 5 – Tabulated protection energies – water depth 100m (95% survivability)

Shielding	Protection Energy Inner zone (radial distance)	Protection Energy Middle zone (radial distance)	Protection Energy Outer zone (radial distance)
0%	757 kJ (0-13m)	45 kJ (14-24m)	0 kJ (25-65m)
25%	738 kJ (0-13m)	8 kJ (14-24m)	0 kJ (25-65m)
50%	543 kJ (0-13m)	0 kJ (14-24m)	0 kJ (25-65m)
75%	342 kJ (0-13m)	0 kJ (14-24m)	0 kJ (25-65m)
90%	220 kJ (0-13m)	0 kJ (14-24m)	0 kJ (25-65m)
95%	0 kJ (0-13m)	0 kJ (14-24m)	0 kJ (25-65m)

Table 6 – Tabulated protection energies – water depth 200m or more (95% survivability)

Shielding	Protection Energy Inner zone (radial distance)	Protection Energy Middle zone (radial distance)	Protection Energy Outer zone (radial distance)
0%	630 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)
25%	496 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)

50%	338 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)
75%	229 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)
90%	0 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)
95%	0 kJ (0-20m)	0 kJ (21-49m)	0 kJ (50-125m)

Other equipment that may be hit by dropped objects on the seabed or on the way down to the seabed (such as risers, anchor lines and structures) are not covered by the RISP methodology and special studies of these arrangements must be performed to assess robustness against collision with dropped objects.

4.4.3 Crane boom fall

A crane boom impact is likely to be on the top deck of the facility. If the top deck is highly congested or if there are large quantities of hazardous liquids stored, one should consider protecting the critical equipment from crane boom fall as a part of the ALARP process.

In order to identify hazardous/critical areas topside plot plans or weather deck plot plans must be reviewed. The critical areas must be identified. This is typically areas that can lead to release of hydrocarbons or areas with critical safety equipment/functions such as lifeboats, helideck and so on. In this process it can be useful to use dividers to draw up the area that can be reached by the crane. The critical areas within the reach of the crane must be assessed for likelihood of being hit by a crane. Some of the critical areas might be protected by structures that have a higher elevation, which will take the impact energy of the crane boom.

It might be difficult from the plot plans to get a good understanding of the relative placement of structures and their elevations. In this case it can be helpful to look at a 3D model if one is available.

The Figure 7 below illustrates a very simplified example with two critical areas within the crane reach in case of a crane boom fall.

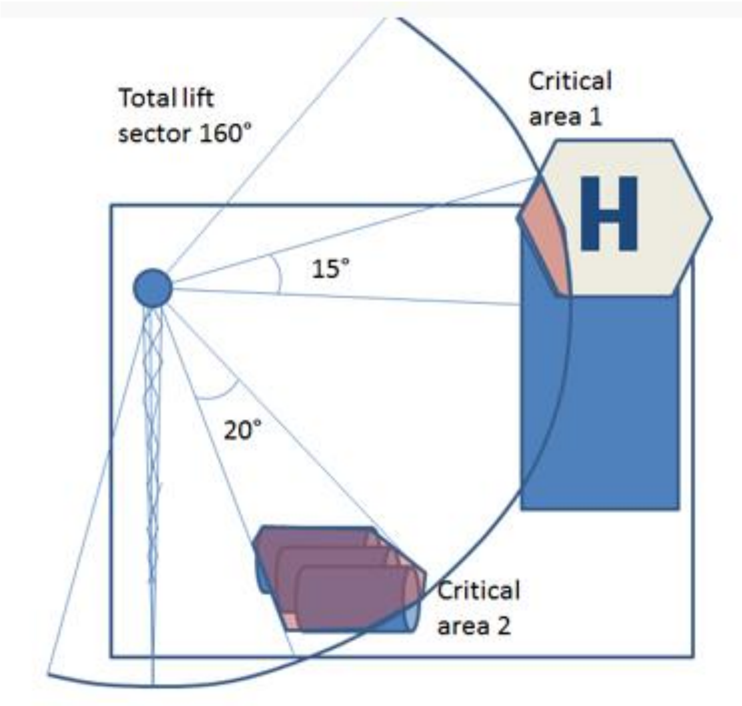

Figure 7 – Identification of critical areas for crane boom fall

The impact energy is calculated as potential energy of the crane boom during the lift. To calculate the impact energy the difference in elevation (Δh) between the crane boom and the critical area must be found. If designing against crane boom fall one should aim to absorb the energy associated with the highest credible energy over the critical area (i.e. fall from the highest credible position of the crane boom).

The proposed RISP method assumes that the crane boom has uniformly distributed mass (i.e. the centre of mass is in the middle of the crane boom). Information about the crane weight (M) is therefore necessary. The maximum impact energy is calculated by:

$$Impact\ Energy = M \cdot g \cdot \frac{\Delta h}{2}$$

where g is the gravity constant (9.81m/s^2).

The drop height (Δh) calculation is illustrated in Figure 8. Note that the impact energy will be associated with the vertical distance the crane tip moves before any point on the crane hits an object. If the crane hits an object some distance in from the crane tip, the crane tip will move a longer vertical distance than from the start height of the crane tip to the height of the hit point. The vertical distance from the tip start to the tip resting point shall be used for energy calculation.

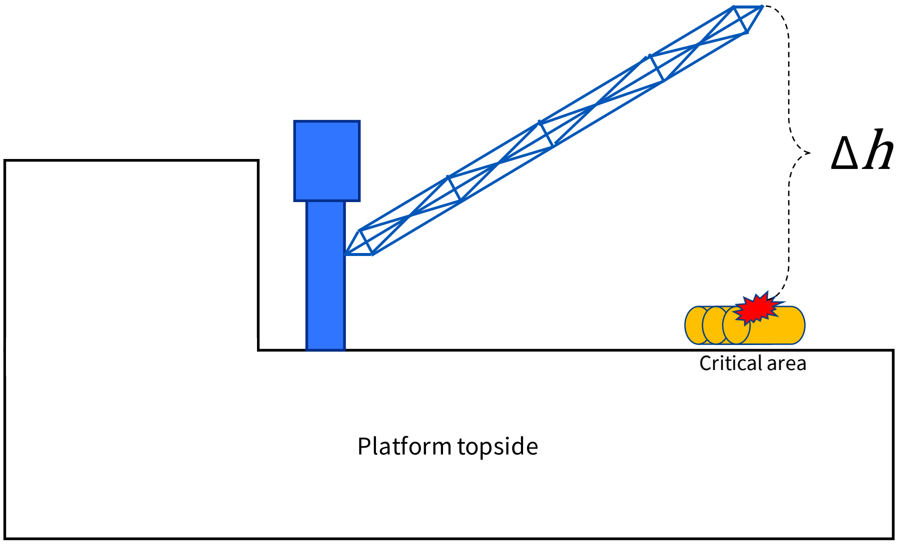

Figure 8 – Drop height for crane boom fall energy calculation

Note that the crane boom may deform during the impact and hence absorb some of the energy involved in the fall. The RISP model conservatively assumes that all energy must be absorbed by the crane boom fall protection. Reduction of absorbed energy can be assessed by special studies.

4.5 Application of RISP model

4.5.1 Protection of topside arrangements

When applying the RISP model for falling and swinging loads the methodology given for topside protection in Section 4.4.1 can be applied directly without additional considerations.

The main principle is that objects shall not be lifted over any equipment on the topside unless the equipment is designed to survive the energy that will be generated if the object is dropped. Surviving the dropped object energy implies that there should be no release of hazardous material.

If the landing areas and equipment are not designed to withstand drops from all lifts (i.e. the combination of weight and lifting height that gives the highest potential energy) additional assessments are required. These additional assessments must consider the likelihood of drops with high energy, the consequences of such energies and available mitigation efforts according to the ALARP principle.

Note that the RISP approach requires that landing areas and equipment shall resist the energy for all possible drops (all objects for all heights). In traditional designs one can sometimes see that e.g. landing areas does not withstand the highest drop energies, but that this risk can be demonstrated to be acceptable from a frequency assessment. Such assessments are considered special studies and is therefore outside the RISP validity envelope.

An illustration of the RISP method is given in Figure 9.

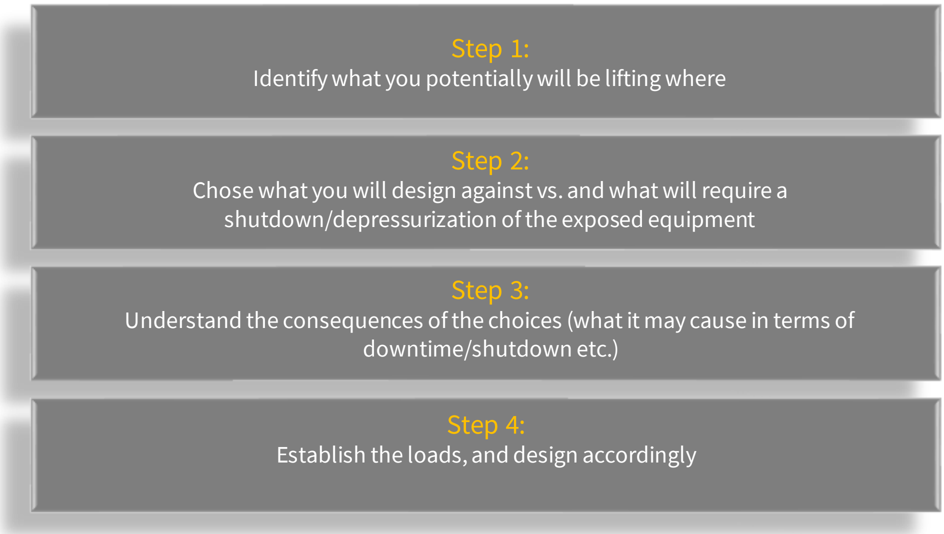

Figure 9 – Summary of RISP method for protection of topside arrangements

4.5.2 Protection of subsea arrangements

The RISP model for protection of subsea arrangements is conservative, but it reflects the potential energies and distances associated with dropped objects according to RNV-RP-107 (ref. /7/). If the RISP model is deemed too conservative, a special study can be performed (see also WG1 Figure 4). One example of a special study can be if no heavy object types are lifted one can calculate a reduced requirement for protection based on the same principles as outlined in Section 4.4.2. Another example of a special study is to apply less protection and calculate if the additional risk is acceptable by assessing frequencies and consequences in more detail.

The RISP methodology outlined in section 4.4.2 (95% survivability) is valid for all seabed pipelines with potential for large releases with long duration. The RISP methodology shall be applied for each pipeline, independent of how many pipelines there are on the seabed.

Following the principle outlined in the WG1 Figure 4 (stating that if a RISP method is too expensive additional assessments can be considered) dropped object protection can also be omitted or reduced if it can be documented that a pipeline rupture is unlikely to cause flammable atmosphere on the surface, either because of very low flowrate or by very deep water. Unlikely in this context should be less than 1E-05 times per year. However, there may still be a reason to protect the pipeline due to environmental considerations or economic considerations. The same considerations can be made around the use of SSIV; the reduced consequences of a release from a riser with SSIV may allow for reduction in pipeline protection.

The RISP methodology implies that all types of objects described in Table 2 are being lifted. If only smaller objects are lifted, the protection energies can be reduced based on special studies.

The shielding factor to be applied can be based on either geometrical shielding or operational shielding. Geometrical shielding is when a dropped object is physically prevented to hit the pipeline due to objects between the drop point and the pipeline. One example is illustrated in Figure 10 where the jacket structure reduces the likelihood for dropped objects to hit the pipeline near the platform (in the orange zone) since this area is in the shadow of the jacket structure. In these cases, dropped object protection can be omitted or reduced in the shielded area. The HAZAN must discuss the efficiency of the shielding from the actual jacket structure. Outside the shielded area the pipelines must be protected according to the RISP model for relevant radial distances.

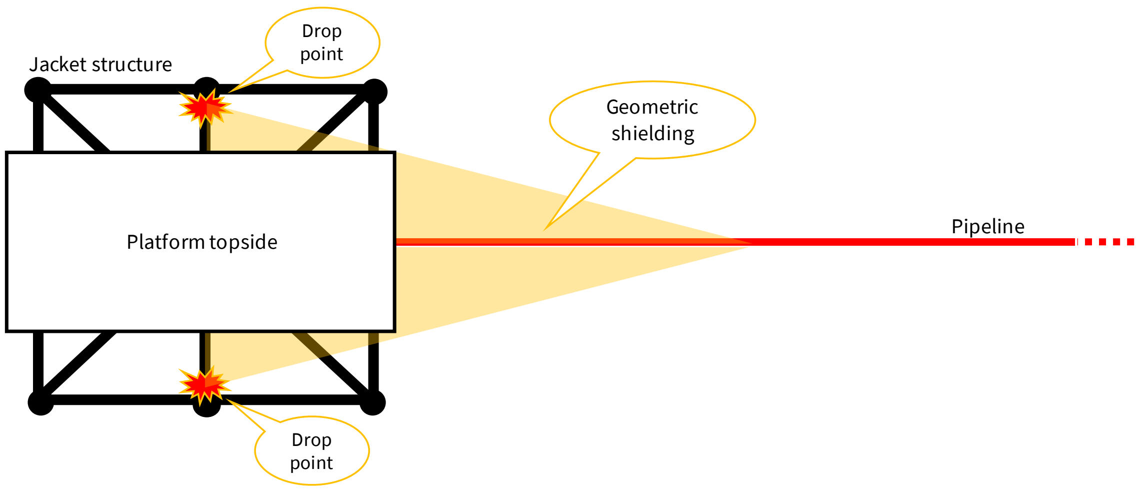

Figure 10 – Geometric shielding from physical objects (jacket structure)

Operational shielding is when the operational procedures ensures that lifting over the side with pipelines is reduced to a minimum. In Figure 11 this is illustrated with ensuring that lifts over sea (and hence drop points) are located on the opposite side of the platform from where the pipelines are located. This means that in the case of a drop to sea, the pipeline is shielded by the jacket structure. This type of shielding can be provided by any gravity-based substructure. For floating substructures, this shielding is limited (but can be partly applied e.g. for SPAR FPSO concepts). If the design is dependent on operational shielding, this must be clearly communicated to the operations management to be included in the operation strategy, e.g. by lifting maps or no lifting zones.

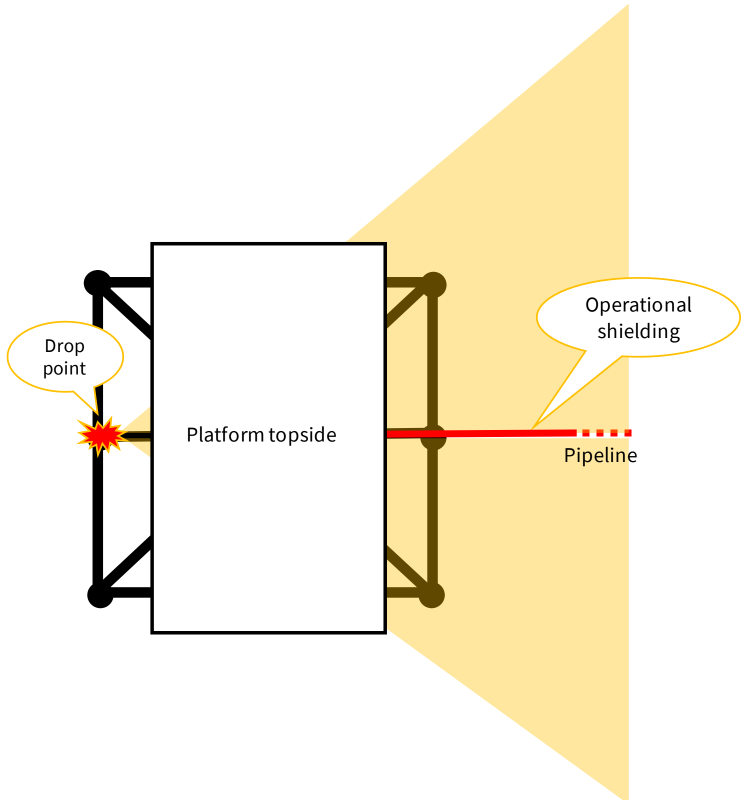

Figure 11 – Operational shielding by ensuring lifting over sea is done on the opposite side of the platform from where the pipelines are located

When planning for operational shielding in an early phase development projects one must assess possible consequences for all major accident risks. As an example, one can perform a trade-off assessment between ship collision strength and need for protection of pipelines; if one decides to design the main load bearing of the platform to withstand all possible collision energies caused by drive-offs and drift-offs, one can more easily allow for lifting over sea only on the opposite side of the pipelines (i.e. one can more easily allow for lifting between platform and supply vessel even if the wind and current is towards the platform).

A lifted object can be dropped in any location inside the operational radius of the crane, see Figure 12. When using the RISP model one shall assume that the radial distance for protection of the pipeline shall be measured from the outer circumference of the possible drop points. Parts of the pipeline that is within the operational radius of the crane shall be protected according to radial distance = 0.

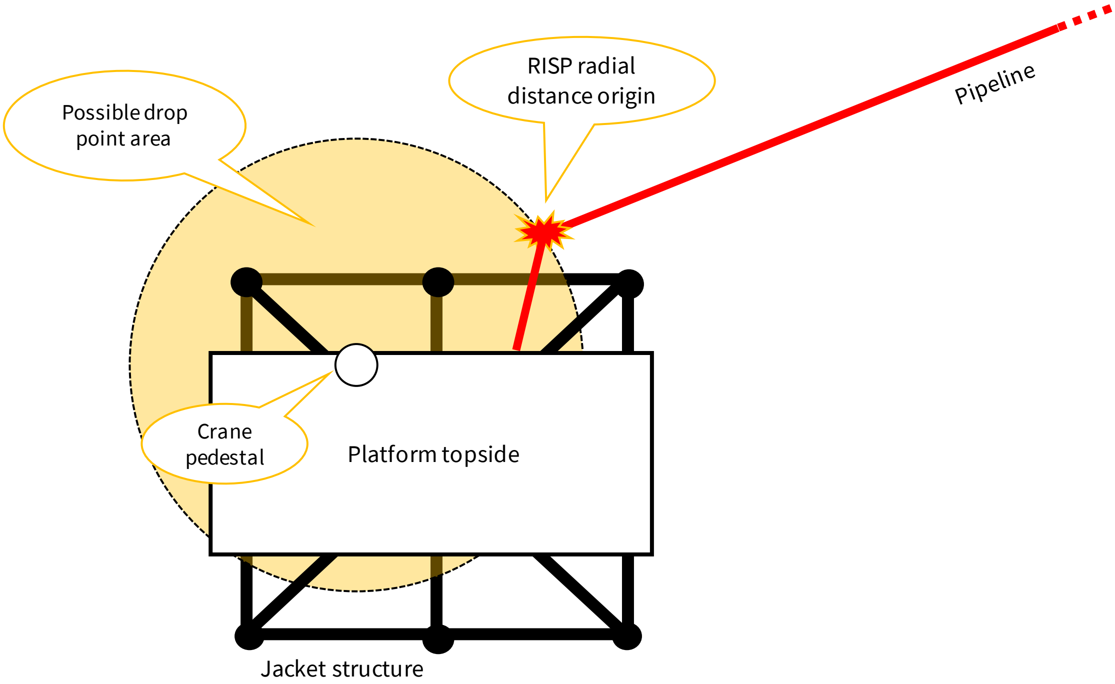

Figure 12 – Radial distance origin for pipeline protection by the RISP model

If a template or other important structure (containing hazardous material) is located within the radial distances requiring protection as defined by RISP, they must be protected against the same energies as indicated by RISP for subsea arrangements. If these templates are especially vulnerable, e.g. if being a main barrier towards the reservoir, one must consider additional protection by special studies (this case will be outside RISP).

An illustration of the RISP method is given in Figure 13.

Step 1:
Identify RISP radial distance origin (see Figure 4-10)

Step 2:
Assess operational and geometric shielding

Step 3:
Identify need for seabed protection as function of distance from drop origin

Step 4:
Assess if there are special conditions that allows for reduction in seabed protection

Figure 13 – Summary of RISP method for protection of seabed arrangements

5 Toxic and suffocating loads

5.1 Strength of knowledge

The strength of knowledge around designing against toxic and suffocating loads is considered to be high. NORSOK S-001 already covers the design elements that must be addressed during the early stage development phases. If NORSOK requirements are adhered to, the safety for these events is considered to be good and equal to the current industry practice.

Also note that toxic and suffocating events are unlikely to escalate to larger events that may potentially threaten the integrity of the whole facility, but the impact area may cover large parts of the facility in the event of very large toxic releases.

Important topics for the HAZAN robustness discussion of toxic and suffocating loads are presented in section 5.2.

5.2 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1). During the HAZAN the following should be assessed for toxic and suffocating loads:

As a main principle for RISP the design shall provide for reliable detection of toxic releases and for alerting personnel sufficiently early to allow for safe evacuation to safe areas.

Assessment of design against toxic and suffocating loads shall be based on NORSOK S-001. The following sections of NORSOK S-001 gives guidance to the design against toxic hazards:

NORSOK S-001 Section 6 (Functional requirements)
NORSOK S-001 Section 8 (Containment)
NORSOK S-001 Section 12 (Emergency depressurisation and Flare/Vent system)
NORSOK S-001 Section 13 (Gas detection)
NORSOK S-001 Section 16 (Human – machine interface for CCR systems)
NORSOK S-001 Section 17 (Natural ventilation)
NORSOK S-001 Section 18 (PA, alarm and emergency communication)
NORSOK S-001 Section 20 (Passive fire protection)
NORSOK S-001 Section 22 (Escape and evacuation)
NORSOK S-001 Section 23 (Rescue and safety equipment)

The NORSOK S-001 standard (Section 13.4.1) states that

> "*The basis and assumptions used for detector selection and location shall be documented. Dispersion studies should be performed for verification and optimisation of location and number of detectors*".

This is considered especially important when designing against toxicity, and it is therefore required as a part of a RISP study to perform dispersion simulations to estimate the credible size of toxic clouds, their possible locations and the required time to build up toxic concentrations. This information will allow for robust design with a minimum risk to personnel.

The design must prevent personnel to be trapped in the case of toxic releases. This implies that detection of toxic gas, plus alerting and evacuating personnel into safe areas should be completed before anyone has been exposed to unacceptable toxic doses. As acceptable limits for toxic exposure the LD_1 can be applied. The value of LD_1 for a substance is the dose required to cause fatal injuries in 1% of the members of a population.

The time of exposure while escaping shall only include the time personnel are being exposed while escaping (plus exposure before being alerted). Traditional designs with open modules with at least two escape routes will normally provide escape before unacceptable toxic doses are reached, but special considerations must be given for the following conditions:

- Confined areas with toxic content
- Enclosed areas with long escape time (e.g. shafts).

According to the Norwegian PSA (2006), irrationality due to toxic effect can occur at hydrocarbon gas concentrations of 20-30% of LEL. This will depend on the composition of the gas and the duration of exposure. Gas consisting of heavier hydrocarbons is more severe than gas consisting of lighter hydrocarbons. Toxic effect can occur very quickly, typically after 4-5 breaths. For areas where escape is more demanding, e.g. shafts, irrationality can cause that personnel is not able to escape from the area which again can lead to fatalities.

When evaluating the robustness of escape, it should be taken into account if there are breathing masks (or other PPE) in the area and if the escape routes are overpressure protected.

5.3 Proposed RISP method

Design against toxic and suffocating loads are considered to be sufficiently covered by standard assessments according to NORSOK S-001, see also section 5.2, and no additional RISP model is therefore deemed necessary.

6 High voltage transformer fires and explosions

6.1 Introduction

Electrical transformers are used to transform electricity from low voltage at production to a high voltage at end user to minimize energy losses during long distance transfer. At the end user, e.g. an offshore facility, transformers are used to bring the high voltage back again to low voltage before being used. High voltage transformers often use one form of liquid for cooling, and oil-filled transformers are considered as a possible source to fire and explosion accident scenarios in this section.

The explosion potential in dry transformers is small compared to oil-filled transformers since these do not contain oil which can contribute to an explosive atmosphere. The hazards related to dry transformers is therefore less serious and the explosion risk is regarded as insignificant compared to oil-filled transformers. Dry transformers can be assessed under electrical fires.

Failure in the oil-filled transformer may cause a high voltage arc to appear. The arc will crack/decompose cooling oil into lighter components due to very high arc temperature (typically 15 000-30 000°C) and lack of oxygen, and flammable gas will be generated. Typical components that are generated could be e.g. hydrogen, acetylene, methane, ethylene, ethane and propylene.

Parts of the cooling oil will also boil and evaporate in the vicinity of the electrical arc. This will further contribute to pressure increase and possible rupture of the transformer box. If the transformer has a built-in pressure relief function, there might still be an internal explosion due to the low ignition point of oil steam/acetylene and the low ignition energy needed to ignite hydrogen. Acetylene can decompose into hydrogen and carbon and release significant amounts of energy at pressures above 1 barg (while this decomposition is strictly not a combustion, acetylene is often defined with an upper flammability limit of 100 vol. %).

As long as best available technology is applied (see section 6.3), transformer fires and explosions are normally not considered risk drivers for offshore production facilities. Events are unlikely to spread to the production systems or wells, and fatality risk is low and limited to the immediate vicinity of the transformers. The only main safety function that may be influenced by transformer events is loss of escape due to smoke production, but this is most relevant for low flashpoint oils. The risk associated with smoke from transformer fires should be investigated in special studies, see section 6.4.5.

More detail of transformer fires and explosions can be found Ref /8/.

6.2 Strength of knowledge

Transformers have been used for more than 100 years in Norway, as these were required for transfer of electricity from waterfalls where it was generated to the towns it should be used. The strength of knowledge associated with transformer fires and explosions must therefore be considered high. However, details to the series of events that leads to explosions are not fully known to the extent that there exist industry models that can predict explosion loads as a function of all parameters and barriers in place for each event.

Conservatism in the proposed RISP method is therefore linked to the simplified approach with less detailed analyses than what is normally done in a traditional risk analysis. Barriers for risk reduction is discussed in the validity envelope section (Section 6.3).

Transformer fires and explosions are historically seen to occur with a frequency per transformer in the order of 1E-04 times per year (see Ref /8/). Transformer fires and explosions must therefore be considered to be design events for RISP developments, even if the likelihood of fatalities and loss of main safety functions is low for these events (see also Section 6.1).

6.3 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG 1 report Section 2.2). During the HAZAN the following should be assessed for high voltage transformer fires and explosions:

6.3.1 Regulatory requirements

If the use of high voltage transformers is to be considered within the RISP validity envelope it must as a minimum document compliance with the following regulatory and standard requirements:

- PSA (Management regulations & Facility regulations)
- NMA for floating facilities
- NORSOK E-001
- NORSOK S-001.

6.3.2 Venting

Transformers should only be placed in areas with sufficient venting in case of an explosion. For practical purposes, this implies that transformers should be located outdoors in open areas.

Indoor transformers are considered outside the RISP validity envelope and should only be used for smaller transformers and with special studies to document that the transformer room can contain the energy in case of an explosion.

6.3.3 Electrical protection

Electrical protection of transformers must be applied for RISP projects. Electrical protection includes methods for reducing the clearing time for internal arcing faults. This can be achieved also by current limiting fuses. Also, the fault current can be reduced by appropriate design of the electrical system of which the transformer is a part. This can be achieved by current limiting reactors, high impedance cable of upstream transformers.

All transformers must have fast reacting electrical protection, and for serious faults like short-circuit at the HV terminal, the reaction time must be in milliseconds. However, if the failure is in the windings, in particular if they are located at LV side, there is a risk of the safety system not reacting so fast, allowing the failure to develop. The impedance in the windings limits the short-circuit current, making it harder to detect for the overcurrent protection system. At the same time, since the impedance limits the short-circuit capacity of the transformer, is also limits the energy in the arc.

6.3.4 Power disconnection

The primary explosion in a transformer will normally be strongly limited if there are good mechanisms installed to quickly disconnect the power in the event of an arc. Buchholz-relay is standard protection in transformers which may stop an arc quite efficiently, and this will limit the energy in the primary explosion (which also gives fuel to the secondary explosion). Pressure sensor inside the transformer will detect pressure from an arc even faster. With this information, it will be possible to estimate reactive gas volume developing in the oil due the arc, and depending on the arc-depth and duration, there may be more or less hot oil (mist) expelled from the broken transformer box, and potential for some overpressures. The overpressures will primarily be of concern if enclosed in a building.

Ignition probability is high for a serious arc event, and a secondary explosion may develop. Due to the very reactive gases (hydrogen and acetylene from cracking of oil) together with some oil vapour/mist ejected from the transformer due the heat and high pressure caused by the arc, strong explosions may result. The amount of oil mist that will contribute to an explosion is highly uncertain, (it likely depends on depth of arc) and for this reason a distribution of amount of oil mist contributing is often assumed. Some of the reported accidents from the past (in particular confined secondary explosions) have shown behaviour that could indicate that detonations took place (e.g. situations in which explosion destroyed concrete structures or robust walls instead of venting through a designated vent opening), or where the time from initiation of arc to reported blast damage was very short. For secondary explosions outdoor it is expected that the detonation risk is much less, because the gas concentrations in ejected gas will quickly fall significantly below stoichiometry. Whether a detonation or strong deflagration should be expected would depend on the arc energy and transformer room volume. In either case such an event is likely to damage the transformer room and give comparable worst-case blast loads into the far-field (far-field starts at a distance of 2-3 cloud size diameters from the flammable gas).

6.3.5 Water mist

NORSOK S-001 states that water mist system is the preferred extinguishing system for enclosed compartments such as transformer rooms for oil filled transformers.

The water mist systems shall provide a quick and reliable discharge of water mist at a sufficient density and at sufficient duration for adequate fire suppression and control. General requirements for water mist systems are covered in ISO 13702. NFPA 750 should be used as guideline for design of water mist systems. Selection of type of water mist system (local and/or full flooding) shall be based on fire scenario and be described in safety strategy.

Water mist systems shall also comply with the following requirements:

- Automatic release of water mist at fire detection;
- easily accessible manual release facilities shall be provided at each entrance to the protected areas;
- the ventilation (fans and/or dampers) shall be closed and the area disconnected before release of water mist systems
- the water mist cabinet shall be located outside of the protected room;
- the water mist skid including compressed gas bottles shall be certified for the actual maximum operating pressure
- compatible materials shall be used throughout the system, e.g. nozzle/distribution piping.

A fire hose connection should be installed between the water mist skid and the protected room for extended water supply.

Water quantities and release duration should typically be determined taking into consideration the size of the area and the degree of congestion, the fuel type and the nature of the fires which may be experienced, equipment types within area (e.g. the effect on electrical and other sensitive equipment within the area of water-mist application), protection inside equipment such as turbine enclosures, etc. Release duration and design should be in accordance with contractor's recommendations, and/or typically range from 5 up to 30 minutes as indicated in NFPA 750 depending on application.

Selection of a water mist system will allow for both more efficient cooling and less use of water (less likelihood for overspill to sea) than massive flooding systems. If high flashpoint oils are used, there will be less need for cooling and fire quenching since they are unlikely to sustain fires.

6.3.6 Separation

Separation between the transformers and the surroundings must meet the requirement from NORSOK S-001:

Generators (including prime mover), transformers, major distribution panels, rooms for ventilation equipment and equipment used for storage of flammable commodities or easily ignitable material shall be separated from the surroundings with at least Class A-0 fire divisions.

6.3.7 Condition monitoring

Online condition monitoring must be applied for RISP projects. Online condition monitoring includes dissolved gas monitoring and other indicators of increased likelihood of an arcing fault. Condition monitoring will allow for operational intervention of an event before it develops to be large and potentially fatal.

6.3.8 Type of cooling agent

Explosion and even more fire properties will strongly depend on the type of oil used. One important question will be whether normal mineral oil is used (flashpoint ~130-140 °C) or if ester or silicon-based oils (flashpoint ~250-300 °C) will be used. Since the oil may locally be at 80-90 °C during operation, short-circuit and primary explosion may well heat local volumes of oil above 130-140 °C so that a fire can start, thereafter the fire may continue heating surrounding oil to above the flashpoint and give a sustained fire. A sustained oil fire will give extensive amounts of smoke and heat. If a high flashpoint oil is used the fire after a primary explosion is much less likely (or unlikely), which gives less concern for smoke and heat loads and no need for a pit to collect the oil (a bund will do). Cost is the main reason that mineral oil (low flashpoint) is prevalent for onshore facilities; for offshore installations one should expect that high flashpoint oils would be used as the costs of incidents would potentially be very high.

6.3.9 Pressure Relief Valve (PRV)

Oil-filled transformers are commonly equipped with pressure relief valves that are mounted directly at the tank. The valve will open at high pressure. The set-point for a PRV could typically be 0.35 barg, and the diameter up to 150mm. The PRV can be equipped with a switch that could trip the power supply for the transformer. A pressure-relief device shall be fitted in the cover of all transformers 2 500 kVA and larger or with insulation levels 200 kV and higher (ref. /9/).

It is normal for onshore applications that gas or oil released through the PRV is released in the transformer room rather than being vented to a safe location. This could represent a hazard for personnel in the area, possibly also representing a fire and explosion risk.

The PRV can be too slow to respond to fast pressure increase from a short circuit but will effectively protect the transformer tank in scenarios with gradual pressure build-up and low-energy arching faults. This could be the case with fire exposure, oil filling operation or other maintenance operations or transformer malfunction scenarios.

PRV is not mandatory in RISP developments but should still be considered.

6.3.10 SPR – Sudden Pressure Relay

An SPR is a device that detects a fast pressure increase in the transformer, gives alarm and trips the transformer. The SPR is mounted at the transformer tank. Its function is overlapping the function of the Buchholz relay, but the SPR will have shorter response time.

SPR shall be considered in RISP developments.

6.3.11 Pressure relief through use of rupture disk

Tank rupture can be prevented by relieving the pressure developed as result of an internal arc. A pressure relief valve will in many scenarios respond too late and with insufficient capacity to prevent rupture.

A “transformer protector” is a protective system comprised of a large rupture disk mounted on the transformer tank, an oil/gas separation tank and a vent. Such a system is activated within milliseconds, and static pressure build-up can be prevented in scenarios with too fast pressure build-up for the PRV or Buchholz relay.

Rupture disks shall be considered in RISP developments. Note that for large transformers the arc may be located at a distance from the rupture disk, and in these cases the effect of the rupture disk is limited (since the pressure increase is too rapid for the disk to be able to vent out a larger column of oil).

6.3.12 Enhanced transformer tank construction

In principle, a transformer tank can be built to withstand the static pressure build-up from an internal arc. This would require that the transformer is constructed and operated as a pressure vessel. Available transformers are not designed as pressure vessels, but transformer manufacturers specify at least 1.0 bar overpressure capacity [ETEP]. According to Ref. /9/, rectangular transformer tanks can withstand a (static) pressure of about 1.4 to 2.1 barg, while a cylindrical transformer tank can be designed to withstand 3.5 barg. This could still be insufficient to survive a high energy fault scenario, and if so, the resulting explosion could actually be more severe, as more explosive gas is formed before the tank rupture occurs. So, unless the tank is designed to withstand the credible internal arcing scenarios, the transformer explosion risk will not be reduced.

The trade-off between enhanced tank construction (with higher explosion loads if they rupture) or lower integrity tanks (with more frequent ruptures but with lower explosion loads given rupture) shall be discussed during the HAZAN. Both alternatives are acceptable for RISP, since the frequency for normal integrity tanks is already low (in the order of 1E-04 per year, see Ref. /8/).

Note that an alternative tank design which was not stronger, but instead deflected like a balloon, would probably be more successful in avoiding rupture of the tank. However, this solution is not applied in normal designs and must be regarded as uncertain for RISP developments.

Enhanced transformer tank construction is not mandatory in RISP developments but is discussed here as a part of inherent safe design and ALARP process.

6.3.13 Active fire protection

The transformer rooms must be protected with water mist initiated upon fire detection in the room.

For low flashpoint oils an additional deluge system with foam will effectively reduce the fire loads and may also extinguish the fire in some cases.

6.3.14 Safety distances

If there are several transformers, they must be protected so that escalation of an event from one transformer to another can be considered unlikely.

This can be achieved by ensuring that the design renders it unlikely that projectiles or high explosion loads leads to significant releases in neighbouring transformers.

6.3.15 Projectiles

During a secondary explosion the resulting explosion loads can be high, and it is important the design of the transformer itself (including barriers and pressure relief panels) is sufficiently robust to render projectile formation unlikely.

6.3.16 Drain, bunding and open drain

There shall be a bund below the transformers sized for full containment of the transformer oil. There shall be an overflow line to sea sized for oil and deluge capacity when low flashpoint oils are being applied.

When high flashpoint oils are used, there may not be a need for deluge and hence no overflow to sea line.

A rupture (internal explosion) of a transformer would most likely disperse the cooling media (oil) to the area around the transformer. The location of the transformers should be selected with regard to the possible location of oil spreading. E.g. if the transformers are located close to the edge of the deck, then large quantities can be dispersed both to the local deck area and the sea. Further, if the deck area on the cellar deck is grated around the bounded areas for the transformers, this can result in a pool fire, both at sea and on the deck, and unless the spread of mineral oil is prevented, this can result in a large pool fire.

Oil filled transformers must have bunding and an open drain system to limit the potential fire size and duration in the case of a transformer fire.

6.4 Proposed RISP method

6.4.1 General

The RISP method presumes that the HAZAN assessments has concluded that the design of the transformers is within the validity envelope defined in Section 6.3.

Design of transformers is done according to industry standards and need not additional support from RISP. However, input to design and context of nearby structure is given by RISP. By using the RISP method and guidance to safety barriers it can be deemed unlikely that a transformer event is going to escalate to the facility production system or the wells.

In the basis for the RISP model it is considered the uncertainty of both the volume of the flammable cloud in a secondary transformer explosion and the intensity of the source strength. However, it can be expected that the volume of the flammable cloud is small and that the intensities therefor will rapidly decay with distance according to the TNO-MEM. Due to the short duration of transformer explosions the design loads are given in impulse (i.e. both intensities and duration are included). A model load distribution for transformer explosions is presented in Figure 14. Low flashpoint (LFP) oils are estimated with a 50 m3 cloud of butane with source strength 5 barg, and high flashpoint (HFP) oils are estimated with a 30 m3 cloud with source strength 2 barg (the reduced cloud volume results from assuming less oil contributes to the external explosion from HFP oils). A yield factor of 50% is used for both. Impulse is calculated by assuming a triangular pulse with given duration and intensity.

Note that pressures given in Figure 14 are side-on pressures, and a reflection factor of 2.0 is applied to estimate the reflected impulses given as proposed RISP design loads.

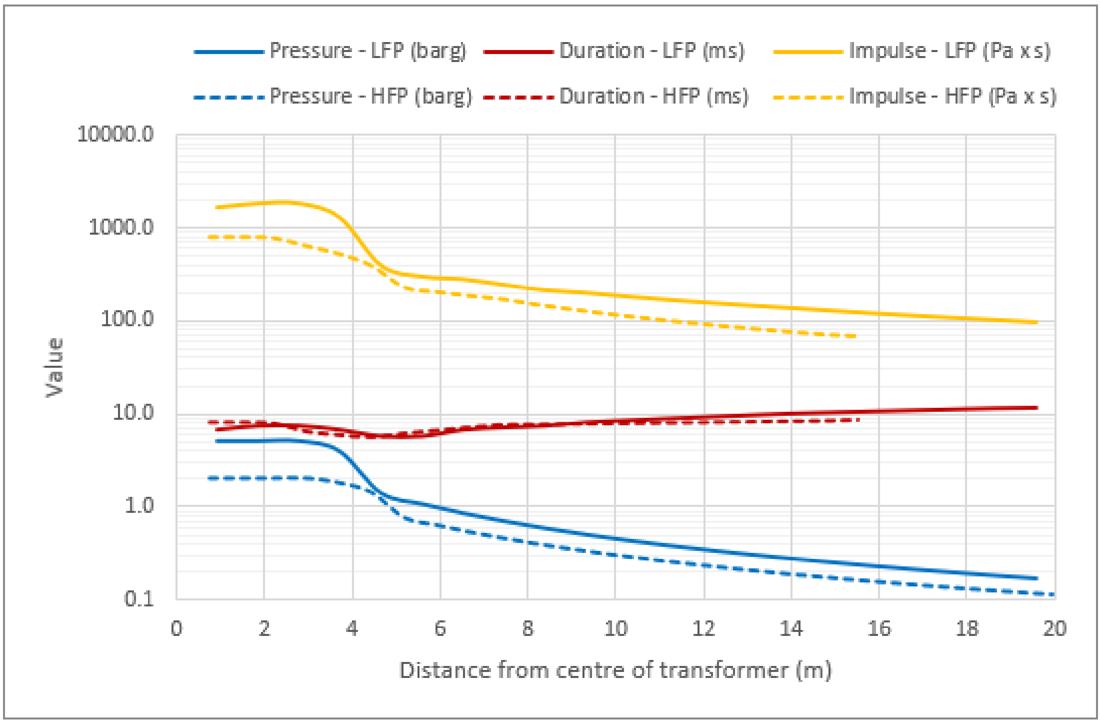

Figure 14 – Model explosion loads for transformer explosions (low and high flashpoint)

6.4.2 Dry transformers

If dry transformers are used, these can be regarded as electrical rooms with no significant risk associated with fires and explosions.

6.4.3 High flashpoint oils

When using transformers with ester or silicon-based cooling oils (flashpoint ~300 °C) the likelihood of strong explosions and sustained fires will be significantly reduced compared to use of traditional low flashpoint mineral oils (flashpoint ~130 °C).

The following is required for RISP projects:

Venting

The surroundings must be protected against events in the transformers by using transformer houses. The transformer houses must provide venting in case of rupture of the transformer tank to ensure that rupture products are directed in a safe direction. Preferred safe direction must be assessed in each case but is typically upwards or towards open sea.

Projectiles

While the intensities in case of a secondary explosion of transformers can be high (DDT may occur for the largest events) due to release of highly reactive products (hydrogen and acetylene), the volumes of the flammable clouds are moderate (30 m^3 is applied in the RISP model). Consequently, the explosion intensities will decay very rapidly with distance from the cloud. However, the high intensities may form projectiles that could potentially escalate the event.

All parts of the transformer and the transformer house should therefore be designed to not form projectiles for explosion impulses below 1000 (Pa)s.

Safe distances

Given the transformer is designed robust against projectiles (see above), a safety distance of 7 meters must be applied between the edge of the transformer house and any other hazardous equipment.

Transformers may be located closer than 7 meters to blast walls, if these walls are demonstrated to resist transformer explosions with local loads impulses of 1000 (Ps)s.

Blast protection

Equipment located at safe distances (7 meters from the centre of the transformer) must be able to resist explosion loads of resulting in an impulse of 350 (Pa)s. Note that the duration of the blast will be very short, in the order of 7.5 ms, and this indicates an intensity of 0.9 barg to result in the dimensioning impulse.

10 meters away from the centre of the transformer the design impulse is reduced to 225 (Pa)s.

Passive fire protection

By use of high flashpoint oils, it is unlikely that a fire will be sustained, and there is no need for additional fire protection of surrounding equipment.

Drain

By use of high flashpoint oils, it is unlikely that a fire will be sustained, and there is no need for efficient drain systems to limit the fire duration.

However, all oil that potentially could leak should be captured efficiently by bunding and draining to prevent the oil to flow places where it can represent an additional hazard.

6.4.4 Low flashpoint oils

When using transformers with mineral cooling oils (flashpoint ~130 °C) the likelihood of strong explosions and sustained fires will be significantly higher compared to use of high flashpoint oils (flashpoint ~300 °C).

The following is required for RISP projects:

Venting

The surroundings must be protected against events in the transformers by using transformer houses. The transformer houses must provide venting in case of rupture of the transformer tank to ensure that rupture products are directed in a safe direction. Preferred safe direction must be assessed in each case but is typically upwards or towards sea.

Projectiles

While the intensities in case of a secondary explosion of transformers can be fairly high (DDT may occur for the largest events) due to release of highly reactive products (hydrogen and acetylene), the volumes of the flammable clouds are moderate (50 m2 is mentioned in Ref. /8/).

Consequently, the explosion intensities will decay very rapidly with distance from the cloud. However, the high intensities may form projectiles that could potentially escalate the event.

All parts of the transformer and the transformer house should therefore be designed to not form projectiles for explosion impulses below 1700 (Pa)s.

Safe distances

Given the transformer is designed robust against projectiles (see above), a safety distance of 10 meters must be applied between the edge of the transformer house and any other hazardous equipment.

Transformers may be located closer than 10 meters to blast walls, if these walls are demonstrated to resist transformer explosions with local loads impulses of 1700 (Ps)s.

Blast protection

Equipment located at safe distances (10 meters from the centre of the transformer) must be able to resist explosion loads of resulting in an impulse of 370 (Pa)s. Note that the duration of the blast will be very short, in the order of 8.5 ms, and this indicates an intensity of 0.9 barg to result in the dimensioning impulse.

13 meters away from the centre of the transformer the design impulse is reduced to 300 (Pa)s.

Note that it is also possible to trade off distance with intensity and use the same safety distances as for high flashpoint oils, i.e. 7 meters from the centre of the transformer. At a 7 meters distance the design impulse for low flashpoint oils is 500 (Ps)s. Typical duration is 7 ms.

Passive fire protection

By use of low flashpoint oils, it is likely that a fire will be sustained, and additional fire protection of surrounding equipment if impairment of this equipment is considered hazardous.

Surrounding equipment must be designed to resist 250 kW/m2 for the full duration of the transformer fire, see paragraph on drain below.

Drain

By use of low flashpoint oils, it is likely that a fire will be sustained, and an efficient drain system is required to limit the fire size and duration.

All oil that potentially could leak should be captured efficiently by bunding and draining to prevent the oil to flow places where it can represent an additional hazard. The bunding must cover the main areas where oil leaks are likely to fall to the ground, but at the same time limit the likelihood for oil to form a large evaporation surface (which will lead to potential large fires and impairment of escape).

The drain capacity must be dimensioned to absorb both the oil spill and the fire water. The duration of the fire (and hence the required amount of passive fire protection of surroundings) will be depending on the drain capacity.

6.4.5 Loss of escape due to fires

Transformer fires and explosions are likely to remain local events.

However, if low flashpoint mineral oils are used as cooling medium, the potential for impairing escape due to smoke must be assessed in a special study.

7 Utility fires (MEG, TEG, MeOH, diesel)

7.1 Introduction

In this report the term "utility fires" covers any fires and explosions that are not caused by releases from the hydrocarbon systems on the platform.

The following utility systems are covered in this report:

- Monoethylene glycol (MEG) is an organic compound mainly used for antifreeze formulations and medium for convective heat transfer. It is an odourless, colourless, sweet-tasting, viscous liquid. Ethylene glycol is toxic and has a flashpoint of 111 °C, explosive limits between 3.2-15.2% (vol), and autoignition temperature of 410 °C.
- Triethylene glycol (TEG) or triglycol is a colourless, odourless and viscous liquid used by the oil and gas industry to "dehydrate" natural gas. It may also be used to dehydrate other gases, including CO2, H2S, and other oxygenated gases. It is necessary to dry natural gas to a certain point, as humidity in natural gas can cause pipelines to freeze and create other problems for end users of the natural gas. TEG is placed into contact with natural gas and strips the water out of the gas. TEG is heated to a high temperature and put through a condensing system, which removes the water as waste and reclaims the TEG for continuous reuse within the system. The waste TEG produced by this process has been found to contain enough benzene to be classified as hazardous waste (benzene concentration greater than 0.5 mg/L). TEG has a flashpoint of 165 °C and a boiling point of 285 °C. The explosive limits are between 0.9 – 9.2% (vol). Autoignition temperature is 370 °C.
- Methanol (MeOH) is mainly used for dehydration and de-icing in the oil and gas industry. Methanol is injected both continuously and intermittently. It prevents the formation of hydrates and lowers the freezing point of water percentages during the oil and gas transport. It is a light, volatile, colourless, flammable liquid with a distinctive odour similar to that of ethanol (drinking alcohol). Methanol has a flashpoint of 11-12 °C, a boiling point of 64 °C, and explosive limits between 3-36% (vol). Autoignition temperature is 385-470 °C. Net calorific value when burning is 23 MJ/kg (hydrocarbons has in the order of 40-50 MJ/kg).
- Diesel is used for miscellaneous energy production on an offshore facility (e.g. alternative fuel to main generators, main fuel for emergency generators and smaller pumps). Diesel systems includes storage, pumps, distribution lines and end users. Diesel has a flashpoint of 52-96 °C, and a boiling point between 250 °C and 350 °C. Explosive limits is between 0.6-7.5% (vol), and autoignition temperature of 210 °C. Net calorific value when burning is 42.7 MJ/kg (hydrocarbons has in the order of 40-50 MJ/kg).

7.2 Strength of knowledge

Both MEG, TEG, MeOH and diesel is extensively used by the petroleum industry, and the general strength of knowledge for these substances is regarded as being high.

However, even though that MeOH can generate violent explosions there is no industry practice for detailed explosion risk analyses of methanol leaks. The complex physics of methanol leaks, ignition and combustion is therefore discussed in more details than the other utility substances (MEG, TEG and diesel). The strength of knowledge for methanol explosions and fires is considered to be lower than for MEG, TEG and diesel, and this should be reflected in the design process when relevant.

Due to the reduced strength of knowledge for methanol fires and explosions (compared to MEG, TEG and diesel) some important safety elements of methanol releases are given below.

Physics of methanol leaks

Methanol has a flashpoint of 11-12 °C and can therefore form flammable atmosphere in normal temperatures (opposite to MEG, TEG and diesel).

Methanol leaks can have a leak frequency in the same order as traditional hydrocarbon leaks, and the leak frequency argument is therefore not appropriate to disregard methanol leaks as a contributor to explosion and fire risk.

However, it can be concluded that large flammable methanol vapor clouds is not a credible outcome of a high-pressure methanol leak (provided normal ventilation). This is because the high flashpoint (11 degrees centigrade) results in a very slow vapor driven evaporation, even for very small droplets. It can be expected that only large leaks (say liquid rate of 30 kg/s and above) has the potential to reach flammable concentrations, but this will take in the order of several hundred seconds. As a result, there will be plenty of time from gas detection to the gas reaches flammable concentrations, and the pumps will be tripped a long time before flammable concentrations can be reached.

The only contributor to methanol blasts is therefore expected to be "dry" aerosol leaks (i.e. a leak causing liquid aerosols but no or minimal vapor). A dry aerosol can explode violently only a few seconds after the leak has occurred. However, the ignition probability for dry aerosol leaks is significantly lower than for aerosol leaks with vapor (which is not likely for methanol) and pure gas leaks. In addition, to obtain a severe explosion, it is required that a relatively large part of the cloud (more than 5 meters) has a uniform distribution of small droplets (resulting in high flame acceleration and break-up of larger droplets, allowing the whole aerosol cloud to participate).

The likelihood of methanol leaks to result in severe explosions can therefore be expected to be low compared to the contribution from severe explosions from hydrocarbon leaks.

It should be noted that even though the burning energy of methanol is only half of the burning energy for methane, the heat capacity is correspondingly lower for methanol, and the adiabatic flame temperature is therefore the same for methane and methanol (only a shift in concentration), see Figure 15. This, combined with the increased flame velocity, is resulting in methanol explosions being more intense than process gas explosions, given the same size of the flammable gas cloud (however, the likelihood of accumulating large flammable gas clouds is significantly smaller from methanol leaks than process leaks).

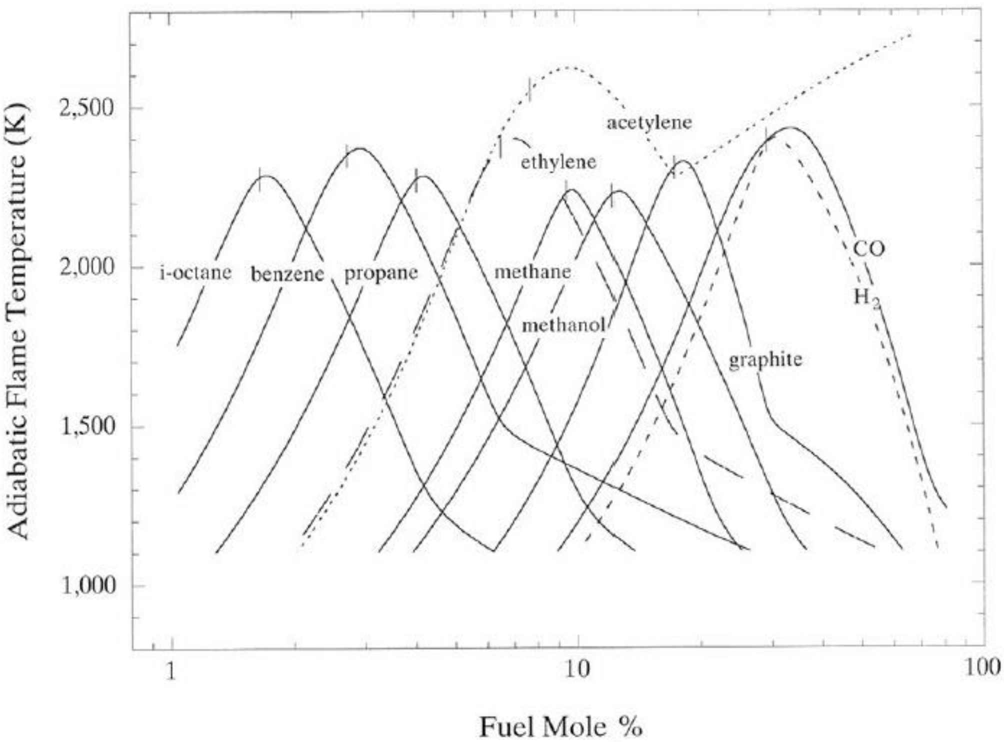

Figure 15 - Adiabatic flame temperature as a function of gas concentration (ref. /10/)

7.3 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for utility fires:

7.3.1 MEG

With a flashpoint of 111 °C MEG releases will not be able to sustain a fire in normal temperatures. In risk assessments MEG is therefore categorised as a non-hazardous liquid. The below design principles are considered sufficient to ensure robust MEG system designs.

Storage protected from use

Storage (day tanks etc.) must be located in a different location from the consumers. An event in the consumer area (which is often in an area with hydrocarbons) should not be able to spread to the MEG storage tanks.

Consumer area and storage area must be separated with fire rated walls and isolation valves.

NORSOK S-001 requires that valves located in, or are the nearest shutdown valve to, a hydrocarbon riser shall always be categorised as ESD valves. The following clarification is given on chemical injection:

- Chemical injection to subsea wells does not require ESD valves topside provided that two independent well barrier elements in accordance with NORSOK D-010 are installed;
- Chemical injection subsea at riser base, e.g. MEG and methanol for hydrate prevention during shutdown, shall be subject to special considerations and may require topside ESD or block valve (normally closed).

Pressure barrier towards HC process

If the end user operates under high pressure, there must be a barrier to prevent the high pressure to propagate to the storage tanks.

Bunding and drain

There shall be a bund and drain below the MEG storage tanks sized for full containment of the content. There shall be an overflow line to sea.

Leak detection

Leaks in the MEG system must be detected by appropriate detectors so that the system can be rapidly brought to a zero-overpressure condition. When the back pressure is removed, e.g. by stopping the pumps, there will be limited spray formation.

Fire fighting

When using MEG, one must provide efficient ways of fighting MEG fires.

Suitable extinguishing media:

- Fine water spray (or fog), dry agent (carbon dioxide, dry chemical powder), alcohol resistant foam

Unsuitable extinguishing media:

- Water jets

If a MEG line passes through a hydrocarbon area there is no need for additional firefighting systems than what is already defined as suitable for the hydrocarbon system.

7.3.2 TEG

With a flashpoint of 165 °C TEG releases will not be able to sustain a fire in normal temperatures. In risk assessments TEG is therefore categorised as a non-hazardous liquid. The below design principles are considered sufficient to ensure robust TEG system designs.

Storage protected from use

Storage (day tanks etc.) must be located in a different location from the consumers. An event in the consumer area (which is often in an area with hydrocarbons) should not be able to spread to the TEG storage tanks.

Consumer area and storage area must be separated with fire rated walls and isolation valves

NORSOK S-001 requires that valves located in, or are the nearest shutdown valve to, a hydrocarbon riser shall always be categorised as ESD valves. The following clarification is given on chemical injection:

- Chemical injection to subsea wells does not require ESD valves topside provided that two independent well barrier elements in accordance with NORSOK D-010 are installed;
- Chemical injection subsea at riser base, e.g. MEG and methanol for hydrate prevention during shutdown, shall be subject to special considerations and may require topside ESD or block valve (normally closed)

Pressure barrier towards HC process

If the end user operates under high pressure, there must be a barrier to prevent the high pressure to propagate to the storage tanks.

Bunding and drain

There shall be a bund and drain below the TEG storage tanks sized for full containment of the content. There shall be an overflow line to sea.

Leak detection

Leaks in the TEG system must be detected so that the system can be rapidly brought to a zero-overpressure condition. When the back pressure is removed, e.g. by stopping the pumps, there will be limited spray formation.

Fire fighting

When using TEG, one must provide efficient ways of fighting TEG fires.

Suitable extinguishing media:

- Fine water spray (or fog), dry agent (carbon dioxide, dry chemical powder), alcohol resistant foam

Unsuitable extinguishing media:

- Water jets

If a TEG line passes through a hydrocarbon area there is no need for additional firefighting systems than what is already defined as suitable for the hydrocarbon system.

Toxic effect

TEG may be heated to a high temperature and put through a condensing system, which removes the water as waste and reclaims the TEG for continuous reuse within the system. The waste TEG produced by this process has been found to contain enough benzene to be classified as hazardous waste (benzene concentration greater than 0.5 mg/L).

The benzene challenges must be addressed in the operation of the TEG system, and the design must facilitate operation with a limited exposure to benzene.

7.3.3 MeOH

With a flashpoint of 11 °C methanol releases will be able to sustain a fire in normal temperatures. In risk assessments methanol is therefore categorised as a hazardous liquid. However, the likelihood of ignition of methanol leaks is lower than for hydrocarbon leaks (see also Section 7.2), and the below design principles are considered sufficient to ensure robust system designs.

Ventilation

Since the flammability is driven by the slow vapor driven evaporation (see section 7.2), the methanol areas must have enough ventilation to prevent build-up of large flammable volumes. Normally ventilated offshore modules are considered sufficiently ventilated. Enclosed modules must have a reliable HVAC system providing at least 12 ACH.

Storage protected from use

Storage of methanol must be located in a different location from the consumers. An event in the consumer area (which is often in an area with hydrocarbons) should not be able to spread to the storage tanks.

Consumer area and storage area must be separated with fire rated walls and ESD valves.

NORSOK S-001 requires that valves located in, or are the nearest shutdown valve to, a hydrocarbon riser shall always be categorised as ESD valves. The following clarification is given on chemical injection:

- Chemical injection to subsea wells does not require ESD valves topside provided that two independent well barrier elements in accordance with NORSOK D-010 are installed;
- Chemical injection subsea at riser base, e.g. MEG and methanol for hydrate prevention during shutdown, shall be subject to special considerations and may require topside ESD or block valve (normally closed)

Pressure barrier towards HC process

If the end user operates under high pressure, there must be a barrier to prevent the high pressure to propagate to the storage tanks.

Bunding and drain

There shall be a bund and drain below the methanol storage tanks sized for full containment of the content. There shall be an overflow line to sea.

Leak detection

Leaks in the methanol system must be detected quickly so that the system can be rapidly brought to a zero-overpressure condition. When the backpressure is removed, e.g. by stopping the pumps, there will be limited spray formation.

Fire detection

Methanol fires burns with practically no visible flame or smoke production. The fire detector systems must be able to detect methanol fires.

Fire fighting

When using methanol, one must provide efficient ways of fighting methanol fires.

Suitable extinguishing media:

- Water should be used to cool storage tanks to prevent super-heated liquid inside tanks. Dry agent (carbon dioxide, dry chemical powder) and foam.

Unsuitable extinguishing media:

- Water monitors can be useless. Methanol is lighter than water and can spread if exposed to water jets.

If a methanol line passes through a hydrocarbon area there is no need for additional firefighting systems than what is already defined as suitable for the hydrocarbon system.

Safety showers and eye baths

Methanol is toxic in contact with human skin and therefore requires available safety showers and eye baths in the area (NORSOK S-001).

7.3.4 Diesel

With a flashpoint of 52-96 °C diesel releases will not be able to sustain a fire in normal temperatures. In risk assessments diesel is therefore categorised as a non-hazardous liquid. Diesel systems are also more separated from the hydrocarbon process systems than MEG, TEG and MeOH, and contamination of hydrocarbons in the diesel systems is therefore unlikely. However, diesel can be stored in large quantities, and has a net calorific burning value similar to hydrocarbons (see also section 7.1). Diesel will therefore require more attention than e.g. MEG and TEG in the design phase.

Two main safety principles are put forward for design of safe diesel systems:

1. Long duration diesel fires must be prevented
2. Fires in the diesel system should not escalate to the process system or wells, or vice versa.

The below design principles are considered sufficient to ensure robust diesel system designs.

Storage protected from use

Storage (day tanks etc.) must be located in a different location from the consumers. An event in the consumer area (which is often in an area with hydrocarbons) should not be able to spread to the diesel storage tanks.

If diesel storage is not located in a different main area than the process equipment, the diesel storage area must be protected to resist the worst credible process fire (WCPF).

Essential equipment

If the diesel system is needed as a part of the essential power generation it must be designed to maintain its operability for drilling and production in the case of single gas alarm.

Prevention of long exposure time for fires

The diesel storage system must be designed in a way that no leak points with long leak duration can directly expose the storage tank.

Bunding and drain

There shall be a bund and drain below the diesel storage tanks sized for full containment of the content. There shall be an overflow line to sea.

Leak detection

Leaks in the diesel system must be detected so that the system can be rapidly brought to a zero-overpressure condition. When the back pressure is removed, e.g. by stopping the pumps, there will be limited spray formation.

If heated above the flashpoint the diesel fumes are heavier than air and can migrate downwards, e.g. through the drain system, and ignite remotely.

Fire fighting

When using diesel, one must provide efficient ways of fighting diesel fires.

Suitable extinguishing media:

- Fine water spray (or fog), dry agent (carbon dioxide, dry chemical powder), alcohol resistant foam

Unsuitable extinguishing media:

- Water jets

If a diesel line passes through a hydrocarbon area there is no need for additional firefighting systems than what is already defined as suitable for the hydrocarbon system.

7.4 Proposed RISP method

Design against MEG, TEG and diesel fires are considered to be sufficiently covered by standards and codes, and no new RISP model is therefore necessary as long as the design can be deemed to be within the validity envelope for RISP outlined in 7.3.

7.4.1 MeOH

There is a somewhat reduced strength of knowledge linked to methanol explosion risk. This uncertainty must be addressed in the design of explosion barriers.

For hydrocarbon-containing areas one can expect the additional explosion risk from high-pressure methanol to be low compared to the intrinsic robustness of the RISP explosion model. No additional margin to the RISP explosion design loads is therefore needed.

For non-hydrocarbon containing areas with high pressure methanol, the minimum robustness against explosions is proposed to be 0.1 barg with a duration of 100 ms, given that the design can be deemed to be within the RISP validity envelope outlined in Section 7.3.3.

No additional fire protection is required against MeOH fires when the design is deemed within the RISP validity envelope outlined Section 7.3.3.

8 Helicopter accidents

8.1 Introduction

Primary personnel transport between shore and offshore platforms is normally done by helicopter.

A helicopter flight has three phases: take-off, cruising and landing. The probability of an accident during the cruising phase is dependent on the duration of the flight, while the probability of an accident during take-off and landing is scalable with the number of take-offs and landings.

Similarly, the consequences of a helicopter accident during the cruising phase would expose the personnel under transport, while the consequence of an accident during take-off and landing can expose personnel on the helideck and/or the facility.

8.2 Strength of knowledge

Assessment of the risk associated with helicopter accidents has been performed over many years and is well understood in the petroleum industry. The RISP method for helicopter accidents does therefore not require additional conservatism due to lack of knowledge about the phenomenon.

The historical data indicate that 30 % of the fatalities is during take-off/landing (TO/L), and 70 % of the fatalities is during the cruising phase for all offshore regions. This is mainly based on data from the SINTEF helicopter report, ref. /11/.

Helicopter accidents are in very little degree linked to the operation of offshore facilities; the risk is mostly related to travelling to and from the platform.

8.2.1 Risk to people on the facility

Helicopter accidents may, in addition to harming and possibly killing personnel onboard the helicopter, be of serious consequence to the installation/location which is impaired. It can be assumed that accidents hitting the landing area/helideck normally only will be of danger to the personnel onboard the helicopter, or platform helideck-personnel. The helideck/landing area must be able to withstand a helicopter impact as such loads in general are a part of the design accidental loads for the platform/installation.

A helicopter crash during take-off/landing is assumed to result in one of the following scenarios:

- Crash on helideck, not harming other areas on the installation
- Crash into sea, not harming the installation
- Crash into platform (outside helideck) causing damage to the installation and personnel.

Evacuation by lifeboats is required in case of major accidents with potential to threaten the structural integrity. A helicopter crash is not considered being of a magnitude that evacuation of platform is required. Hence, loss of lifeboats due to a helicopter accident is considered unlikely to contribute to additional risk to personnel.

8.2.2 Risk to personnel on helipad

The risk to the personnel located on the helipad will be higher than the average values for the platform because they are more exposed to helicopter accidents.

One heliguard and fire fighters (usually three) will be located in a waiting area close to helideck during landing and take-off on the platform. These will be exposed to all helicopter crashes except for crashes into the sea. Luggage personnel shall be located under the helideck and are hence not directly exposed to helicopter crashes.

The heliguard and fire fighters are not expected to be located in the vicinity of one another and hence no more than one fatality is expected in case of an accident where the helicopter crashes with the helipad.

8.2.3 Risk for personnel during helicopter transport

Operating personnel are transferred to the facility by helicopter directly from shore or between other offshore facilities. Helicopter risk (including cruising and take-off/landing) can typically represent in the order of 1/3 of the personnel risk on a traditional offshore facility.

However, as long as best industry practice is used for helicopter transport, see section 8.3, the personnel risk associated with helicopter accidents can be regarded acceptable.

8.3 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for helicopter accidents:

8.3.1 Regulatory requirements

For the helicopter assessment to be considered within the RISP validity envelope it must as a minimum document compliance with the following regulatory and standard requirements:

- Luftfartstilsynet: Forskrift om luftfart med helikopter – bruk av offshore helidekk
- Norsk Olje & Gass: 095– Norsk olje og gass Anbefalte retningslinjer for begrensning i flyging med helikopter på norsk kontinentalsokkel (NOROG 095)
- NORSOK S-001
- NORSOK C-004 (Helicopter deck on offshore installations).

For compliance with NORSOK S-001 the following must be addressed:

- Section 6.4.1.1 Exposure of hot air on helideck
- Section 12.4.3 Flare, vent and knock out drum
- Section 17.4.6 Ventilation inlet and outlets
- Section 18.4.4 External emergency communication
- Section 19.4.4 Emergency power consumers
- Section 19.4.5 Emergency and escape lighting
- Section 21.4.2 Fire water supply system
- Section 21.4.9 Helideck firefighting system
- Section 22.4.2 Evacuation system.

8.3.2 Layout

In the design phase the most important decision is to locate the helideck at a safe and operable location.

In addition to minimising interference with operation of the facility (exhaust, flaring and venting) the location of the helideck must meet the requirement from NORSOK S-001 that the layout must facilitate effective emergency response and provide for adequate arrangements for escape and evacuation.

Operability must also be discussed and facilitated. Special challenges must be addressed, e.g. in the case of weather vaning facilities the landing approach may be affected by the lighting conditions in unfavourable direction relative to the wind direction (landing in front of facility with wind from the front and process lighting from aft).

8.3.3 Number of flights

The personnel risk is proportional with the number of flights per year, but the risk is not likely to approach unacceptable limits for any number of flights per year. However, if more than 720 flights per year is required to operate the facility, special helicopter risk mitigation studies should be performed.

8.3.4 Helicopter type and capacity

Helicopter size and type is not considered a limitation for RISP as long as they meet all regulatory requirements for helicopter flights to offshore facilities.

Type and capacity must be able to meet the emergency preparedness strategy (i.e. personnel in sea after a helicopter crash shall be rescued within 120 minutes, NOROG 095)

8.3.5 Flight time per trip

The risk will increase with longer flights, but the increase in risk is marginal compared to the overall risk levels and traditional acceptance criterion for personnel risk.

In a RISP context it is therefore not restrictions on flight time per say, but one need to ensure that all regulatory requirements and emergency preparedness requirements can be met with the field flight time.

8.3.6 Number of transit stops

If the flight has transit stops on the way it will add number of landings and take-off per travel, and the overall risk will increase slightly.

However, in a RISP context there are no risk-based limitations to the number of transit stops that can be allowed before the risk is unacceptable. Nevertheless, transit stops should be limited to a minimum.

8.3.7 Personnel located in vicinity of the helideck

Personnel onboard the facility with tasks during helicopter take-off and landing is exposed to a higher risk than other personnel on the platform.

The design of the helideck area must ensure that no personnel without a task related to helicopter landing and take-off are positioned near the helideck during landing and take-off.

Personnel located in the vicinity of the helideck during take-off and landing should be limited to one heli-guard, three fire fighters and two luggage assistants. The luggage assistants should be located in an area where they will be safe in case of a helicopter crash (e.g. under the helideck).

8.3.8 Location of hazardous material

No large quantities of hazardous material should be located in the vicinity of the helideck. Jet fuel tanks and diesel tanks should be placed at a sufficiently safe distance from the helideck, at least 10 meters.

8.3.9 Safety standard

All helicopter flights are assumed to be operated according to the same safety standard as used in the North Sea.

8.4 Proposed RISP method

8.4.1 Design loads

No RISP models are deemed necessary to provide design loads for safe design of helidecks.

Following existing regulations and standards, helidecks will be designed to withstand helicopter crashes. The other platform facilities (LQ, lifeboats and hydrocarbon systems) are normally not dimensioned for helicopter crashes.

Following the guidance given for RISP validity envelope assessments as part of the HAZAN (section 8.3) is considered sufficient to provide a safe and robust design of the helideck.

8.4.2 Helicopter regularity

According to S-001 the regularity of helicopter landing must be assessed with special studies. The following must be documented:

- Hot air exposure of the area above the helideck according to NORSOK C-004 and CAP-437 (ref. /12/). Sources can be exhaust releases or vent releases.
- Helicopter turbulence according to CAP-437. This study will document that the turbulence production from surrounding geometry is within acceptable limits.

9 Extreme weather

An extreme weather failure accident is when an installation loses its ability to support its topside, or ability to float or keep position, due to environmental loads. The failure is hence the cause of the accident rather than the consequence.

9.1 Strength of knowledge

The early phase design phase will normally have little uncertainty linked to extreme weather. The design process is governed by good industry practice, design standards and regulatory requirements (PSA and NMA).

Design against extreme weather is considered to be a type "A" risk in the risk related decision-making framework defined by ISO 17776 (see also WG1 report Figure 2) which is sufficiently covered by using systems and solutions indicated by existing requirements in standards and established good practice.

A new RISP method on this topic is therefore not required. However, NORSOK Z-013, Annex B (B.3) states that when assessing loss of main safety functions, one should amongst other things take into consideration extreme environmental loads such as wind, wave and current. Following the intentions of the Facility regulations §11 one must ensure that loss of integrity of elements being part of a main safety function should survive extreme environmental loads with frequency above 1E-04 times per year.

In a frequency study for Johan Sverdrup (ref. /13/), historical incidents with loss of installation due to environmental loads were investigated. The incidents were split into the following categories:

- Hurricane (14, all in GoM)
- Heavy weather (8, in GoM and outside North Sea)
- Tropical storm/typhoon/cyclone (4, in GoM and outside the North Sea)
- Volcanic eruption (1, in the Caspian Sea)

The frequency study estimated a worldwide frequency for loss of installation due to environmental loads for fixed installations of 3.0E-05 per year (based on the time span from 1980 to 2013). However, wind, wave and geological conditions are specific for each geographical region, and accidents outside the North Sea are therefore not directly applicable for NCS facilities. The frequency study did not uncover any accidents due to environmental loads that have led to loss of facility in the North Sea. However, this does not mean that there is no environmental risk in the North Sea.

Hurricanes, tropical storms and volcanic eruptions are not a threat in the North Sea. Of the 8 heavy weather accidents 2 occurred on fixed installations. The frequency of loss of installations due to heavy weather when only considering fixed installations worldwide is 9.9E-06 per year. Where there have been no failures in the observed period, the above approach may still be used, assuming a failure was about to occur at the end of the observed period. A slightly less conservative (and more intuitively reasonable) estimate of the underlying frequency is given by the 50% confidence limit on the true mean of a Poisson distribution when no failures have been observed (also equal to the 50% point on a chi-square distribution with 1 degree of freedom).

By this approach the frequency in the North Sea is estimated to 6.6E-05 per year.

By combining the world statistics of loss of fixed installations due to extreme weather and the fact that is has been no loss of fixed platform in the North Sea due to extreme weather, but with much fewer installation years, a geometric middle of the worldwide frequency and the estimated North Sea frequency can be applied as an estimate of the North Sea likelihood of main load bearing capacity due to extreme weather.

This results in a value of 2.6E-05 for loss of main load bearing due to extreme weather in the North Sea. This is in alignment with an OGP report (ref. /14/) where the average frequency for loss of integrity in the order of 5E-5 times per year.

For floating facilities, the mooring system must be designed for the combination of wind, wave and current conditions that may arise and induce high loads on the mooring system. Requirements to permanent mooring systems according to NMD regulations (anchoring regulations 09) and ISO 19901 is that the system shall be designed to withstand 2 broken mooring lines with 100-year weather conditions. Operation can continue with one line out of service, using the 1-year weather event as a limitation.

For scenarios that give loss of facility, the number of fatalities will depend on whether there has been a pre-warning or not. In case of a pre-warning, most of the personnel has evacuated prior to the time of the event. As gross error accidents represent scenarios caused by errors in design, systems etc., it is not expected that pre-warnings will be given. Based on experience there are usually some survivors even in accidents of total facility collapse, and therefore a fatality rate of 75 % can be applied.

A fatality rate of 100 % is often assumed for evacuation with Davit launched lifeboats during heavy weather. This is a conservative estimate to reflect the reduced performance of the lifeboats during heavy weather, especially when launched from an upwind direction. The chances for successful rescue will also be reduced during heavy weather.

9.2 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for extreme weather:

9.2.1 Regulatory requirements

The design of main load bearing, floating and position keeping must be designed according to good industry practice and relevant standards.

9.2.2 Concept

The chosen concept for main load bearing, floating and position keeping must be standard and previously applied in the North Sea.

9.2.3 Wind and currents

It is assumed that for the North Sea, the frequency for impairment of main safety functions due to extreme wind and currents is judged negligible compared to loads from waves.

However, floating facilities with a high degree of winterisation may require special studies on stability (due to winterisation is capturing wind loads). These designs are considered to be outside the RISP validity envelope.

9.2.4 Waves

Impairment of main safety functions due to extreme weather can be assumed to be dominated by extreme waves. A wave return frequency of 1E-04 must be used as design case.

When applying standards to design against wave loads one must consider whether subsidence could cause problems with the air gap throughout the installation lifetime and/or related to sudden movements of the formation. Subsidence up to maximum 1 m shall be added to initial water depth for gravity-based facilities. Additional creep must be measured and assessed during operation.

9.3 Proposed RISP method

Design against extreme weather is considered to be sufficiently covered by standard assessments according to NORSOK N-003, see also section 9.2.1, and no new RISP model is therefore deemed necessary.

10 Earthquakes

10.1 Strength of knowledge

Ground movements such as earthquakes have the potential to damage a gravity-based installation (i.e. floaters are usually not vulnerable to earthquakes). The magnitude of earthquake that would damage or cause the collapse of offshore platforms is not known with any precision due to lack of experience.

NORSOK Z-013, Chapter 5, Section 5.5.4, mentions earthquake as a possible accident that could have an external impact on an offshore installation and should be assessed in a risk analysis if relevant.

From the 341 known "total loss" accidents around the world, one accident has been reported as a caused by an earthquake. The accident occurred in 1994 in South America, Venezuela, on a drilling jack-up. The jack-up was severely damaged and was claimed "total loss" only from an insurance point of view. Hence, the accident is not deemed relevant for a frequency study.

It is a challenge to estimate the frequency when there are zero historical accidents. If it is assumed that the recorded accident of loss due to earthquake can be included in this frequency evaluation, it corresponds to a frequency of 3.0E-06 per year for all types of installations worldwide, and a frequency of 3.5E-06 per year for all fixed installations worldwide. It can be argued that this is not applicable for the North Sea facilities as earthquake risk is very geographically dependent. Nevertheless, ground movements must be taken into account during design so that the installation can withstand the 1.0E-04 yearly ground movement (which follows the requirement from Facility regulations §11).

For the North Sea the same methodology as for heavy weather (section 9.1) can be applied. It is assumed that 0.7 incidents have occurred (that the system was 70 % of the way to its first failure at the end of observed period). This assumption results in a frequency of 6.6E-05 per year. The frequency is estimated by dividing 0.7 on total number of platform years for fixed installations in the North Sea. The North Sea impairment frequency due to earthquakes is assessed to be less than 1E-05 times per year.

NORSOK N-003 states that: "Earthquake design includes ULS (strength) check of components based on earthquakes with an annual probability of occurrence of 1.0E-02 and appropriate action and material factors; as well as an ALS check of the overall structure to prevent its collapse during earthquakes with an annual probability of exceedance of 1.0E-04 with appropriate action and material factors, given in NORSOK N-001.

Normally the ALS requirement will be governing, implying that earthquakes with an annual probability of exceedance of 1.0E-02 can be disregarded."

Following NORSOK N-003, the annual probability of loss of the main bearing structure due to earthquake should be less than 1.0E-04 per year. Based on the above frequency estimation, the expected average frequency in the North Sea is well below this (less than 1E-05 per year).

For scenarios that give loss of facility, the number of fatalities will depend on whether there has been a pre-warning or not. In case of a pre-warning, most of the personnel has evacuated prior to the time of the event. As gross error accidents represent scenarios caused by errors in design, systems etc., it is not expected that pre-warnings will be given. Based on experience there are usually some survivors even in accidents of total facility collapse, and therefore a fatality rate of 75 % can be applied.

10.2 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for earthquakes:

10.2.1 Regulatory requirements

The design of main load bearing shall be based on regulatory requirements (NORSOK N-003) and managed according to good industry practice.

10.2.2 Project management

The management of the development project must be according to good industry practice.

10.3 Proposed RISP method

Design against earthquakes loads are considered to be sufficiently covered by standard assessments according to NORSOK N-003, see also section 10.1, and no new RISP model is therefore deemed necessary.

11 Engine compartment fires

11.1 Strength of knowledge

The early phase design phase will normally have little uncertainty linked to engine compartment fires. The design process is governed by good industry practice, design standards and regulatory requirements (PSA and NMA).

Design of engine compartment rooms is considered to be a type “A” risk in the risk related decision-making framework defined by ISO 17776 (see also WG1 report Figure 2) which is sufficiently covered by using systems and solutions indicated by existing requirements in standards and established good practice.

A new RISP method on this topic is therefore not required.

However, safety critical engine rooms need special attention and follow-up during the early development projects to facilitate the required safety systems. NORSOK S-001 describes requirements for safety critical engine rooms, and these requirements are also listed as being the validity envelope for RISP.

11.2 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for engine compartment fires:

NORSOK S-001(section 21.4.3): In case of gas detection in air inlet to the fire water pump engine room, the ventilation shall be automatically shut down, dampers closed, and the cooling air shall be taken from the engine room itself. Cooling of the fire water pump engine room shall be by an air/fire water-cooling unit powered directly from the fire water pump engine. The combustion air inlet shall be separated from the ventilation air inlet of the room.

The combustion air inlet shall be equipped with a flame arrestor and an overspeed protection system. Automatic stop of FW pump engine driven FW pumps shall only be permitted due to over-speeding. Gas detectors in combustion air inlet are not required due to installation of flam arrestors.

NORSOK S-001(section 21.4.10.1): Water mist system is the preferred extinguishing system for enclosed compartments such as diesel engine rooms.

11.3 Proposed RISP method

Design against engine fires are considered to be sufficiently covered by standard assessments according to NORSOK S-001, see also section 11.2, and no new RISP model is therefore deemed necessary.

12 Stability and ballasting failures

12.1 Introduction

Requirements to design of maritime systems includes:

- The framework regulations § 3 - Application of maritime regulations in the offshore petroleum activities
- The management regulations § 17 - Risk analyses and emergency preparedness assessments. (When performing risk analyses of maritime systems and of stability, the Norwegian Maritime Authority's Regulations relating to risk analyses for mobile facilities (in Norwegian only) should be used in addition.)
- Facilities regulations § 11 – Loads/actions, load/action effects and resistance
- Facilities regulations § 39 – Ballast systems
- Facilities regulations § 39 – Open drain
- Facilities regulations § 56 – Load-bearing structures and maritime systems
- Facilities regulations § 62 – Stability
- Facilities regulations § 63 – Anchoring and positioning
- Activities regulation § 50 - Special requirements for technical condition monitoring of structures, maritime systems and pipeline systems
- Activities regulation § 90 – Positioning
- Norwegian Maritime Authority's Regulations relating to risk analyses for mobile facilities (in Norwegian only)
- Norwegian Maritime Authority's Regulations relating to ballast systems on mobile facilities (in Norwegian only)
- Section 8 up to and including Section 51 of the Norwegian Maritime Authority ' s Regulations relating to stability, watertight subdivision and watertight/weathertight closing means on mobile facilities (in Norwegian only)
- Section 6 up to and including Section 17 of the Norwegian Maritime Authority's Regulations relating to positioning and anchoring systems on mobile facilities (the anchoring regulations 09) (in Norwegian only)
- Norwegian Maritime Authority's Regulations relating to construction of mobile facilities

12.2 Context

- The potential for MAH are related to:
  - Maloperation or technical failure of ballasting system or cargo systems
  - Anchor system failures
  - Structural failures, local explosions or collision impact causing compartment filling and accidental heel.
- The design is primarily governed by regulations and standards. Key design standards include:
  - Norsok S-001 – Chapter 9 and 24
  - Norsok N-001 – Chapter 7.10, 7.11 and 7.12.
  - Norsok N-003
  - Norsok N-004
  - Norsok P-002 Chapter 28.
  - DNVGL – OS – D101
  - DNVGL-OS-C104

- Learnings from experienced accidents (such as the P36 accident in 2001) are assumed collected and implemented in design standards and good practises.
- Decision support needed in the early phase of a development project based on a floating installation includes:
  - Definition of design accidental heel angels
  - Definition of weather criteria to combine with the accidental heel conditions
  - Requirements to systems which shall be designed to survive or operate in accidental heel conditions
  - Define anchor failure cases and any impact on the concept
  - If emergency relocation is a premise for the concept, several special aspects needs to be considered (outside RISP)

12.3 HAZAN

- The Guide words presented in Z-013, Annex C can be used as a starting point

12.4 RISP Method for DeAL/DeAE

- Validity envelope:
  - Fixed floaters – Semi submersible and FPSO: inside validity envelope
  - Installations with emergency disconnection systems: outside validity envelope
  - Safety barriers including evacuation systems to be designed for DeAE's
- Anchor line failure is a DeAE
  - Single-line failure on mobile units
  - Two-line failures combined in the most unfavourable way on fixed installations
- Accidental heel is a DeAE
  - No design case shall give more than 17 degr. static heel
  - Static heel to be combined with 1year weather condition giving dynamic roll and pitch as calculated for the installation

12.5 Application of method in design

- No specific input

13 Structural failures and gross errors

This chapter addresses structural failures that are not caused by overload, i.e. accidents where structural failure is the cause rather than a consequence. Examples of causes are:

- Design faults
- Corrosion
- Fatigue
- Foundation failure.

These failures are often referred to as "gross errors" and are further discussed below. Gross errors may cause platform collapse even though the loads at the time of the event are within the design limits of the platform.

13.1 Strength of knowledge

Data and knowledge with regards to structural failure, including gross errors, are limited. However, there is an increasing focus on major accidents classified as "gross errors" leading to loss of structural integrity. In a paper published by Inge Lotsberg et al (Ref. /15/), gross error is considered to be the most difficult to handle as this type of risk cannot be alleviated by additional safety coefficients. In the same paper, the authors listed reasons for why gross errors can occur:

Lack of human understanding of the methodology used for design

- Negligence of information
- Mistakes such as calculation errors (this can be input errors to the analysis programs used and errors in computer software that are used for design)
- Lack of self-check and verification
- Lack of follow-up of material data testing, welding procedures, inspection during fabrication, etc.
- Mistakes resulting from lack of communication or misunderstanding in communication
- Lack of training of personnel on-board the platform that may lead to mal operation of ballasting systems
- Errors in systems used for operation of the platform

The risk imposed from inherent failure and gross errors related to structural elements is fairly new in connection with risk analysis of offshore installations. Requirements for project management, technical skills of personnel involved in design and construction as well as procedures for quality control are required to achieve success in a complex development project.

Manufacturing defects in mooring lines and other equipment is a possible cause for failure. In 2012 the Transocean Spitsbergen drilling rig lost a mooring line where false anchor chain material certificates were identified as the root cause. This is a type of weakness that will be difficult to discover after the system has been installed. If a mooring line for some reason is out of service, this type of failure may lead to multiple mooring line failure if the system is further stressed in bad weather. This scenario emphasizes the need for appropriate follow up in terms of QA procedures, testing and approval. Failure due to poor construction, false material certificates etc. is very difficult to quantify and is typically included as part of a "gross error" analysis.

As long as the facility is designed according to all relevant codes, and the management of the development project is according to industry standard, the risk associated with gross errors can be expected to be low.

Lotsberg et al (Ref. /15/) proposed a weighted combined grade whereby the risk influencing parameters (RIP) contributing to gross errors can be graded. Grade 5 is the highest possible grade that can be achieved during the assessment of RIPs. A Grade 5 for all RIPs, according to the paper, will result in a platform that is close to that of "perfect" in terms of probability of gross errors. For the purpose of impairment frequency assessment, a value of 1.0E-05 per year can be proposed to correspond to Grade 5. The cause of gross error may occur in engineering, fabrication, installation or in operational phase, but the frequency reflects the risk of failure due to gross error materialized in operational phase.

For scenarios that give loss of facility, the number of fatalities will depend on whether there has been a pre-warning or not. In case of a pre-warning, most of the personnel has evacuated prior to the time of the event. As gross error accidents represent scenarios caused by errors in design, systems etc., it is not expected that pre-warnings will be given. Based on experience there are usually some survivors even in accidents of total facility collapse, and therefore a fatality rate of 75 % can be applied.

13.2 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG1 report Section 2.2). During the HAZAN the following should be assessed for gross errors:

13.2.1 Regulatory requirements

The design of main load bearing shall be based on industry codes and regulatory requirements

13.2.2 Project management

The management of the development project must be according to good industry practice.

14 Summary of key results

Key results from the evaluation made for the various Major Accident Hazards (MAH) considered in Chapter 0 to 0, are summarised in Table 7 Further details can be found in the respective Chapters.

Table 7 – Summary of key results for evaluated MAH.

Ref. (Chapter)	**Hazard**	**Key RISP requirements**	**Validity envelope / premises**	**Comments**
3	All passing vessels	Not a DeAE	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) Location away from traffic separation scheme (TSS), at least half of the width of TSS.	Important to do a Vessel traffic survey of AIS data and assess degree of operational barriers in place.
3	All visiting and attending vessels – on arrival	Not a DeAE	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure	
3	All visiting and attending vessels in waiting position	Not a DeAE	Selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) Weather conditions - vessel is not exposing any nearby installations in case of a black out scenario. Drive-off event fully recoverable	
3	Supply-vessel – Manoeuvring from standby position to operating position W2W vessel	Head-on collision with larges vessel with impact speed of 4 m/s.	G-OMO-procedure Waiting position downwind facility	Consider impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact, dissipation of energy between installation and vessel.
3	Supply-vessel – Operating position W2W vessel	The corresponding speed in head-on collisions with largest vessel shall be 0.5 m/s and 3.0 m/s for ULS and ALS checks respectively.	G-OMO-procedure Loading position down-wind	
3	Shuttle tanker vessel – Manoeuvring from standby position to operating position	Minimum collision energy of 100 MJ for collision scenario involving shuttle	G-OMO-procedure Weather vaning FPSO 80-100 m offloading distance	

Ref. (Chapter)	Hazard	Key RISP requirements	Validity envelope / premises	Comments
	and operating position	tanker hitting the stern of a FPSO.	DP-operation	
3	Shuttle tanker Conventional (No DP) – visiting	Outside RISP		
3	Standby vessel	Not a DeAE		In downwind position
3	Flotel	Outside RISP		Use JIP model
4	Protection of topside from dropped and swinging objects	Topside structures must be designed to withstand drops with all planned weights and heights	-	RISP slightly more robust than traditional approach (allowing for some damage if the resulting consequences does not lead to impairment of main safety functions above acceptance criterion
4	Protection of seabed arrangements	Pipelines must survive 95% of all drops over sea	Objects lifted are within categories defined by DNV-RP-107	RISP model gives more robust protection than traditional models near the facility where the consequences of a seabed release is more severe
4	Crane boom fall	Not a DeAE	Crane design is based on industry standards, no additional RISP requirements needed.	Crane boom fall is defined as part of ALARP process. Guidance is given on protection energies and layout
5	Toxic and suffocating loads	DeAE	Requirements to design is according to NORSOK S-001, no need for additional RISP guidance	
6	High voltage transformer fires and explosion	Local event with limited potential for escalation, but happens so often that it needs to be considered a DeAE	Design of transformers is according to industry standards, RISP guidance is given to ensure robustness of nearby structures and equipment	Guidance is given on safety barriers, layout and design capacity for nearby structures
7	MEG fires	Sufficiently covered by standards and codes – no additional RISP model required	Guidance is given on required safety barriers	
7	TEG fires	Sufficiently covered by standards and codes – no additional RISP model required	Guidance is given on required safety barriers	

Ref. (Chapter)	Hazard	Key RISP requirements	Validity envelope / premises	Comments
7	Methanol explosion in process area.	Not DeAE	Sufficient ventilation and detection system required	Discussion of risk drivers associated with Methanol leaks given. Efficient barriers presented
7	Diesel fires	Sufficiently covered by standards and codes, no additional RISP model required	Guidance is given on required safety barriers	
8	Helicopter accidents	No DeAE	Special considerations must be made if helicopter traffic is high (above 720 flights per year)	Design sufficiently covered by standards and codes, no additional RISP model required
9	Extreme weather	Sufficiently covered by standards and codes, no additional RISP model required		
10	Earthquakes	Sufficiently covered by standards and codes, no additional RISP model required		
11	Engine compartment fires	Sufficiently covered by standards and codes, no additional RISP model required		
12	Anchor line failure	Anchor line failure is a DeAE: - Single-line failure on mobile units - Two-line failures on fixed installations	Design according to regulations and standards	Consequences of DeAE needs to be assessed and survivability requirements for safety systems to be defined.
12	Accidental heel	Accidental heel is a DeAE on floaters. Credible heel scenarios shall not cause a static heel exceeding 17 degrees. Static heel to be combined with 1-year weather condition giving dynamic roll and pitch as calculated for the installation.	Design according to regulations and standards	Consequences of DeAE needs to be assessed and survivability requirements for safety systems to be defined.
13	Structural failure and gross error	Sufficiently covered by standards and codes, no additional RISP model required		Strength of knowledge is good. Critical failures are seen to be linked to human errors and poor project management

15 Recommendations for further work

A new methodology for replacing traditional quantitative risk analysis with simplified experience-based methods for improved decision support in development projects has been outlined and substantiated in this report. Based on the work in WG 4, the following recommendation for further work is given:

- For collision risk modelling there may be a wide variation in impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact. This will affect dissipation of energy between installation and vessel. In the RISP models, the impact scenarios are not modelled in detail, hence the design loads may be high and give conservative results. It is recommended to further develop the collision impact model in RISP reflecting the development in the industry.

16 References

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

Main report Workgroup 5 - Risk management and regulatory framework including standards

Report for:
RISP Participants, att: Equinor

Report no: 0647/R4 Rev: Final

Date: 6 December 2019

Summary

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

Main report Workgroup 5 - Risk management and regulatory framework including standards

Security classification of this report: Distribute only after client's acceptance

Report no:	**Revision:**	**Report date:**
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Prepared by:	**Reviewed by:**	**Approved by:**
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Revision	Date	Description/changes	Changes made by
Final	6 December 2019	Comments from RISP participants implemented	Workgroup 5
Draft	1st November, 2019	Issued to RISP participants for comments	

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1. List of abbreviations and definitions

1.1 Abbreviations

AIS	Automatic Identification System
ALARP	As Low As Reasonably Practicable
ALS	Accidental Limit State
BAT	Best Available Techniques
CAD	Computer-Aided Design
CAPEX	Capital Expenditure
CCR	Central Control Room
DDT	Deflagration to Detonation Transition
DeAE	Design Accidental Event(s)
DeAL	Design Accidental Load(s)
DiAL	Dimensioning Accidental Load(s)
DP	Dynamic Positioning
DP2	Dynamic Positioning – Redundancy Class 2
EERS	Escape Evacuation and Rescue Strategy
ESD	Emergency Shutdown
FEED	Front End Engineering and Design
FES	Fire and Explosion Strategy
FPSO	Floating, Production, Storage and Offloading
GBS	Gravity Based Structure
G-OMO	Guidelines for Offshore Marine Operations
HAZAN	Hazard identification and analysis
HAZID	Hazard identification
HC	Hydrocarbon
HSE	Health, Safety and Environment
ISD	Inherent Safe Design
JIP	Joint Industry Project (In this case the RISP project)
LD	Lethal Dose
LEL	Lower Explosion Limit
MAH	Major Accident Hazard
MEG	Mono Ethylene Glycol
MeOH	Methanol
NCS	Norwegian Continental Shelf
NOROG	Norwegian Oil and Gas
PDO	Plan for Development and Operation
PFP	Passive Fire Protection
PIO	Plan for Installation and Operation
PPE	Personal Protection Equipment
PRV	Pressure Relieve Valve
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Analysis
RISP	Risk Informed Decision Support in Development Projects
SC	Steering Committee
SoW	Scope of Work
SPR	Sudden Pressure Relay
SSIV	Subsea Isolation Valve
TEG	Tri Ethylene Glycol
TRA	Total Risk Analysis
TSS	Traffic Separation Scheme

ULS	Ultimate limit state
W2W	Walk to Work
WCPF	Worst Credible Process Fire
WG	Workgroup

1.2 Definitions

Terminology as used in the RISP project:

- Safety premises: Identified aspects presumed to be true and therefore used as a basis for the management of MAH. This can typically be presumption made in the HAZAN as a basis for concluding that the design is within the validity envelope of the RISP models. It can also cover other aspects such as operational restrictions. Safety premises typically needs to be verified at a later stage.
- Safety program: The safety program is a high-level plan describing the goals, means (resources), activities and analyses planned to manage MAH in a development project. Responsibilities, organisation and interaction arenas related to implementation of MAH design in the development project should be described. The safety program may also be called the HSE program or similar.
- Safety strategy: The safety strategy is a high-level plan giving the link between the safety program and the design development with respect to MAH. The strategy describes how the end goals will be achieved. The safety strategy should also cover the needs related to fire and explosion strategy (FES) and escape, evacuation and rescue strategy (EERS). The safety strategy should outline applicable overall principles for design, layout, arrangements, philosophies and other high-level design and operational aspects related to barriers, e.g.:
    - Describing MAH relevant for the development (e.g. area by area) and describing key design measures and safety premises.
    - Describing how specific MAH are managed by the use of barrier functions, systems and elements. Typically, this should include a reference to standard requirements (e.g. NORSOK S-001) and whether there are special solutions required (not covered by the standards).
- Proven design: Design or concepts that are considered prequalified through operational experience and/or previous engineering documentation and analyses to such a degree that the RISP methodology and models can be applied.
- RISP methodology: The principles that has been used to establish methods and models in the JIP. The term is also applied as the totality of RISP methods and RISP models.
- RISP methods: The work steps and procedures proposed to be used for risk-based decision support in development projects
- RISP models: The assessment tools proposed to be applied for risk-based decision support in development projects

2. Introduction

This report describes the work undertaken by Workgroup 5 (WG 5) as a part of the joint industry project RISP (Risk informed decision support in development projects). WG 5 has been constituted by representatives from Lilleaker Consulting, Proactima, DNV GL, Aker Solutions and Safetec.

A new methodology related to handling of MAH (Major Accident Hazards) in development projects has been established. The basis has been to allow for consistent use of industry experience rather than more analyses to support robust design of offshore facilities. The methodology is especially intended for use in project planning phase for projects.

This report is one of the workgroup reports constituting the basis for the overall RISP report, see also Figure 1.

2.1 Overall RISP project

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project) with results and proposals for further work was presented in the Operations Committee meeting in NOROG and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The RISP joint industry project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is likely to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

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

The JIP consists of two Sub-Projects. Sub-Project 1 has been carried out in 2018 (includes WG 1 and WG 2). The RISP project organisation for Sub-Project 2 is illustrated in Figure 1. Sub-Project 2 includes WG 3, WG 4 and WG 5.

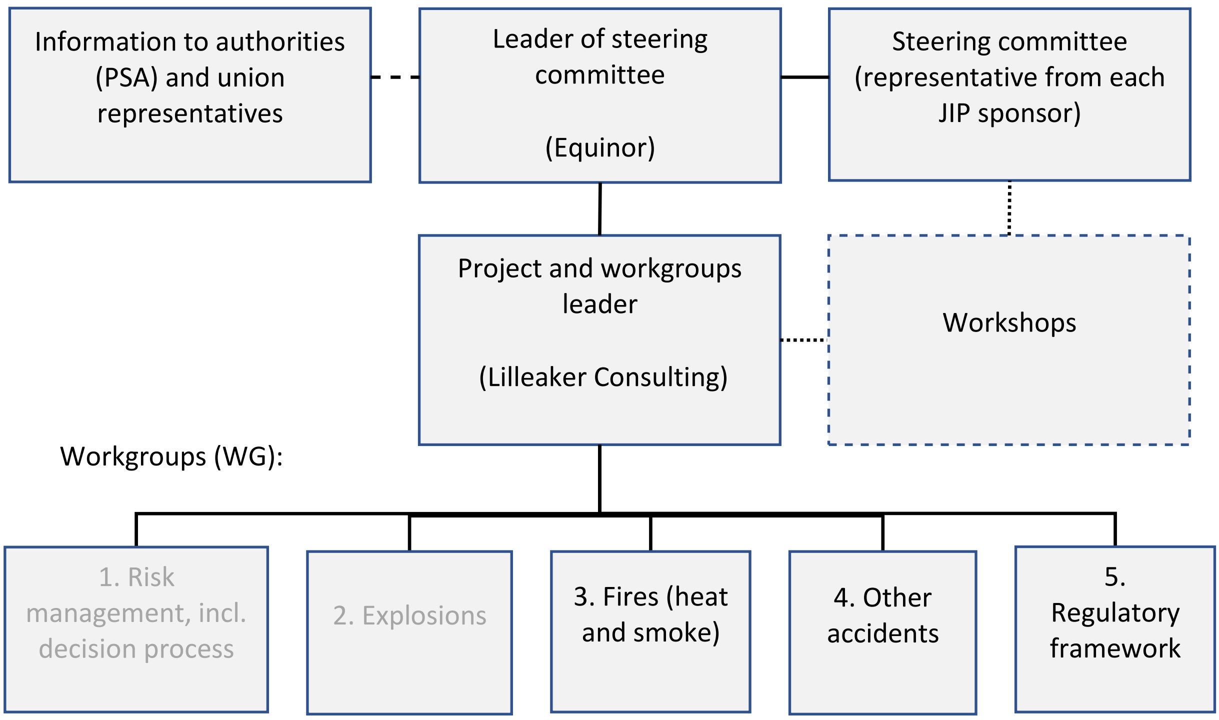

Figure 1 – The RISP project organisation overview

The five workgroups are undertaken by vendors nominated by the sponsors, and different work packages are defined for the different workgroups. The vendors are: Lilleaker Consulting, Gexcon, DNVGL, Lloyd's Register, Aker Solutions, Proactima and Safetec.

Both sponsors and vendors are participants in the JIP.

The PSA has been involved as observer in the RISP project.

2.1.1 Overall RISP context

Risk analyses have played, and still play, a key role in the safety work of the petroleum industry and have given the industry detailed and broad knowledge about risk factors and design principles. However, the present practice in use of models and tools often request input data on a very detailed level. 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. Consequently, the decision support often arrives too late.

Experience and insight gained throughout the years from making analyses have barely impacted the way analyses are made. In general, "everything" is looked at anew each time, the knowledge acquired from incidents that may occur and how plants can be optimally designed is not sufficiently utilised or reflected in the way the analyses are specified and performed.

A main recommendation from the NOROG project was that during a development project, traditional quantitative risk analyses should for proven designs as a main rule be replaced by simplified assessments. This should be done to provide the best possible support for decisions being taken on an on-going basis. Thus, the emphasis on detailed calculations of total risk, and measurement against risk acceptance criteria such as FAR and $1x10^{-4}$, should be changed. Rather than continuing to seek very detailed risk descriptions, the aim in the future should be to provide necessary decision support at the right time. This is also in line with the "new" definition of risk given in Norwegian regulations (see guidance to PSA Frame agreement §11), which is an important basis for the JIP.

The NOROG project drafted several principals and ideas for how to better deal with the above-mentioned factors. These ideas and principles have been further matured and specified in the RISP project. Proven and acceptable methods and tools can be developed for the industry's use based on the methodology outlined in this report. This will move risk management of proven designs away from total (quantitative) risk analysis as the governing element, and towards specific decision support related to each individual decision.

2.1.2 Overall RISP objective

The overall objective of the RISP project is to further develop the principles and ideas provided by the NOROG project into methods, models and guidelines, and establish a new common "industrial practice". This practice should describe how various decisions in a development project are to be based on general and specific knowledge about the incidents that the installation may be exposed to (such as leaks, fires and explosions).

Traditional quantitative risk analyses with considerable focus on detailed calculations of total risk and measurement against risk acceptance criteria such as FAR and frequencies of loss of main safety functions (1×10^{-4}) should, when technology and challenges are known, be replaced by input based on knowledge and experience acquired by past projects and analyses, providing a robust safety level. Instead of searching for detailed descriptions of what the risk level is, the objective should be to provide valid decision support at the right time.

All models to be developed as a part of the RISP methodology should, as far as possible, be based on the principles for risk-related decision support provided in ISO 17776, see Figure 2. The figure also illustrates the focus area for the work carried out as part of this JIP (RISP).

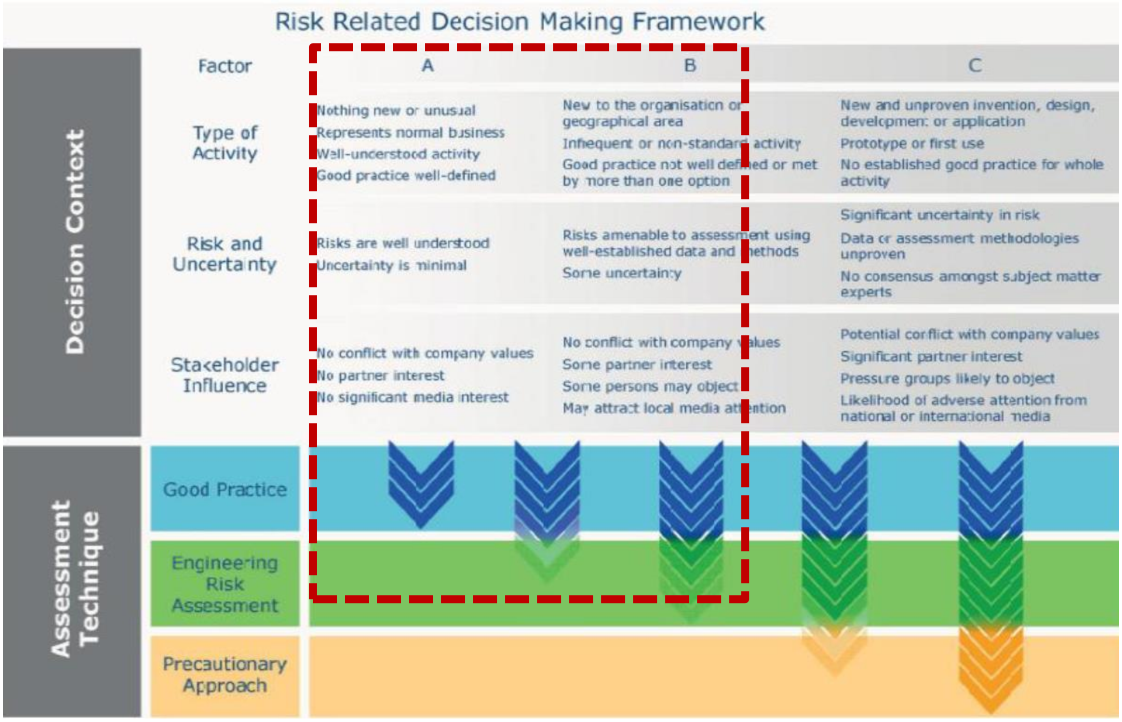

Figure 2 - Risk related decision-making framework from ISO 17776 /2/. The red doted box illustrates the focus area for the work carried out as part of this JIP (RISP).

The new «industrial practice» developed aims to clarify:

a) if a potential type of hazard/incident is sufficiently covered by using systems and solutions indicated by requirements in standards, established good practice and results of former analyses. Typically, left part of situation A in Figure 2. Or

b) if a potential type of hazard/incident can be sufficiently covered by simplified methods and models established based on knowledge and experience acquired by past projects and analyses. Typically, right part of situation A and major part of situation B in Figure 2 . Or

c) if there is a need for obtaining and using additional assessment techniques (compared to item b) for the hazard/incident. Typically, situation C in Figure 2.

When situation b) applies, the new "industrial practice" must specify the methods and models that should be applied and give guidance on how results (and the conditions/assumptions they are based on) can/should be used in the decision-making process. In this way the decision maker should also be made aware of the importance of the decision and the impacts of the various decision options.

The methods and models to be included in the new «industrial practice» will be adapted to the knowledge and information typically available at the time when the specific decisions of interest are normally made. The decision support provided shall be sufficiently robust, meaning that the recommendations given should not be subjected to scrutiny, reconsiderations or reassessment later in the project, provided that the basis for the decision support (the input used and the restrictions related to further design development) has not been changed throughout the project. This will minimise the need for late design changes, when e.g. more detailed information is available. An as-built total risks analysis/quantitative risk analysis (TRA/QRA) will thus not be required within the new "industrial practice", but verification activities need to be developed. Verification shall ensure compliance with the validity envelope of the new approach, and that any changes in assumptions made during the development project are considered.

Barrier management, in its wide context, should found the basis for risk management in operations. A balanced description of the risk comprehensive enough for the operational phase, should be established also within the new "industrial practice".

The RISP methodology includes decision gates related to whether the MAH in question can be handled with use of the established RISP methods and models as decision support in development projects. The need for possible additional assessment techniques for the risk related decision-making process is identified. However, no details are established as part of this RISP project for these additional techniques except referring to ISO 17776, PSA regulations and present practices for management of MAH.

The RISP methods and models established are applicable for proven design where technology and challenges are known, and decision support can be based on experience and knowledge acquired by past projects and analyses. The intention has also been to identify the design standards which should be used as basis for the design.

2.2 Scope and objectives– workgroup 5

2.2.1 Scope of work for workgroup 5

The scope of work given by the Steering Committee (SC) to WG 5 is presented in this Chapter.

The work in this is work package will be based on the results of all previous work packages. The product of this work package shall be a description of areas where there is a possible mismatch/conflict between the proposed methods, models and guidance and the requirements given in the existing regulatory framework, including standards referred to in the regulations. NORSOK Z-013 shall in particular be evaluated. Proposal for changes in regulations and standards, and/or work needed to define the needed changes, shall be stated. Signals and guidance received from PSA during the progress of the RISP project must be considered. Preliminary signals from PSA are that the industry should propose the principles it believes provide the best solutions, and not be restricted by current regulations. This work package will concretise and specify where and which changes are needed, if any, to be able to implement the RISP methodology.

Since WG 5 is to be based on all previous work packages, also topics relevant for the overall scope for the RISP project is commented in this report when found relevant and appropriate.

Relevant topics for WG 5 specified by the SC include:

<u>Priority 1:</u>

- How to demonstrate ALARP, ref e.g. Framework regulation Section 11
- How to demonstrate risk management and management of change in project development, ref e.g. Management regulations Section 11
- How to handle quantitative requirements (i.e. risk acceptance criteria) which normally require risk numbers from a QRA/TRA, ref. Management regulations Chapter III and V and Facilities regulation section 11
- How to handle requirement for robustness, ref e.g. Management Regulations Section 4 and 9
- Consider need to give guidance for barrier management, ref. e.g. Management Regulations Section 5 and NORSOK S-001 Chapter 5.
- Need for updating of NORSOK Z-013, and possibly S-001
- Consider need for further work to complete the RISP methods for use.
- Update WG 1 report if required to reflect experiences so far in the RISP project

<u>Priority 2:</u>

- How to handle need for verification

- How to handle need to keep proposed RISP methods and models updated.
- Performing a GAP analysis to identify possible decision support in projects or later in the operational phase that typically are provided by the current QRA/TRA regime that will not be provided by the proposed RISP methodology. Propose compensating methods were relevant.

Priority 3:

How to handle situations (design/solutions/issues) that cannot justify the use of the methods and recommendations included in the RISP methodology, i.e. “novel” solutions/type C in the ISO 17776 model (Figure 2), with principle/brief discussions on some examples.

Note: Type C decision contexts require alternative approaches in decision making that go beyond traditional engineering risk assessments to more principle-based approaches, due to the significant uncertainties involved. Thus, today’s QRA practice/approach is not an alternative for the assessment of novel concepts/issues outside the scope of the proposed methods since it builds on information not available. QRA related elements (e.g. CFD modelling) may however still be relevant.

3. Summary - review of regulations and standards

3.1 Introduction

A review of the existing Norwegian Continental Shelf (NCS) regulatory framework, including standards referred to in the regulations, has been performed. The intention has been to identify areas where there is an inherent or potential conflict between the RISP methodology and the requirements given in the existing regulatory framework.

The review has included the Facility regulations, Activities regulations, Management regulations and Framework regulations.

The absence of inherent conflicts does not mean that a given method or models is compliant with the regulation in question. Regulatory compliance must be achieved and documented by the correct implementation and verification of the methods and models in question,

Based on the work, identified challenges and proposed changes in regulations and standards, and/or work needed to define the needed changes, are summarised in the following Chapters. For an elaboration on the evaluations, reference is given to Appendix A, B and C for Facilities regulations, Activity regulations and Management regulations, respectively.

The evaluations in Sections 3.2 to 0 are summarized in tables with one line for each section in the regulations that are considered relevant for the RISP method. To provide a quick overview, colours yellow and red have been used in the tables, with the following meaning:

Yellow colour: There is no conflict between the RISP methodology and the section of the regulations. However, there are requirements in the section where the workgroup has found requirements that are relevant for RISP and where there is a possible challenge or concern using RISP to meet PSA requirements.

Red colour: There is a potential conflict between the section of the regulations and the RISP methodology.

3.2 Facilities regulations

This section summarizes the review of the PSA Facility regulations. Details about the review is found in Appendix A. Table 1 lists the relevant sections where the workgroup has found requirements that are relevant for RISP and where there is a possible challenge using RISP to meet PSA requirements.

Table 1 RISP relevant sections in Facility Regulations.

Section in Management Regulations	Crit.	RISP relevant requirements and references
§3 Definitions	Yellow	Guideline refers to load/action that occurs with an annual likelihood greater than or equal to 1x10-4.
§ 11 Loads/actions, load/action effects and resistance	Red	*Installations, systems and equipment that are included as elements in the realisation of main safety functions, cf. Section 7, shall as a minimum de designed such that dimensioning accidental loads/actions or dimensioning environmental loads/actions with an annual likelihood greater than or equal to 1x10-4, shall not result in loss of a main safety function.* At some point of time it needs to be demonstrated compliance to this requirement. For the RISP methodology this is achieved by prequalification by the RISP models.

Using RISP, a safety level at least equal to present practice shall be obtained, hence the risk will be within acceptance level of risk for loss of main safety functions, hence meet the PSA requirements. In designing the RISP methods and models, a key aspect has been to assure solutions that at least fulfil the 1x10-4 requirement related to main safety functions, given design within the validity envelope. The RISP methods and models provide solutions that are prequalified. Hence demonstration of fulfilling quantitative criteria are in principle fulfilled. This puts requirements for documentation of the RISP models as well as requirements for keeping them updated. Within RISP, detailed studies have been available and are utilized for the RISP models established. The requirement for demonstration may introduce need for further documentation to be considered as part of further work.

NORSOK S-001 is referenced a lot in the Facilities regulations. The basis for the RISP approach and a design within the validity envelope, is that design of safety systems is according to NORSOK S-001.

NORSOK S-001, Section 5.6 opens up for other method than load-frequency assessments, hence not a limitation for using RISP methods and models.

General comment:

It is our impression that NORSOK standards also to a large extent is functional based with respect to requirements. To fulfill the objective to be a clear and unambiguous basis for design, the requirements in the standards should be more prescriptive.

3.3 Activities regulations

The review of the Activities Regulations has not identified any requirements that are conflicting or misaligned with the proposed RISP methodology. Consequently, use of the RISP methods and models should not require any update of the Activities Regulations.

However, the RISP methodology must take into consideration the input required to establish emergency preparedness, Ref. Section 73.

Table 2 RISP relevant sections in Activities Regulations.

Section in Activities Regulations	Crit.	RISP relevant requirements and references
§ 73: Establishment of emergency preparedness.		*The operator or the party responsible for operating a facility shall prepare a strategy for emergency preparedness against hazard and accident situations, cf. also the Management Regulations Section 9 litera c. The emergency preparedness shall be established, inter alia, on the basis of results from risk and emergency preparedness analyses as mentioned in Section 17 of the Management Regulations and the defined hazard and accident situations and barrier performance requirements, cf. Section 5 of the Management Regulations.*

A more comprehensive review of the Activities Regulations, including review of references to Sections in other regulations which could be relevant for RISP, is included in Appendix B.

There are no references to NORSOK Z-013 or NORSOK S-001 in the Activities Regulations.

3.4 Management regulations

This section summarizes the review of the PSA Management regulations. Details about the review is found in Appendix C. Table 3 lists the relevant paragraphs where the workgroup has found requirements that are relevant for RISP and where there is a possible challenge using RISP to meet PSA requirements.

Table 3 RISP relevant sections in Management Regulations.

Section in Management Regulations	Crit.	RISP relevant requirements and references
§ 4: Risk reduction		How can we demonstrate that RISP contributes to reduce the likelihood sufficiently? Need to ensure RISP provides a good decision basis for barrier management. Reference to Framework regulations Section 11.
§ 5: Barriers		The section puts extensive requirements to barrier management which is not fully solved by the present RISP methods and models. Reference is given to a number of standards, also NORSOK Z-013.
§ 6: Management of health, safety and the environment		How can continuous improvement be demonstrated in RISP? Reference to Framework regulations Section 17.
§ 9: Acceptance criteria for major accident risk and environmental risk		How can acceptance criteria be demonstrated in RISP? Reference to framework regulations section 11/17, and to NORSOK Z-013. Acceptance criteria for loss of main safety functions as mentioned in Section 11 of the Facilities regulations.
§ 11: Basis for making decisions and decision criteria		Need to ensure RISP provides sufficient decision criteria.
§ 16: General requirements for analyses		Need to ensure RISP provides a necessary basis for making decisions. Defines requirements that RISP will have to adhere to.
§ 17: Risk analyses and emergency preparedness assessments		Includes many risk analysis related requirements. The Section also puts requirements for analyses that needs to be performed in addition to the RISP methods and models. Need to ensure RISP meets all defined criteria. Reference to NORSOK Z-013 and ISO31000.
§ 23: Continuous improvement		How can continuous improvement be demonstrated in RISP?

Sections of the Management regulations, relevant for the RISP method, are highlighted in Table 3 above. For most sections, indicated with yellow colour in the table, there is no conflict between the regulations and the RISP methodology. For acceptance criteria, indicated with red colour, we have discussed implications of the RISP methods and models more in depth below.

Section 4 has requirements to risk reduction. These requirements are functional based and may be achieved in several ways. There is no conflict between the RISP methodology and this part of the regulations.

Section 5 includes requirements to safety barriers and is closely related to barrier management. As emphasized in Section 5, barrier management is relevant for all phases. Since the RISP method has its focus in the planning phase of an offshore installation, the focus is on barrier management in the planning phase, as well as *planning* of barrier management in later phases. Examples are to ensure there is a robust safety strategy, enabling robust safety barriers in the operations phase. The relation between RISP and barrier management is also elaborated on in Chapter 0 and 4.6.

Sections 6 and 11 have functional based requirements to the management of health safety and the environment, as well as the decision-making processes in the companies. The RISP methodology is not in conflict with these requirements. Oppositely, it may be argued that the RISP methodology *contributes* to improved decision-making processes through early identification of what is "new", such as special characteristics, and what is "business as usual" through the HAZAN part of RISP. Section 9 in the regulations states that acceptance criteria shall be established not only for loss of main safety functions, but for personnel, acute pollution and damage to third party in addition. There are not explicit requirements (in the regulations) for specific criteria for these three additional measures, as it is for loss of main safety functions (ref. Section 3.2) above. However, the guideline to the regulations refers to NORSOK Z-013, which has a quantitative approach to these measures too.

The acceptance criteria for personnel, acute pollution and damage to third party is set by the individual company and not by PSA, hence they may vary between the companies. Today, for personnel risk, it is common to use criteria for accumulated risk, such as FAR, PLL and IR. However, there are no obligations in the regulations for such cumulative criteria. As an example, it would also be possible to use other kinds of criteria such as considering each hazard (process risk, dropped objects etc.) separately, criteria based on "at least as safe as", or criteria related to which level is the organization that can make certain decisions, without being in conflict with the statements in the regulations. One could argue that meeting and demonstrating that risk for loss of main safety functions is below the acceptance criteria, risk for personnel on the facility is within acceptable level.

For an elaborative discussion on the relation between the RISP methodology and the use of risk acceptance criteria, reference is also given to Chapter 0.

According to Section 16, recognized methods, models and data shall be used. As long as the RISP methods and models are qualified and implemented sufficiently, it can be argued that it is recognized and that there is no conflict between the RISP methodology and the requirements in Section 16.

Section 17 provides a list of properties that risk analyses will have to adhere to. None of these requirements are in conflict to the RISP methods and models. However, the requirements are covered on a generic rather than specific level. This is compensated by the HAZAN in each case but it is not clear that this is compliant to the requirements in this Section. The RISP methods and models does not cover all studies and requirements referred to in the section. This means that additional studies, providing input for example to emergency preparedness and environmental risk analysis, for example studying impacts in case of oil spills, needs to be carried out in addition to the RISP methods and models. This is also the case in today's use of QRA/TRA.

Section 23 is related to continuous improvement. This section requires the companies to identify processes, activities and products that can contribute to improved safety. This section does not mean that all aspects shall be improved all the time. Rather, it means that aspects that needs to be improved are identified and dealt with. In such regard, it can be argued that development of the RISP method is an improvement example. For a more elaborative discussion on continuous improvement, reference is made to Chapter 4.2.

3.5 Framework regulations

No aspect of the proposed RISP methodology is found to be inherently incompatible with the Framework regulations. Table 4 below summarises notable aspects.

Table 4 RISP relevant sections in Framework Regulations.

Section in Framework Regulations	Crit.	RISP relevant requirements and references
§ 10 Prudent activities		RISP must be prudent with regard to HSE and must enable establishing and maintaining a high level of HSE. RISP must also enable continuous improvement of HSE. See also Section 11 below
§ 11 Risk reduction principles		RISP must enable, where applicable, additional risk reduction broadly in accordance with the ALARP principle. The main implication this has for RISP is that RISP must not weaken ALARP processes (e.g. by providing a weakened basis for identification or assessment of possible, additional risk reduction measures). There is no reason to believe that RISP would weaken ALARP process, though it can be envisaged that risk analysis (incl. quantitative risk analysis) techniques may need to be employed to understand the effect to provide (part of) a suitable and sufficient decision-making basis.
§ 12 Organisation and competence		The section requires that the responsible party shall ensure that everyone who carries out work on its behalf has the competence necessary to carry out such work in a prudent manner. Simplified models, as provided by RISP, may be easy to use, however the RISP methodology relies on a competent user organization and corresponding system for management of MAH, to obtain the intended results. Section 18, qualification and follow-up of other participants, is also relevant in this respect.
§ 17 Duty to establish, follow-up and further develop a management system		RISP should be part of the management system and as such must enable compliance with the HSE legislation. Consideration of this requirements is central to the work being performed by this working group (I.e. working group 5)
§ 19 Verifications		The responsible party shall determine the need for and scope of verifications, as well as the verification method and its degree of independence, to document compliance with requirements in the health, safety and environment legislation. .... this also includes verification of the internal requirements set by the responsible party… As regards the scope of verification, this will depend on the type of requirement. For example, there will

		normally be a need to verify compliance with requirements in the health, safety and environment legislation in these technical areas. As regards the degree of independence, this normally entails that the verifications shall be carried out by a party other than the one that has carried out the work to be verified, or the party that has prepared the verification basis, as well as there being organisational independence for reporting in the line.
§ 27 Matters relating to health, safety and the environment in the Plan for Development and Operation (PDO) of petroleum deposits and the Plan for Installation and Operation (PIO) of facilities for transport and utilisation of petroleum		The section describes when PDO shall be submitted and what shall be covered by the PDO. The paragraph requires that the PDO include Risk Acceptance Criteria (RAC). It is envisaged that this requirement can be met by, where applicable, the operator incorporating RISP into their RAC.
§ 47 Placement of facilities, choice of routes		This section states facilities shall be placed a safe distance from other facilities, vulnerable environmental values and 3rd parties such that they do not constitute an unacceptable risk. It may be the case that risk analysis techniques (incl. consequence analysis) may need to be employed to demonstrate compliance with this requirement.

3.6 NORSOK S-001

General compliance with NORSOK S-001 is one of the key premises for application of the RISP methodology.

NORSOK S-001 is also extensively referenced in the Guidelines to the Facilities Regulations.

Generally, there are few requirements in NORSOK S-001 that are conflicting or misaligned with the proposed RISP method. However, some adjustments to NORSOK S-001 would be required for the standard to be fully aligned with RISP method.

Requirements where rephrasing should be considered includes;

- Definition of Dimensioning load/dimensioning gas cloud (Chapter 3) in relation to RISP
- General alignment of Safety Management process described in chapter 5, including inclusion of HAZAN
- Chapter 5.6.2 states that the establishment of accidental loads due to gas explosion shall be based on "a recognised method (e.g. NORSOK Z-013) and a representative geometric explosion model with representative equipment density". The requirement for using an explosion model needs to be modified.
- Chapter 5.6.3.2 Main load bearing structures; "A validated computational fluid dynamics (CFD) model shall be used to provide realistic modelling of the fire source and the effect of the surroundings in order to define the design accidental load."
- The target design coverage of gas detector detectors (Chapter 13.4.1) is related to the dimensioning gas cloud. The use of RISP methodology would require an alternative method of establishing the target design coverage.

The word should, is used a lot in the standard to describe "a suggested possible choice of action deemed to be particularly suitable without necessarily mentioning or excluding others". This causes some uncertainty to what is required to be compliant to the standard and to the regulations.

3.7 ISO 17776

The workgroup has not seen any need for addressing the need for updating ISO 17776. The risk related decision-making framework from ISO 17776 has been a vital part of the context for development of the RISP methodology.

3.8 NORSOK Z-013

The NORSOK Z-013 standard (Ref. /3/) is referenced in the PSA regulations. The following references are found:

- The guideline to Management regulations § 5 Barriers:
    - *Performance requirements to barriers to limit possible damage or negative consequences to the environment in case of acute pollution offshore, should express functionality, be easy to understand, be concrete and measurable and realistic (NORSOK Z-013).*
- The guideline to Management regulations §9 Acceptance criteria for major accident risk and environmental risk:
    - *See Annex A of the NORSOK Z-013 standard for a description of different types of acceptance criteria that may be used for major accident risk and environmental risk⋯.*
    - *See Annex B Chapter 4 of the standard for a complementary description of the acceptance criteria for loss of main safety functions.*
- The guideline to Management regulations § 17 Risk analyses and emergency preparedness assessments:
    - *The NORSOK Z-013 and ISO 31000 standards should be used, amongst others, to fulfil the requirements for risk analyses and emergency preparedness analyses.*
- The guideline to Facilities regulations § 11 Loads/actions, load/action effects and resistance:
    - *In order to assess the loss of main safety functions as mentioned in the third subsection, the standard NORSOK Z-013 Appendix B should be used.*

The NORSOK Z-013 standard was established with a quantitative approach in mind to establish a risk picture using risk calculations to demonstrate the risk level. The standard opens up for alternative approaches, but have an overall quantitative approach, where risk is a combination of the probability of occurrence of harm and the severity of that harm.

The standard should be updated to reflect PSA definition of risk and risk reduction and be more open for use of other approaches to risk assessments, more in line with the latest revision of ISO 17776 (Ref. /2/) and use of RISP methods and models.

There are also other definitions including comments and guides that need to be reviewed.

Section 4 The role and use of assessments in risk management should be rewritten to also reflect the variations for assessments given in ISO 17776.

Section 5 in the standard is not limiting the use of RISP methods and models but should to a larger extent be rewritten to open for alternative approaches.

Both section 6 and 7 should be rewritten to reflect the overall ISO 17776 approach including the RISP methodology. An alternative is to build the following sections according to the risk related decision-making framework in ISO 17776, see Figure 3. The standard should be simplified and instead include more examples and best practices in Appendices.

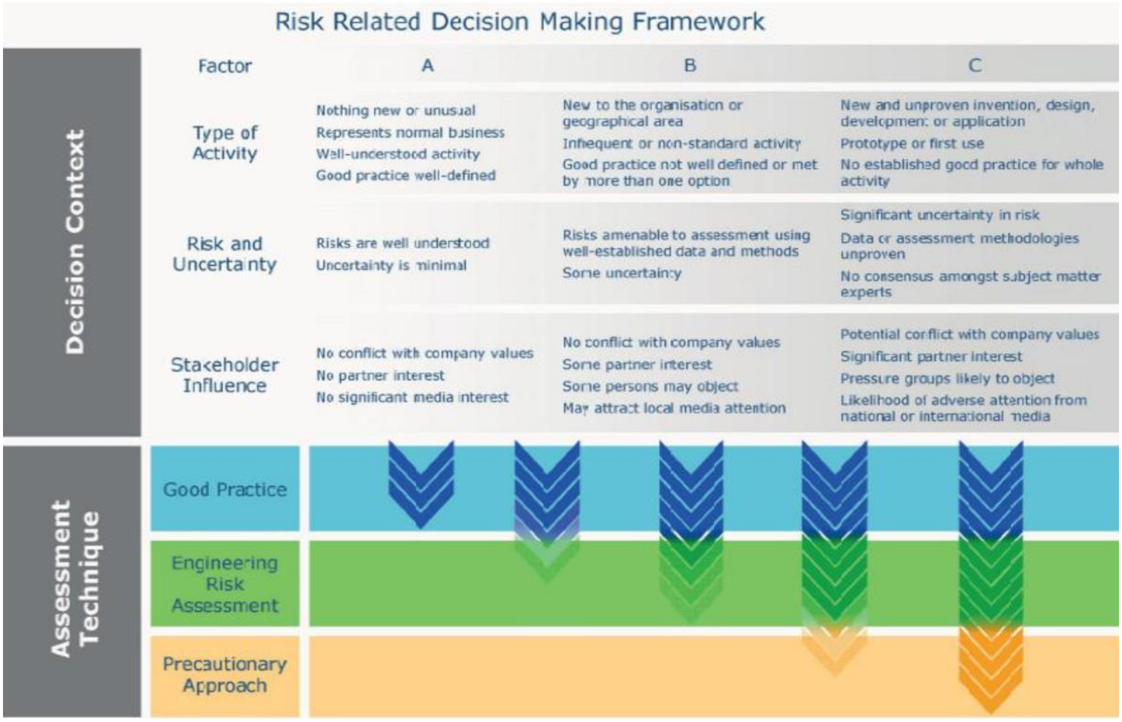

Figure 3 - Risk related decision-making framework from ISO 17776 /2/).

Section 8 covering the operational phase, need further discussion, as this is not discussed in detail in the RISP development project.

Section 9, 10, 11, 12 in NORSOK Z-013 covers emergency preparedness analyses. There are aspects related to HAZID that should be included in the HAZAN.

4. Evaluation of specific topics

4.1 Introduction

Discussion and evaluation of specific topics mentioned in SoW for WG 5 are covered in this chapter.

The content includes when relevant:

- Reference to sections in regulations
- How the requirements are reflected in use of the RISP methods and models
- Potential mismatch or conflicts between the regulatory framework and the RISP methods and models
- Discussion of pros, cons, dilemmas or practices related to compliance to the regulative regime in development projects
- Conclusions and recommendations from WG 5

4.2 How to demonstrate ALARP (Pr.1)

The regulations refer several places to stringent requirements for risk reduction in line with the ALARP principles, e.g.:

- Framework regulations § 11 – Risk reduction principles (Risk shall be further reduced to the extent possible)
- Framework regulations § 10 – Prudent activities
- Management regulations § 4 – Risk reduction (Collective measures and inherent safety)
- Management regulations § 6 – Management of HSE (Prudent activities and continuous improvement)
- Management regulations § 7 – Objectives and strategies (E.g. responsibility to set higher goals in accordance with the degree of goal achievement)
- Management regulations § 23 –Continuous improvement

The regulations put high expectations to the parties in the petroleum activity to reduce the risk to the extent possible. E.g. as stated in Framework regulations Section 11, the responsible party shall choose the technical, operational or organisational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved. If there is insufficient knowledge concerning the effects solutions can have on HSE, solutions reducing the uncertainty shall be chosen. Factors that could cause harm or disadvantage to people, the environment or material assets in the petroleum activities, shall be replaced by factors that, in an overall assessment, have less potential for harm or disadvantage.

The key objective of the RISP methods and models has not been to assure or demonstrate that the solutions chosen in design are ALARP. However, in developing the RISP methods and models, risk reduction principles such as ALARP, Inherent Safe Design (ISD), BAT and Robustness have been included. Examples are:

- In establishing the RISP models, ALARP/ISD/BAT/Robustness/ISD issues have been considered in the output given in terms of design values and requirements. An overall requirement has been to provide models that gives at least the same safety level as today. In this context, safety measures implemented in normal design today has been included as a type of BAT. In addition, potential or need to provide solutions that are more robust, give less uncertainty or less potential for harm or disadvantage have been considered in a cost perspective. Hence the ALARP principle has affected the outcome from RISP models in terms of e.g. design accidental events, design accidental loads and/or design requirements.

- The RISP methodology provides specific topics to be considered as part of HAZAN. The HAZAN is planned performed in early Project Planning Phase. This is considered an important and efficient stage to include best possible solutions into design. The RISP models provides input to key risk drivers that shall be considered in the HAZAN. Likewise, ALARP/ISD/BAT/Robustness considerations are part of the scope for the HAZAN (and at later stages in the project development) and will provide input to risk reduction and maturation of the design.

The demonstration of ALARP is a task within the risk management of a development project. Although the RISP methods and models can be a part of the demonstration of ALARP, the full demonstration is largely outside the scope of RISP. However, some views and considerations are provided by WG 5.:

- No mismatch/conflict has been identified between the proposed methods, models and guidance and the requirements given in the existing regulatory framework. including standards referred to in the regulations.
- The present practice in identifying and documenting compliance with these regulations varies and are governed by procedures by operators and contractors. In general, the practice is not very efficient. It seems to be to high focus on detailed cost and risk calculation methods and documentation long after decisions have been made. Also, ALARP measures feasible at one stage, may be disregarded since it is identified to late when the cost of implementation is too high.
- The ALARP process expected is a structured knowledge-based approach to identify and follow up improvements. This does not mean that everything shall be improved all the time. Sometimes doing less can be an improvement since resources can be used where more needed giving potentially better risk reducing effects.
- The content and focus of the ALARP work differ in the various stages of a development project. In early planning phase of a development project, it is recommended to perform systematic risk reduction (including identification and evaluation of risk reduction measures/solutions) as part of the ongoing engineering for most disciplines. This will give input to the maturation of layout and design by early phase considerations of risk drivers. During execution phase, ALARP measures are generally part of any design development and the need for rigorous work processes and documentation is less obvious. ALARP sessions/analysis may primarily be applicable for special cases at this stage. The use of an ALARP register as a tracking system, is judged to be valuable for the process. The register and the corresponding documentation should be established early in the project planning phase.

To stimulate an improved practice for ALARP process and demonstration as part of development projects, WG 5 recommends establishing a common best practice for the industry. The basis could be the present various procedures applied by operators and contractors. A key aspect will be how to assure efficient integration into the normal design development. The outcome could be included as an attachment to NORSOK Z-013, Ref. /3/.

4.3 How to assure risk management and management of change in project development (Pr.1)

Relevant regulations include:

- Management regulations § 6 – Management of health, safety and the environment
- Management regulations § 11 – Basis for making decision and decision criteria
- Management regulations § 16 – General requirements for analyses
- Management regulations § 17 – Risk analyses and emergency preparedness analysis

The performed work in the RISP project covers only briefly risk management and management of change within development projects. However, in designing the RISP methods and models, the objective has been to provide risk-based information at the right time to allow for efficient risk management. The intention has been to provide prequalified solutions that requires less analyses and documentation as part of qualifications for each development project. This methodology requires that the RISP methods and models established are qualified for use and kept updated.

For the qualification of use in each development project, the following is especially noted:

- The validity envelope for the RISP models with respect to design values and premises should be as precise as possible to allow follow up during the development project
- The validity of RISP methods and models shall be reviewed as part of the HAZAN
- The development project should have a follow up system to assure changes affecting the validity of RISP models used, are identified and managed
- The Management regulations Section 17, states requirements for comprehensive analyses as a basis for decision support. Whether the RISP methods and models alone provides sufficient decision support or if additional analyses are required in each case needs to be evaluated.

The present practice for risk management is governed by procedures by operators and contractors. This also includes procedures for business management. Obviously, it can be questioned whether the practice in development projects in all relevant aspects are optimal and efficient to obtain the intentions of these paragraphs of the regulations. To a large extent this is outside the SoW for RISP. However, some relevant items are noted:

- Important tools in risk management includes:
    - Safety program
    - HAZAN (extended HAZID)
    - Design Accidental Load Specification (DeAL)
    - Safety Strategy and Performance Requirements.

- The overall principles to be used with respect to MAH management are well described in standards such as:
    - ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016. See ref /2/
    - Petroleum Safety Authority Norway, "integrated and unified risk management in the petroleum industry", dated June 2018. See ref. /4/.

It is a recommendation from the RISP WG 5 to establish a common recommended practice for how to manage MAH in development projects.

4.4 How to handle quantitative requirements (i.e. risk acceptance criteria) which normally require risk numbers from a TRA/QRA (Pr.1)

Relevant regulations include:

- Activity regulations § 73 – Establishment of emergency preparedness
- Management regulations § 5 – Barriers
- Management regulations § 9 – Acceptance criteria for major accident risk and environmental risk
- Facilities regulations § 7 – Main safety functions
- Facilities regulations § 11 – Loads/actions, load/action effects and resistance

The regulations require that acceptance criteria shall be set for:

- the personnel on the offshore or onshore facility as a whole, and for personnel groups exposed to particular risk,
- loss of main safety functions for offshore petroleum activities,
- acute pollution from the offshore or onshore facility
- damage to third party.

Installations, systems and equipment that are included as elements in the realisation of main safety functions, shall as a minimum be designed such that dimensioning accidental loads/actions or dimensioning environmental loads/actions with an annual likelihood greater than or equal to $1x10^{-4}$, shall not result in loss of a main safety function.

In designing the RISP methods and models, a key aspect has been to assure solutions that at least fulfil the $1x10^{-4}$ requirement related to main safety functions. The opinion is that this has been achieved, hence the RISP methods and models provide solutions that are prequalified with respect to this requirement. Whether it is a need for further work to assure and document compliance to the requirement should be evaluated as a follow up of this JIP.

The acceptance criteria to personnel as a whole and for personnel groups are often set as quantitative FAR and/or PLL values. The experience is that these values are not governing for the outcome of the RISP models (design values). These criteria are generally specified as total values including all types of hazards that personnel are exposed to. This conflicts with the RISP models which consider one hazard at a time. Anyway, the topic of personnel risk is expected to be covered in the HAZAN to identify and follow any relevant special issue in a development project. Documentation of fulfilment of acceptance criteria for personnel risk is normally done through TRA/QRA. However, it is up to the operators to stipulate the format of the acceptance criteria for personnel risk. Hence alternative formats can be established which can be documented in alternative ways.

The acceptance criteria related to acute pollution and damage to third party has not been governing for the RISP methods and models. Hence, establishing and fulfilling these criteria needs to be considered separately.

For barriers it is a requirement to define performance requirements. Further it is a requirement that the requirements are verifiable. Often these requirements are quantitative/probabilistic and documentation of fulfilling the requirements are based on input from TRA/QRA. How this shall be solved without a TRA/QRA as basis needs to be considered further.

The regulations refer to NORSOK Z-013 in the Management regulations §§ 5, 9 and 17 as well as in Facility regulations § 11. It is recommended to update the standard to better support the risk assessments that should be done as part of prequalified solutions (as is the RISP methodology).

4.5 How to handle requirement for robustness (Pr.1)

Relevant regulations include:

- Management regulations § 4 – Risk reduction
- Management regulations § 9 – Acceptance criteria for major accident risk and environmental risk

As described also for ALARP, Chapter 4.2, robustness is included in the RISP methods and models. The RISP models are generally considered to provide robust design input. Robustness is also a topic for the HAZAN. The need for additional studies to assure sufficient robustness and improve decision basis should be identified in the HAZAN.

As discussed in Chapter 4.3, it is recommended to establish a best practice for management of MAH in development projects. This should include the topic of robustness. The PSA document "Integrated and unified risk management in the petroleum industry" is considered to give valuable input to the context for such a best practice document.

4.6 Consider need to give guidance for barrier management (Pr.1)

Relevant regulations include:

- Management regulations § 5 – Barriers
- Management regulations § 6 – Management of health, safety and the environment
- Management regulations § 11 – Basis for making decision and decision criteria

The RISP methods and models do not specifically address barrier management. The RISP methodology does, however, reflect requirements to barriers implicitly. E.g. the validity envelope presumes that standards such as NORSOK S-001 are complied with and the RISP models provide input to design accidental loads that should be used to assure survivability of barriers.

Practise in development projects with respect to barrier management varies a lot. The barrier management focus in the industry has to a large extent been on the operational phase. Less experience is gained on how to identify and describing special needs, solutions or performance requirements not covered by prescriptive requirements in standards (e.g. as specified in NORSOK S-001) for each development project. Traditionally, an important basis for establishing performance requirements to barriers has been results presented in TRA/QRA. Within the RISP methodology it is considered that this can be compensated by establishing standard requirements to the barriers as default values. E.g. functional based requirements given in NORSOK S-001, could be modified giving default prescriptive requirements. Also, the recommended SIL requirements given in ref. /5/ could be made mandatory as part of the RISP methodology.

It is a recommendation from the RISP WG 5 to establish a common recommended practice for barrier management in development projects. The practice should reflect the need to assure the necessary barriers are included in the technical basis for the design during project planning phase (e.g. as part of safety strategy) while more detailed performance requirements are established in the execution phase.

4.7 Need for updating of standards to reflect RISP (e.g. Z-013 and S-001) (Pr.1)

No extensive update of NORSOK S-001 is considered necessary to allow for use of the RISP method. However, there are some modification that would be required to align NORSOK S-001 with the RISP method.

The NORSOK Z-013 standard should be updated to reflect PSA definition of risk and risk reduction and be more open for use of other approaches to risk assessments, more in line with the latest revision of ISO 17776 and use of RISP methods and models.

The standard should be built according to the risk related decision-making framework in ISO 17776. The standard should be simplified and include more examples or best practises in Appendices.

See also Chapter 3.6, 3.7 and 3.8 for more details.

4.8 Consider need for further work to complete RISP methods for use (Pr. 1)

As far as possible within the limitations of time and resources available, the RISP models have been completed for use. However, it is recommended to review the models and documentation prepared to evaluate that the models in every aspect fulfil requirements to be considered complete.

To make the RISP methods and models ready for use, possible topics for further work could include:

- Establishing a precise description of validity envelope for the methods and models
- Assuring that the RISP methods and models are documented to show compliance to the 10^{-4} criteria and fulfilling risk reduction requirements (ALARP/ISD/BAT/Robustness).
- Assuring necessary input to topics for the HAZAN is provided
- Assuring valuable design recommendations are captured and provided.

4.9 Need for updating of WG 1 report (Pr. 1)

The WG 1 report presents the context for this JIP and has been a basis for the work done in all workgroups. Through the JIP execution, considerable maturation and consolidation has been achieved among the RISP participants. Hence, it is recommended to update the WG 1 report to improve clarity in the context and basic ideas for the RISP methods and models.

4.10 How to handle need for verification (Pr. 2)

Relevant regulations include:

- Framework regulations § 19 – Verifications

The Framework regulations § 19 states:

> *The responsible party shall determine the need for and scope of verifications, as well as the verification method and its degree of independence, to document compliance with requirements in the health, safety and environment legislation.*

In the context of RISP the following verification aspects are considered relevant:

- The need to verify and qualify that regulatory requirements are met by using the RISP methods and models.
- The need for independent verification of the use of RISP methods and models in development project.
- The need to verify that during the execution of a development project the design remains within the RISP validity envelope.

The first aspect is covered in other sections of this report. For the second aspect the operator should define the need for verification of use of RISP methods and models in each development projects.

The third aspect is related to the need to assure compliance to the validity envelope of the RISP methods and models, both when the RISP models are applied initially and as the development project evolves to as built.

In the RISP methodology the idea is to make decisions once at the right time and avoid the need to revisit the decision later due to more details available as the project development evolves. The decisions are hence often made based on preliminary design input. It is, however, a prerequisite that the design remains within the validity envelope defined. Safety premises which needs to be followed up in the development project, should hence be defined. It is presumed that the development project has a management of change system where the safety premises can be included.

Based on experience from present practice it is recommended to include a mandatory requirement for a verification at the as-built stage that all safety premises are fulfilled.

4.11 How to handle need to keep proposed RISP methods and models updated. (Pr. 2)

Relevant regulations include:

- Management regulations § 17 – Risk analyses and emergency preparedness assessments
- Management regulations § 19 –Collection, processing and use of data
- Management regulations § 23 –Continuous improvement

A basic idea for this JIP has been to utilise the experience and competence in the industry to establish a simplified and prequalified methodology for management of MAH in design. A concern raised in this respect has been whether the new context will be a conservation of present knowledge and solutions rather than stimulating continuous improvement.

The operators are the main responsible for keeping methods and models updated. Some aspects to consider in this respect are:

- Follow up of practices and new knowledge as it evolves and initiate work to considered need for updating of methods and models.
- Periodically, perform more detailed studies to validate the RISP models and maintain a solid knowledge base in the industry. (The management regulations § 17 says, "updating needs shall be assessed every five years")
- Initiate studies to increase knowledge on specific topics
- Stimulate sharing of knowledge and contribute to maintaining professional arenas to share knowledge

4.12 Decision support needed in addition to RISP methods that are typically provided by QRA/TRA (Pr. 2)

The RISP methods and models do not rely on traditional QRA/TRA's to be performed as part of the decision support in development projects. A coarse identification of possible gaps between use of decision support provided by the traditional QRA/TRA regime and use by the new RISP methods and models has been provided. Possible gaps identified are presented and briefly discussed below:

- Detailed figures on individual and collective fatality risk such as FAR and PLL specific for each installation: During project planning phase these figures rarely impact on major design decisions. As discussed in Chapter 0, the topic of personnel risk in this phase may be covered by the HAZAN and identification of special cases for more detailed evaluations or studies when needed. During project execution phase there may be need to considered alternative solutions where results from QRA/TRA traditionally has been applied. It is considered that comparison studies can be done with good quality even though a QRA/TRA has not been prepared.

- FAR and PLL values are often used to communicate risk aspects to employees and 3rd parties in the operational phase. One benefit is the ability to present and compare accumulated risk figures from a personnel perspective and giving contribution from various activities. The need for compensating methods in this respect should be discussed further.
- The QRA/TRA basically aims to present accumulated and best estimates for accident risk. This can be used as basis for cost benefit analysis as basis for selection for various options. As the RISP models are generally conservative, they are less applicable for optimisation between alternatives. Also, they are less applicable to optimise between different hazards, since the models cover each hazard individually.
- Traditionally barrier management has been based on input from the QRA/TRA. It is considered that this can be compensated by use of qualified qualitative evaluations as part of HAZAN and the safety strategy together with use of standardised requirements to barriers.
- Emergency preparedness analysis are traditionally prepared based on input from QRA/TRA. This is also in line with requirements given in the Activity regulations Section 73 which says, "The emergency preparedness shall be established, inter alia, on the basis of results from risk and emergency preparedness analyses". It is noted that it is not an explicit requirement for quantitative analysis in the regulations.
- Environmental risk analyses are traditionally prepared based on input from QRA/TRA. The degree of quantification and detailed results needed as input to the environmental risk analyses should be agreed with The Norwegian Environmental Agency.
- The focus of the JIP has been on decision support needed in development projects. The need for decision support in the operational phase has so far not been considered. Traditionally the QRA/TRA has also been used for operational risk management. E.g. the management regulations Section 17 says "The responsible party shall carry out risk analyses that provide a balanced and most comprehensive possible picture of the risk associated with the activities." The idea for the JIP is that barrier management should be governing for the decision support in the operational phase. It should be further considered how the decision support should be given for the operational phase.

4.13 Decision support in case of novel solutions (type C) (Pr. 3)

The applicability of the RISP methods and models are governed by the RISP validity envelope. The validity envelope describes constrains and conditions for using the RISP methods and models. If there is a new or unproven invention, design, development or application with no established good practice for the whole activity, the activity will typically be outside the RISP validity envelope. In this case advanced/special studies and/or precautionary approach is required. This is to some degree described in Ref. /2/, /3/ and /4/. How to do this needs to be considered specifically in each case and is a task for management of MAH in the development projects. It is noted However, that although some parts of the design, development or application is outside the RISP validity envelope, other parts may be inside the validity envelope.

5. Summary

Key conclusions are summarised below:

- The regulative regime is ambitious and written in a functional based way. The regulations have not explicitly expressed requirements for quantification of risk numbers. Hence, no direct conflict or mismatch has been found between the RISP methodology and the regulations. Although the regulations can be interpreted in different ways, the PSA underlines that it a task for the responsible parties to establish practices that are compliant to the regulations and suitable for the industry.
- The regulations refer to several standards of good practice that relates to management of MAH and for proper safety design. These standards have included the concept of risk quantification to various levels. Alignment to the RISP methodology may hence be required.
- The regulations refer especially to NORSOK Z-013 for the requirement that loads/actions with an annual likelihood greater than or equal to $1x10^{-4}$, shall not result in loss of a main safety function. This has been interpreted as a quantitative requirement by the industry. Likewise, the practice related to probabilistic explosion analysis included as informative materiel in NORSOK Z-013, has been included as a best practice by operators . It is concluded that this standard should be updated to better stimulate good practices for use of risk assessment techniques and management of MAH for decision support. The RISP methodology as a way of documenting prequalified solutions should be a part of this update.
- The NORSOK S-001 standard describes parts of management of MAH which should be aligned with the RISP methodology. The standard is an important basis for describing requirements to safety barriers. This standard can be used as prequalified solutions for safety barriers and serves as a basis for the RISP methodology.
- The NORSOK S-001 standard describes functional based requirements as a basis for setting design requirements (e.g. describing requirements for solutions that minimize risk). Also, the standard uses the word should a lot, which opens for interpretation of what the prequalified solution is. To better suit the RISP methodology, the requirements could be revised to either present a good practice how to decide on a compliant solution or reformulate functional based requirements to prescriptive requirements valid for prequalified solutions.
- The regulations give ambitious requirements for continuous improvement and risk reduction. These requirements are challenging to fulfill. It is judged that both quality and efficiency in management of MAH may be improved by establishing suitable best practices.
- The RISP methodology can play a role and be part of a good practice for management of MAH. The methodology is judged suitable to provide valid decision support at the right time during development projects. Strong focus needs to be put on the HAZAN, both the methodology and involvement of stakeholder in the work process.

6. Recommendations for further work

A new methodology replacing traditional quantitative risk analysis with simplified experience-based methods for improved decision support in development projects has been outlined and substantiated in this report. In order to qualify the new RISP methodology and improve its ability for risk-based decision support in development projects, the following recommendations are given for the SC members to consider:

- To make the RISP methodology qualified and ready for use, it is recommended to evaluate the need for additional work to complete the RISP methods and models. This could include:
    - Establish a precise description of the validity envelope for the methods and models
    - Assure that the RISP methods and models are based on best available knowledge, documented to show compliance to the 10^{-4} criteria and fulfilling risk reduction requirements (such as ALARP/ISD/BAT/Robustness).
    - Assure that required input to topics for the HAZAN is established and identified
    - Assure risk drivers and valuable design recommendations are captured and provided where relevant for the different hazards.

- The management of MAH within development projects has only coarsely been included in the scope performed in this JIP. However, it is a crucial part of assuring a proper design in any development project. In the same way as it is a potential for better and more efficient risk-based decision support, it is judged valid to stimulate improved management of MAH within the development projects. It is hence recommended to establish best practices for management of MAH. The PSA document "Integrated and unified risk management in the petroleum industry" as well as present various procedures applied by operators and contractors are considered to give valuable input to the context for such practices. The practices should include:
    - Practices for risk reduction. A key aspect will be how to assure efficient integration into the normal design development.
    - Practices for how to include robustness into design
    - Practices for barrier management in development projects. The practice should reflect the need to assure that required barriers are included in the technical basis for the design during project planning phase (e.g. as part of safety strategy) while more detailed performance requirements are established in the execution phase.
- Based on experience from performed projects, it is expressed that requirements for verification activities at the as-built stage are important to assure focus and attention on HSE aspects during project execution. As the practice of as-built QRA/TRA is not part of the RISP methodology, it is recommended to consider to implement instead verification at the as-built stage that all identified safety premises for the design are fulfilled.
- The focus of the JIP has been on decision support needed in development projects. The need for decision support in the operational phase has so far not been considered as part of this JIP. The idea for the RISP methodology is that barrier management should be governing for the risk management in the operational phase. Traditionally, the QRA/TRA with comprehensive and detailed risk assessment, has been used as a basis for the barrier management. It is recommended to perform further work to evaluate how the needed and required risk picture should be established as a basis for management of MAH and barrier management in the operational phase.
- It is recommended to update the NORSOK Z-013 standard to reflect the RISP methodology and establish best practices for use of the RISP methods and models. The

updated standard should reflect the risk related decision-making framework in ISO 17776 and the PSA definition of risk and risk reduction. The standard should be more open for different approaches to risk assessments including required risk assessments for prequalified solutions.

7. References

/1/ Norsk Olje & Gass (NOROG): Prosjekt «Formålstjenlige risikoanalyser» Resultater og forslag til videreføring, Versjon: 6. februar 2017

/2/ ISO 17776: "Petroleum and natural gas industries – Offshore production installations – Major accident hazard ", Second edition dated 15.12.2016.

/3/ NORSOK STANDARD, "Risk and emergency preparedness assessment", NORSOK Standard Z-013, Edition 3, October 2010

/4/ Petroleum Safety Authority Norway, "Integrated and unified management in the petroleum industry", dated June 2018.

/5/ Norwegian Oil and Gas Association: "Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry (Recommended SIL requirements), revised June 2018

Appendix A Detailed review of Facilities regulations

Yellow colour: There is no conflict between the RISP methodology and the section of the regulations. However, there are requirements in the section where the workgroup has found requirements that are relevant for RISP and where there is a possible challenge using RISP to meet PSA requirements.

Red colour: There is a potential conflict between the section of the regulations and the RISP methodology.

Green colour: There is no conflict between the RISP methodology and the section of the regulations.

Criticality	Facilities regulations - Section	Facilities regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	§3 Definitions Dimensioning load/action: Characteristic load/action multiplied by load/action coefficients.	Dimensioning accidental load/action: The dimensioning accidental load/action is typically established as part of a risk assessment as the load/action that occurs with an annual likelihood greater than or equal to 1x10-4.	Relevant for RISP, possible conflict	
	Dimensioning accidental load/action: An accidental load/action that a function or a system shall be able to withstand for a given period of time to meet the defined acceptance criteria for risk.			
	Design accidental load/action: Accidental load/action used as a basis for design.	Design load/action: The design load/action can be the same as the dimensioning accidental load/action, but it can be more conservative as well, based on different input and assessments such as ALARP, minimum requirements in the regulations etc. In practice, this may entail that the design accidental load/action must be given a higher value than the dimensioning accidental load/action. As a minimum, the design accidental load/action must always correspond to the dimensioning accidental load/action.		
	Main area: Facility area intended for a specific task or function.			

Criticality	Facilities regulations - Section	Facilities regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	Safety system: Technical barrier elements that are realised in a common system. Safety functions: Technical barrier elements that are intended to reduce the possibility of a concrete fault, hazard and accident situation occurring, or that limit or prevent damage or inconveniences. Accidental loads/actions: Loads/actions that the facility can be exposed to as a result of incorrect use, technical failure or undesirable external influences.			
	§ 5 Design of facilities Facilities shall be based on the most robust and simple solutions as possible, and designed so that a) no unacceptable consequences will occur if they are exposed to the loads/actions as mentioned in Section 11, b) major accident risk is as low as possible, c) a failure in one component, system or a single mistake does not result in unacceptable consequences, d) the main safety functions as mentioned Section 7 are maintained, e) materials handling and transport can be carried out in an efficient and prudent manner, cf. Section 13, … h) barriers are established that can both detect abnormal conditions and reduce the potential for failures and hazard and	For general requirements related to risk reduction, see Section 11 of the Framework Regulations and Chapters II and V of the Management Regulations. To fulfil the design requirements as mentioned in the first subsection, the standards NS-EN ISO 13702 with appendices, NORSOK S-001 and S-002 should be used for the health and safety sections. For lifting equipment, the NORSOK R-002 standard should be used. For mobile facilities that are not production facilities and that are registered in a national shipping register, DNVGL-OS-A101 can be used as an alternative in the area covered by the standard.		

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Criticality	Facilities regulations - Section	Facilities regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	accident situations developing, and which can restrict possible harm and disadvantages, cf. Section 5 of the Management Regulations, … …			
	Measures to protect facilities against hazard and accident situations shall be based on a strategy, with reference to Section 5 of the Management Regulations.	In order to fulfil the strategy requirement as mentioned in the third subsection, the principles in the NS-EN ISO 13702 standard should be used for all hazard and accident situations.	No conflict	
	The facilities shall be divided into main areas. The main areas shall be separated by fire and explosion divisions or sufficient physical distance to prevent escalation. Alternatively, a combination of physical divisions and sufficient distance may be used. Regardless of whether they are defined as main areas or not, areas shall have siting of equipment and layouts that contribute to good inherent safety characteristics and which reduce the risks associated with hazard and accident situations that may arise.	In order to fulfil the requirements for design and siting referred to in the fourth subsection, the facility should be designed so that the potential for and consequences of accidents are reduced. Areas, equipment and functions should be arranged, sited and organised so as to, as far as possible, a) restrict the potential for the accumulation and spread of hazardous materials, b) restrict the potential for ignition, c) separate areas containing hazardous materials from each other and from other areas and d) reduce potential consequences of and the potential for escalation in the event of fire and explosion.		
	§ 6 Design of simpler facilities			Important that RISP can be used for deign of simpler facilities.
	§ 7 Main safety functions		No conflict, see comments to section 11	
	§ 11 Loads/actions, load/action effects and resistance The design loads/actions that will form the basis for design and operation of	Design loads/actions as mentioned in the first subsection, comprise functional, environmental and accidental loads/actions, inter alia fire and explosive		

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Criticality	Facilities regulations - Section	Facilities regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	installations, systems and equipment, shall be determined. When determining design loads/actions, the requirement to robust solutions, cf. Section 5, and the requirement to risk reduction, cf. the Framework Regulations Section 11, shall form the basis. The design loads/actions shall ensure that installations, systems or equipment will be designed such that relevant accidental loads/actions that can occur, do not result in unacceptable consequences, and shall, as a minimum, always withstand the dimensioning accidental load/action.	loads/actions, which form the basis for design and operation of installations, systems and equipment. As regards definitions of the terms design accidental load/action and dimensioning accidental load/action, reference is made to Section 3.		
	When determining design loads/actions, the effects of fire water shall not be considered. This applies to both fire loads/actions and explosive loads/actions.			
	Installations, systems and equipment that are included as elements in the realisation of main safety functions, cf. Section 7, shall as a minimum de designed such that dimensioning accidental loads/actions or dimensioning environmental loads/actions with an annual likelihood greater than or equal to 1x10-4, shall not result in loss of a main safety function.	Dimensioning loads/actions as mentioned in the third and sixth subsection, comprise functional, environmental and accidental loads/actions, inter alia fire and explosive loads/actions. In order to assess the loss of main safety functions as mentioned in the third subsection, the standard NORSOK Z-013 Appendix B should be used. The NORSOK S-001 standard should be used for accidental loads/actions, in particular Chapter 5.6, in addition to other standards mentioned in these instructions. Special fire conditions such as jet fires, under-ventilated fires in modules, fire on the sea and the like may require additional calculation of fire loads / actions. For mobile facilities that are not production facilities, and that are registered in a national ships' register,	At some point of time the risk assessment need to demonstrate that the likelihood for a loss of a main safety function. RISP method demonstrated to have likelihood within these criteria or, These regulations needs to be re-formulated	It is our impression that NORSOK standards also to a large extent is functional with respect to requirements. To fulfill the objective to standardize designs, the requirements in the standards should be more prescriptive.

Commented [TD1]: Husker ikke hva jeg tenkte her

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Criticality	Facilities regulations - Section	Facilities regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
		DNVGL-OS-A101 Paragraph 2 can be used as an alternative.		
	Functional and environmental loads/actions shall be combined in the most unfavourable manner.	Functional loads/actions as mentioned in the fifth subsection, mean, in the case of load-bearing structures, permanent and variable loads/actions.		
	Facilities or parts of facilities shall be able to withstand the design loads/actions and probable combinations of these loads/actions at all times.			
	§ 29 Passive fire protection Where passive fire protection is used, this shall be designed such that it provides relevant structures and equipment with sufficient fire resistance as regards load/action capacity, integrity and insulation properties. When designing passive fire protection, the cooling effect from fire-fighting equipment shall not be considered.	For determination of fire loads/actions according to the first subsection, see Section 11. Adequate fire resistance as mentioned in the first subsection, should be determined in relation to *recognised standards or calculation models.* When stipulating fire resistance for load-bearing structures, varying material utilisation can be taken into account.	OK	
	§ 30 Fire divisions The main areas on facilities shall be separated by fire divisions that, as a minimum, can withstand the dimensioning fire and explosion loads/actions and, as a minimum, satisfy fire rating H-0 if they can be exposed to hydrocarbon fires. ….	… For determination of fire and explosion loads/actions as mentioned in the first and second subsections, see Section 11. …	OK?	
	§ 31 Fire divisions in living quarters	…. In order to fulfil the requirement relating to interior design as mentioned in the second subsection, the NORSOK S-001 standard Chapter 20.4.6 should be used.	Not in conflict with RISP.	

Possible conflicts between Regulation requirements and use of a RISP approach:

§3 Definitions – Guideline refers to the risk assessment as the load/action that occurs with an annual likelihood greater than or equal to 1x10-4.

§ 11 Loads/actions, load/action effects and resistance - *Installations, systems and equipment that are included as elements in the realisation of main safety functions, cf. Section 7, shall as a minimum de designed such that dimensioning accidental loads/actions or dimensioning environmental loads/actions with an annual likelihood greater than or equal to 1x10-4, shall not result in loss of a main safety function.*

At some point of time the risk assessment need to demonstrate that the likelihood for a loss of a main safety function.

- RISP method demonstrated to have likelihood within these criteria or,
- These regulations needs to be re-formulated

General comments:

It is our impression that NORSOK standards also to a large extent is functional with respect to requirements. To fulfill the objective to standardize designs, the requirements in the standards should be more prescriptive.

NORSOK S-001 is referenced a lot. The basis for an RISP approach and within a envelope is that design of safety systems is according to NORSOK S-001.

Statement: NORSOK S-001, Section 5.6 opens for other method than load-frequency assessments.

References to NORSOK Z-013 should be removed/updated or the standard needs to be updated to reflect RISP or develop other reference documents.

Appendix B Detailed review of Activity regulations

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	§ 14 Cleaning Cleaning shall be planned and conducted such that the indoor environment is hygienic and aesthetically satisfactory at all times.	**Re § 14 Cleaning** In connection with planning and execution of cleaning activities, the NS-INSTA 800 standard should be used, with the following additions: a) it is assumed that a decision regarding the level of quality is made as mentioned in ***Section 11 of the Management Regulations***, ……	Not relevant	
	§ 16 Installation and commissioning During installation of facilities and parts of these, it shall be ensured that the loads they are exposed to, do not exceed the loads mentioned in ***Section 11 of the Facilities Regulations.*** Upon completion of facilities, it shall be ensured that they fulfil the requirements in the Facilities Regulations, cf. also Section 23 of the Framework Regulations and Section 5 of the Management Regulations. The technical condition of facilities, systems and equipment shall be maintained until the facilities, systems and equipment are put into service..		Not relevant	
	§ 19 Accommodation and cabin sharing …… In the event of cabin sharing as given in second subsection litera b and c, the total individual strain shall be taken into account and, if necessary, use of cabin sharing shall be spread so that it comprises all employees accommodated on the facility at the time in question. Use of cabin sharing shall be compensated for.		Not relevant	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	In the event of a decision regarding the duration and scope of such accommodation, cf. also ***Section 11 of the Management Regulations,*** the consequences shall be clarified and compensating measures shall be implemented to ensure safety and necessary rest and restitution. Which compensating measures to implement, shall be discussed with the employee representatives.			
	§ 20 Start-up and operation of facilities Before facilities and parts of these are started up for the first time or after technical modifications, the commissioning as mentioned in Section 16, shall be carried out. During start-up as mentioned in the first subsection, and during operation,a) the management system with associated processes, resources and operations organisation shall be established, b) governing documents, including technical operations documents, shall be available in an updated version and the operations personnel shall be familiar with them, c) systems for employee participation shall be established, cf. Section 13 of the Framework Regulations, d) the health service shall be in accordance with Section 8 and e) the occupational health service shall be in accordance with Section 5.	**Re Section 20** **Start-up and operation of facilities** The operational organisation as mentioned in the second subsection litera a, also means the emergency preparedness organisation. Governing documents as mentioned in the second subsection, litera b, also mean the guidelines, procedures, plans and programmes that are prepared according to these ***regulations and the Management Regulations.*** In order to fulfil the requirement for technical operations documents as mentioned in the second subsection litera b, Chapter 4 and Appendices A, C and D of the NORSOK Z-001 standard should be used. For drilling and well technical equipment, Chapter 5 and Annexes A, B and C of the NORSOK D-001 standard should also be used.	Not relevant	
	Section 25 Use of facilities	**Re Section 25** **Use of facilities**	No conflict	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	Use of facilities and parts of these shall be in accordance with requirements stipulated in and in pursuance of the health, safety and environment legislation and any additional limitations that follow from fabrication, installation and commissioning. The use shall at all times be in accordance with the facility's technical condition and the assumptions for use that form the basis for prudent activities. When setting restrictions for the activity level on the facility, the maintenance status shall also be considered.	Limitations for use as mentioned in the first subsection, can ensue from the loads that the facility and its individual parts shall be able to withstand, ***cf. Section 11 of the Facilities Regulations.*** The loads can include chemical loads, environmental loads such as waves, wind and temperature and functional loads such as pressure, weight, temperature and vibration. When conducting drilling and well activities with mobile facilities, the vertical movements of the facility and movements brought about by resonance between the wave frequency and the frequency of the facility itself should also be taken into account, as well as movements in the event of loss of position due to anchor line breakage or drift, or because of dynamic positioning failure. Cf. Section 50 of the Facilities Regulations. Facilities and parts thereof as mentioned in the first subsection, also include less complex facilities as mentioned in ***Section 6 of the Facilities Regulations*** and temporary equipment.		
	Section 26 Safety systems The measures and restrictions that are necessary for maintaining the safety systems' barrier functions in the event of overbridging, disconnection or other impairment, shall be set in advance. The compensatory measures shall be implemented as rapidly as possible when such impairment occurs.	**Re Section 26** **Safety systems** A safety system means technical barrier elements realised in a common system, cf. the ***Management Regulations Section 5*** and ***the Facilities Regulations Section 3.*** The requirement in the first subsection entails that the measures and limitations shall result in a risk reduction which is relevant, and which is proportionate to	No conflict. No requirement to RISP	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	The status of all safety systems shall be known by and available for relevant personnel at all times.	the barrier functions that are affected; examples of which are limitation in the level of activities, full shut down or other risk reducing measures. The status of active safety systems, cf. the second subsection, shall be available in the central control room, cf. the Facilities Regulations Section 8. To fulfil the requirements for measures and limitations as mentioned in the first subsection, Chapter 7.7 of the IEC 61508-1 standard and Chapter 7.6 of the IEC 61508-2 standard , and Chapters 10 and 11 of Norwegian Oil and Gas' Guidelines no. 070 should be used for electrical, electronic and programmable electronic safety systems.		
	§ 27 Critical activities It shall be ensured that critical activities are carried out within the operational restrictions set during the engineering phase and in the risk analyses as mentioned in ***Section 16 of the Management Regulations,*** cf. also Section 30 of these regulations.	**Re § 27 Critical activities** It shall be ensured that critical activities are carried out within the operational restrictions set during the engineering phase and in the risk analyses as mentioned in Section 16 of the Management Regulations, cf. also Section 30 of these regulations.	No conflict.	
	§ 28 Simultaneous activities The responsible party shall define which activities that, in combination with other activities, shall be considered simultaneous activities. When conducting simultaneous activities that contribute to an unacceptable increase in risk, the necessary measures shall be implemented, cf. ***Section 9 of the Management Regulations***.	**§ 28 Simultaneous activities** Activities as mentioned in the first subsection, can be production activities, drilling and well activities, and maintenance and modification activities, including activities as mentioned in Section 27. Measures as mentioned in the second subsection, can be limitations or prohibitions that are to be implemented in connection with certain types of	No conflict.	

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Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
		simultaneous activities during start-up, operation and shutdown. …….		
	§ 29 Planning When scheduling activities on the individual facility, the responsible party shall ensure that important risk contributors are kept under control, both individually and overall, cf. also Section 12 of the Management Regulations. The planning shall consider the status of important risk contributors and changes in risk evident from the risk indicators, cf. ***Section 10 of the Management Regulations.***	**Re § 29 Planning** The requirement for planning as mentioned in the first subsection entails, inter alia, ensuring that the activities are executed within the limitations mentioned in Chapter VI.	No relevant	
	§ 33 Organisation of work The employer shall ensure that the work is organised so as to avoid hazardous exposure and unfortunate physical and psychological strains for the individual employee, and to reduce the likelihood of mistakes that can lead to hazard and accident situations. The organisation shall be based on an individual and overall evaluation of acute and long-term effects from the various working environment factors, and on an evaluation of how technology and organisation affect the opportunity to work safely. The work shall be organised with sufficient consideration for the employee's opportunities, limitations and need for a meaningful work situation, cf. Section 35.	**Re Section 33** **Organisation of work** The organisation as mentioned in the first subsection, should, inter alia, take into account the need for individual adaptation, including work capacity and age. Cf. also Chapter IV of the Facilities Regulations and Sections 18 and 19 of the Management Regulations. Hazardous exposure and unfortunate loads as mentioned in first subsection, mean exposure and loads that result from ergonomic conditions, chemical influences, radiation, noise, vibrations, climatic conditions and psychosocial conditions. Factors that can influence the psychosocial working environment, can be the interaction between requirements relating to work performance, the employee's perception of control over	Not relevant	

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Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	The work shall be planned such that as much work as possible is carried out during the daytime, and such that the employees are ensured the necessary rest and restitution. The employer shall reduce unfortunate workloads and risks of injury and accidents based on conducted analyses, mapping and gathered information on the employees' own experience of work-related risk and work load conditions.	own work and social support in the working environment. To avoid exposure that is hazardous to health as mentioned in the first subsection, measures or solutions should be selected at the highest of these levels:a) elimination of the causes of the exposure, b) technical measures that reduce the likelihood of exposure, c) technical measures that reduce exposure, d) operational measures that reduce exposure. Organisation as mentioned in the first and second subsections, should be a continuous process where both employers and the employees strive to improve the working environment, cf. also ***<u>Section 23 of the Management Regulations.</u>*** ...		
	Section 45 Maintenance The responsible party shall ensure that facilities or parts thereof are maintained, so that they are capable of carrying out their required functions in all phases of their lifetime.	**Re Section 45 Maintenance** Maintenance means the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function, cf. definition 2.1 (with associated terminology) in the NS-EN 13306 standard. Maintenance includes activities such as monitoring, inspection, testing, trial and repair, and keeping things tidy.	Not relevant	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
		Functions also mean safety functions, ***cf. Section 3 of the Facilities Regulations.*** For these functions, the requirement relating to maintenance entails that performance shall be ensured at all times, cf. Section 8 of the Facilities Regulations. Facilities or parts of facilities also mean temporary equipment. All phases also mean periods in which the facility or parts of the facility are temporarily or permanently shut down.		
	§ 49 Maintenance effectiveness The maintenance effectiveness shall be systematically evaluated based on registered performance and technical condition data for facilities or parts thereof. The evaluation shall be used for continuous improvement of the maintenance programme, ***cf. Section 23 of the Management Regulations.***		Not relevant	
	§ 57 Detection and mapping of acute pollution The operator shall as soon as possible detect acute pollution, cf. the Framework Regulations Section 48 and the Management Regulations Section 29 first subsection litera e. The operator shall have a system for detecting acute pollution. The system shall be as independent as possible of visibility, light and weather conditions and shall consist of different methods that are generally suitable for detecting relevant types and amounts of acute pollution that may arise from the facilities. The system	**Re § 57 Detection and mapping of acute pollution** …. The requirements for continuous improvement laid down in ***Section 23 of the Management Regulations*** also mean that the operator shall contribute to the necessary further development of tools for the detection and mapping of acute pollution. Section 57 of the Activities Regulations replaces, from 1 January 2019, the requirements for discovering acute pollution that is given in the permits for	Not relevant	

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Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	shall also provide sufficient information about minor leakages that may represent significant pollution over time. The area around the facility shall be monitored regularly with a view to detection of acute pollution. The need for continuous monitoring shall be considered. Acute pollution that has been detected, shall be mapped, among other things, with regard to propagation, drifting direction, amount of discharge and properties. Mapping shall be started as soon as possible after the acute pollution has been detected. Thickness distribution of oil flakes on the sea surface shall be mapped. The operator shall cooperate with operators in other production licenses to ensure that acute pollution is detected and mapped, cf. Section 78 of these regulations. The detection and mapping after detection system shall provide adequate information on the amount of discharge and dispersion to enable decisions to be made on the implementation of necessary measures to limit potential damage to the external environment, cf. the Framework Regulations Section 48. The Environment Agency can set more explicit requirements for detection and mapping of acute pollution.	petroleum activities pursuant to the Pollution Control Act. In the permits where such requirements have been made for the detection of acute pollution, the requirements will continually be taken out in connection with changes being made to these permits.		
	§ 58 Environmental surveys in the event of acute pollution		Not relevant	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	Environmental surveys shall be carried out in the event of acute pollution to identify and describe damage to vulnerable environmental values in the open sea, along the coast and at the shoreline. The surveys shall be initiated as soon as possible and no later than 48 hours after the pollution was detected. They shall build on results from the mapping of vulnerable environmental values that has been carried out in accordance with Section 53 and the data basis from the environmental risk analyses, cf. ***Section 17 of the Management Regulations***. The effect of mechanical clean-up and/or use of dispersants and shoreline cleaning agents shall be investigated, both with regard to the efficacy of the combatting method and the effect on environmental values.			
	§ 59 Characterisation of oil and condensate If oil or condensate is proven in connection with exploration activity, the oil or condensate shall be characterised as soon as possible. The results of the characterisation shall in case of future activities be included in the basis for assessment of environmental risk associated with acute pollution and in the decision basis for risk reduction, including dimensioning and development of emergency preparedness. The characterisation shall cover physical and chemical properties, including weathering and fate in a marine	**Re § 59 Characterisation of oil and condensate** …. Prior to new activities in the same reservoir or in the event of field development, a full weathering study should normally also be completed. The results of the characterization constitute, inter alia, an important basis for implementing simulations of drift and dispersion, ***cf. Section 17 of the Management Regulations,*** and for obtaining a correct description of the efficacy of current emergency preparedness material, cf. Section 42 of the Facilities Regulations.	Not relevant	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	environment under relevant external conditions. Oil and condensate that can occur as acute pollution, shall be measured regularly as regards physical and chemical parameters. If such measurements show significant changes, a new characterisation shall be performed.	Weathering as mentioned in the second subsection, means how the chemical and physical properties of the oil/condensate change over time as a result of the external conditions it is subjected to. Relevant external conditions include expected wind and wave conditions on the location, and the possible occurrence of ice on the sea surface. ….		
	§ 60 Discharge of produced water Produced water shall be cleaned prior to discharge to sea. The oil content in produced water discharged to sea, shall be as low as possible, cf. Chapter II of the Framework Regulations and Sections 7 and 8 of the Management Regulations. In any event, the oil content shall not exceed 30 mg oil per litre of water as a weighted average for one calendar month. On facilities that discharge produced water, the operator shall perform environmental risk assessments of the discharges. These shall be performed as soon as possible after produced water is available. New risk assessments shall be performed in case of significant changes in the discharge or in any event minimum every five years. The Norwegian Environment Agency can set more explicit requirements to implementation and frequency of environmental risk assessments and discharge of produced water.	**Re § 60 Discharge of produced water** …….. Section 11 of the Framework Regulations describes principles for risk reduction, including requirements regarding the use of best available techniques (BAT). ***<u>The Management Regulations set specific requirements for follow-up and improvement in Sections 19-23,</u>*** including requirements for continuous improvement. In addition, the Norwegian Environment Agency shall be informed in case of changes in risk of pollution cf. Section 34 subsection one, litera b of the Management Regulations. Oil content as mentioned in the second subsection, means content of dispersed oil in undiluted water decided in accordance with Section 70. In accordance with principles of risk reduction and management (Chapters II	Not relevant	

Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	Documentation associated with performed risk assessments shall be made available to the Norwegian Environment Agency upon request. Water treatment systems shall be designed and operated such that the environmental strain from discharges to sea will be as low as possible also if the discharge limitations, cf. the second subsection, can be met with reduced treatment effect. The operator shall establish and maintain a best practice for operating and maintaining the processing system, comprising treatment units incorporated in the system on the individual facility. The operator shall regularly assess possible technical solutions that can reduce the environmental strain from discharges of oily water. Documentation associated with such assessments shall be made available to the Norwegian Environment Agency upon request. The operator shall take appropriate measures to limit potential damage to the external environment from oil pollution in cases where discharge of produced water involves visible oil on the sea surface. The obligation under this subsection applies to measures that are in reasonable proportion to the damage and inconvenience to be avoided. The Norwegian Environment Agency and the Norwegian Radiation and Nuclear	and III of the Framework Regulations and ***Chapter II of the Management Regulations),*** the responsible party shall establish a management system that ensures compliance with the HSE regulations and continuous improvement. This entails that the responsible party shall establish and develop goals and strategies for compliance with the regulatory requirement to keep the oil content as low as possible. Section 55 of the Facilities Regulations does also state that facilities for treatment of produced water shall be designed in such a way that oil content in each discharge is as low as possible. …. According to Section 11 of the Framework Regulations, «the responsible party shall choose the technical, operational, or organizational solution that (…) offer the best results. In addition, ***Section 23 of the Management Regulations*** and Section 15 of the Framework Regulations demand continuous improvement. Therefore, the Norwegian Environment Agency expect that the results from the risk assessment are applied further in new BAT assessments and potential measures to reduce the environmental risk for each field. ….		

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Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	Safety Authority can set additional requirements regarding discharges of produced water. The operator shall obtain permission according to Chapter 3 of the Pollution Control Act (in Norwegian only) for injection of produced water.			
	§ 67 Emergency preparedness chemicals If the operator plans to keep chemicals in preparedness for safety reasons, an overview of these shall be prepared. The operator shall have guidelines for when and in what quantities and concentrations the emergency preparedness chemicals will be used. The guidelines shall be based on risk analyses, ***cf. Chapter V of the Management Regulations.***	**Re § 67 Emergency preparedness chemicals** The operator must obtain a permit from the Norwegian Environmental Agency for petroleum activities under Chapter 3 of the Pollution Control Act (in Norwegian only). Application for permit under the Pollution Control Act is subject to Chapter 36 of the Pollution Control Regulations (in Norwegian only), and a fee is fixed for the Environmental Agency's processing relating to applications for permits pursuant to Chapter 36 of the Pollution Control Regulations (in Norwegian only). ….	No conflict	
	§ 73 Establishment of emergency preparedness The operator or the party responsible for operating a facility shall prepare a strategy for emergency preparedness against hazard and accident situations, cf. also the ***Management Regulations Section 9 litera c.*** The emergency preparedness shall be established, inter alia, on the basis of results from risk and emergency preparedness analyses as mentioned in ***Section 17 of the Management Regulations*** and the defined hazard and accident situations and barrier	**Re § 73 Establishment of emergency preparedness** To fulfil the requirement relating to the strategy as mentioned in the first subsection, the standard ISO 15544 should be used for health and safety-related emergency preparedness. The defined hazard and accident situations as mentioned in the first subsection, mean a representative selection of hazard and accident	No conflict, but RISP method must provide necessary input to establishment of emergency preparedness.	

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Criticality	Activities Regulations	Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	performance requirements, cf. ***Section 5 of the Management Regulations.*** For the establishment of emergency preparedness with dispersants and beach-cleaning agents, refer to Chapter 19 of the Pollution Control Regulations (in Norwegian only). The emergency preparedness against acute pollution shall cover the ocean, coast and shoreline. The operator shall have three independent barriers, cf. Section 5 of the Management Regulations, one near the source, one in fjord and coastal waters and one at shoreline. The barrier near the source and in the open sea shall be able to handle the quantity of pollution that can fall to the barrier. Barriers in fjord and coastal waters and at shoreline shall be able to handle the quantity of pollution that can fall to the barrier after the effect of the previous barrier has been taken into account. Where the emergency preparedness is related to activities as mentioned in Section 25 of the Management Regulations, Section 26 of the Management Regulations applies. The Norwegian Environmental Agency can make further demands on the extent of emergency preparedness against acute pollution.	situations used in the dimensioning of the emergency preparedness. In order to fulfil the requirement relating to establishing emergency preparedness as mentioned in the first subsection, the NORSOK U-100N standard, Chapters 5.1.5 and 9, should be used for manned underwater operations. The emergency preparedness shall be coordinated, cf. Section 20 of the Framework Regulations, and the operator shall cooperate with other operators, cf. Section 21 of the Framework Regulations. The results of the environmental risk and emergency preparedness analysis and the description of planned emergency preparedness, as mentioned in the first subsection, should be submitted as part of the application for permit pursuant to the Pollution Control Act (in Norwegian only).		

Appendix C Detailed review of Management regulations

Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	§ 4 Risk reduction In reducing risk as mentioned in Section 11 of the Framework Regulations, the responsible party shall select technical, operational and organisational solutions that reduce the likelihood that harm, errors and hazard and accident situations occur. Furthermore, barriers as mentioned in Section 5 shall be established. The solutions and barriers that have the greatest risk-reducing effect shall be chosen based on an individual as well as an overall evaluation. Collective protective measures shall be preferred over protective measures aimed at individuals.	When choosing technical, operational and organisational solutions as mentioned in the first subsection, the responsible party should apply principles that provide good, inherent health, safety and environment qualities.	Relevant for RISP. No conflict	How can we demonstrate that RISP contributes to reduce the likelihood sufficiently?
	§ 5 Barriers This section includes many requirements to safety barriers. Example: Necessary measures shall be implemented to remedy or compensate for missing or impaired barriers.	Refers to: Norsok Z-013, NS-ENISO 17776, NS-EN ISO 13702, IEC 61508, IEC 61511, IEC 62061, ISO 13849 and Norwegian Oil and Gas' Guideline 070	Relevant for RISP. Possible conflict (with standards)	What does "impaired" mean in RISP?
	§ 6 Management of health, safety and the environment The responsible party shall ensure that the management of health, safety and the environment comprises the activities, resources, processes and organisation necessary to ensure prudent activities and continuous improvement, cf. Section 17 of the Framework Regulations.		Relevant for RISP. Possible conflict.	How can we demonstrate continuous improvement in RISP?
	§ 7 Objectives and strategies The responsible party shall stipulate and further develop objectives and strategies to improve health, safety and the environment. The operator shall ensure		No conflict.	Companies should ensure RISP contributes to meet objectives and strategies.

Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	agreement between short-term and long-term objectives in various areas, at various levels and between various participants in the activities. The objectives shall be expressed so that the degree of achievement can be assessed.			
	§ 8 Internal requirements The responsible party shall set internal requirements that put regulatory requirements in concrete terms, and that contribute to achieving the objectives for health, safety and the environment, cf. Section 7 regarding objectives and strategies. If the internal requirements are expressed as functional requirements, achievement criteria shall be set. The operator shall ensure agreement between its own requirements and between its own and other participants' requirements.		No conflict.	Companies should update internal requirements to reflect RISP
	§ 9 Acceptance criteria for major accident risk and environmental risk The operator and the party responsible for operating a mobile facility, shall set acceptance criteria for major accident risk and for environmental risk associated with acute pollution. Acceptance criteria shall be set for 1. the personnel on the offshore or onshore facility as a whole, and for personnel groups exposed to particular risk, 2. loss of main safety functions for offshore petroleum activities, 3. acute pollution from the offshore or onshore facility,	The acceptance criteria that the party responsible sets for the design of a facility, has great significance for that the acceptance criteria can be met in the operational phase. Hence, both the party responsible for operating a mobile facility and the operator shall set acceptance criteria in areas under their responsibility. Acceptance criteria as mentioned in the first subsection, shall express and represent an upper limit for what is considered an acceptable risk level for the various categories mentioned in literas a to d. As ensues from Section 11 of the Framework Regulations, complying with health, safety and environmental legislation constitutes an important	Relevant for RISP. Possible conflict	How are acceptance criteria demonstrated in RISP? Reference is made to Norsok Z-013 for example. Can RISP be considered an additional example?

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Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	4. damage to third party. The acceptance criteria shall be used when assessing results from risk analyses, cf. Section 17. Cf. also Section 11 of the Framework Regulations.	parameter for this upper limit and it is accordingly not permitted to set aside specific requirements in the health, safety and environmental legislation in respect of risk calculation. Additional risk reduction shall always be considered, even if the results of risk analyses or risk assessments indicate a level of risk that is within the acceptance criteria, cf. Section 11 of the Framework Regulations. The acceptance criteria shall be formulated so that they are in accordance with the requirement for suit-able risk and preparedness analyses, cf. Section 17, and are suitable for providing decision-making support in relation to the risk analyses and risk assessments carried out. Major accident means an acute incident such as a major spill, fire or explosion that immediately or sub-sequently entails multiple serious personal injuries and/or loss of human lives, serious harm to the environment and/or loss of major financial assets. Acceptance criteria for acute pollution shall include the risk of acute pollution to occur (the area of authority of the Petroleum Safety Authority Norway) as well as the risk of harm to the external environ-ment/environmental risk (the area of authority of the Norwegian Environment Agency).Offshore petroleum activities See Annex A of the NORSOK Z-013standard for a description of different types of acceptance criteria that may be used for major accident risk and environmental risk as mentioned in subsection 2 literas		

Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
		a, c and d. See Annex B Chapter 4 of the standard for a complementary description of the acceptance criteria for loss of main safety functions as mentioned in subsection 2 litera b, cf. Section 11 of the Facilities Regulations. For information, see also Section 7 of the Facilities Regulations. The operators that have facilities and activities in the same area, should cooperate on principles for establishing acceptance criteria, so that they are in a comparable form among operators, and so that they 7form a suitable basis for e.g. establishing joint emergency preparedness, cf. Section 21 of the Framework Regulations.		
	§ 10 Measurement parameters and indicators The responsible party shall establish measurement parameters to monitor factors of significance to health, safety and the environment, including the degree of achievement, cf. Sections 7 and 8. The operator or the party responsible for operation of an offshore or onshore facility shall establish indicators to monitor changes and trends in the major accident risk and environmental risk.	The measurement parameters as indicated in the first subsection, and the indicators as mentioned in the second subsection, are used in the work to monitor and assess the risk level. Key measurement parameters and indicators as regards the risk level, are identified on the basis of risk assessments. The requirement in the second subsection includes indicators to monitor key factors that influence risk. The indicators should be both proactive and reactive, and reflect technical, organisational and human factors.	No conflict	Can traditional QRA results be considered an indicator?
	§ 11 Basis for making decisions and decision criteria Before decisions are made, the responsible party shall ensure that issues relating to health, safety and the environment have been comprehensively and adequately considered.	Comprehensively and adequately considered as mentioned in the first subsection, means e.g. that re-ports, data and analyses included in the basis for decisions, are of the necessary quality, that different alternatives and consequences have been studied, and that	Relevant for RISP. Possible conflict	What are the decision criteria in RISP?

Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	The decision criteria shall be based on the stipulated objectives, strategies and requirements for health, safety and the environment and shall be available prior to making decisions. Necessary coordination of decisions at various levels and in different areas shall be ensured so that no unintended effects arise. Assumptions that form the basis for a decision, shall be expressed so they can be followed up.	relevant experts and user groups have been involved		
	§ 16 General requirements for analyses The responsible party shall ensure that analyses are carried out that provide the necessary basis for making decisions to safeguard health, safety and the environment. Recognised and suitable models, methods and data shall be used when conducting and updating the analyses. The purpose of each risk analysis shall be clear, as well as the conditions, premises and limitations that form its basis. The individual analysis shall be presented such that the target groups receive a balanced and comprehensive presentation of the analysis and the results. The responsible party shall set criteria for carrying out new analyses and/or updating existing analyses as regards changes in conditions, assumptions, knowledge and definitions that, individually or collectively, influence the risk associated with the activities. The operator or the party responsible for operating an offshore or onshore facility	The term “analyses” is used in a broad sense here. Specific requirements for analyses are stated in the other sections in this chapter, in the Facilities and Activities Regulations, and in the Technical and Operational Regulations. Recognised methods and models as mentioned in the first subsection, mean the methods and models that have been tested and validated prior to use. Suitable methods and models as mentioned in the first sub-section, mean that various models and methods shall be evaluated and selected in relation to the individual analysis’ purpose and need for decision support. The requirement to use recognised and suitable data as mentioned in the first subsection ,entails clearly detailing that the data is representative and valid, as well as its limitations. Target groups as mentioned in the third subsection, means e.g. decision-makers, employees and their elected representative. The requirement to establish criteria for updating existing	The RISP concept is not in conflict with this section, however the section provides requirements to the methods established in RISP.	What is “necessary basis for making decisions…”? Er RISP en slik basis?

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Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	shall maintain a comprehensive overview of the analyses that have been carried out and are underway. Necessary consistency shall be ensured between analyses that complement or expand upon each other	analyses or for carrying out new analyses as mentioned in the fourth subsection, apply to changes in or deviations from the purpose, limitations, assumptions and premises used as a basis in existing analyses. The criteria shall be established solely with a view to securing the necessary basis for decisions, as mentioned in the first subsection.		
	§ 17 Risk analyses and emergency preparedness assessments Includes many detailed requirements to risk and emergency preparedness analyses.	Reference to Norsok Z-013 and ISO31000. Many requirements to risk analyses. Two relevant regulators: PSA and the Norwegian environmental agency (Miljødirektoratet). Will RISP provide the probabilistic numbers being used in environmental risk analyses?	Relevant for RISP. Possible conflict.	Need to verify that RISP meets all requirements in this section. Many details to be verified.
	§ 23 Continuous improvement The responsible party shall continuously improve health, safety and the environment by identifying the processes, activities and products in need of improvement, and implementing necessary improvement measures. The measures shall be followed up and the effects evaluated. The individual employee shall be encouraged to actively identify weaknesses and suggest solutions, cf. Section 15 of the Framework Regulations. Applying experience from own and others' activities shall be facilitated in the improvement work.	Identification as mentioned in the first subsection, can be based in part on the results of analyses and surveys, investigation of hazard and accident situations, handling of nonconformities, experience gained from internal follow-up or experience gained by others. For requirements as regards implementing improvements, cf. also Section 11and Section 13. See also the following standards: NS-ENISO 9000, Chapter 2.3.5 and NS-ENISO 9004, Chapter 11.2.Applying experience as mentioned in the third subsection, can e.g. include information on faults and defects, as well as examples of good problem-solving and practices.	Relevant for RISP. Possible conflict	How can we ensure continuous improvement in RISP?

Criticality	Management regulations - Section	Management regulations - Guideline	Relevance - Mismatch/Conflict	Comments/Suggestions
	§ 26 Contents of applications for concent Includes many requirements to applications of concent. One example is: G) ...a description of the analyses and assessments that have been carried out as regards health, safety and the environment for the activities and offshore or onshore facilities covered by the application, and the results and measures that will be implemented as a result of these assessments		Relevant for RISP. No conflict.	

RISP – Ship collision risk

Equinor Energy AS

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Table of Contents

1 Introduction

This report covers the assessment of accidental loads related to ship collisions. The main focus is to set realistic design loads for the offshore facility related to vessel traffic in the area and field vessel activity. The intention is to give good input to identify relevant scenarios and set a validity envelope for assessing realistic impact loads using RISP. The work is to a large extent based on the results from a recent industry project related to vessel collision risk (Ref. 1) and further work related to investigating collision consequences (Ref. 2).

2 Context

The applicability for RISP will be assessed in the HAZAN (see Section 3.3). During the HAZAN the following should be assessed to verify applicability for RISP:

- Regulatory requirements
- GOMO guidelines
- Overall layout and plans.

The RISP method is developed for oil and gas operations on the Norwegian Continental Shelf. The RISP method comply with Norwegian regulations for petroleum activities and is based on procedures and operating practices which are considered industry practice on the Norwegian Continental Shelf.

2.1 Regulatory requirements

For the ship collision loads assessment to be considered within the RISP validity envelope, it must as a minimum document compliance with the following regulatory and standard requirements:

- PSA Management regulations
  - Section 9: Acceptance criteria for major accident risk and environmental risk
- PSA Facility regulations
  - Section 11 Loads/actions, load/action effects and resistance
- NORSOK S-001 (2018)
- NORSOK N-003 (2017)
  - Section 9.3 Impact actions.

In addition, it must be assumed that all standards for design and construction of ships and its parts are adhered to.

2.2 G-OMO - Guidelines for Offshore Marine Operations

G-OMO is a standard global approach to encourage good practice and safe vessel operations in the offshore oil and gas industry.

The guideline covers all relevant aspects form vessel procurement, voyage planning, mobilisation, loading, outward voyage, approach to location, working at location, departure from location and inward voyage. However, a specific guide is prepared related to collision risk management within G-OMO. This guide includes recommendations related to (Chapter 8 Collision Risk Management[1]):

- Safety Zones
- Bridge Team Organisation and Management
- Approaching Location
- Selection of Station Keeping Method
- Pre-Entry Check Lists

[1] http://www.g-omo.info/wp-content/uploads/2021/11/Chapter-8-rev-1.pdf

- Setting Up Before Moving Alongside
- Use of Dynamic Positioning
- In Operating Position and Change of Operating Location
- Weather Side Working
- Departure and Commencement of Passage
- Field Transits.

The RISP method apply for facilities applying these recommendations.

2.3 Overall layout and plans for the marine operations

When the supply and lifting strategy are established, a coarse description of procedure and restrictions should be developed. Procedures need to be developed to ensure safe vessel operations including considerations of:

- Material handling
  - location of laydown area(s)
  - crane location
  - supply vessel loading position
- Riser and conductor
  - location relative to vessel operating position
  - protection of risers
- Offloading location
- W2W vessel - Bridge landing area
- Weather restrictions.

All this to define safe loading position and to set operational restrictions. Normally lifting from supply vessels and shuttle tanker offloading is preferred in downwind position of the facility and away from unprotected risers.

Based on these layout considerations, the design loads application areas (for impact loads) are known.

2.4 Framework for design of topside arrangements protection

All topside arrangements that according to the plans may be exposed to collision impact loads should be designed to withstand the loads with enough robustness to render unlikely a release of hazardous material or loss of main safety function.

2.5 Strength of knowledge

Assessment of the risk associated with collision risk has been performed over many years and is well understood in the petroleum industry. The RISP method for collision impact loads/energies has therefore no additional conservatism due to lack of knowledge about the phenomenon. However, the risk modelling of consequences of impacts is still under further development.

Conservatism in the RISP method is therefore linked to the simplified approach.

3 Proposed RISP Method

Main steps of the recommended method are as follows:

1. Establish context of analysis
2. Safety critical systems and barriers that shall withstand collision loads shall be identified.
3. Define the representative collision scenarios i.e. vessel types and phases (HAZAN)
4. Evaluate damage of impact i.e. the allocation of collision/impact energy between the vessel and facility and the impact of the damage
    a. Understand the structural deformations
    b. Understand the damage impact of the deformations
5. For each representative scenario, set the relevant design loads for safety critical systems and barriers
6. Assess and describe uncertainty – Evaluate and demonstrate strength of knowledge

These steps are set up to sort out which design scenarios that are relevant and representative for the concept in question and which of those design scenarios that are within the RISP envelope and which design scenarios that require additional assessments.

3.1 Establish the context

Main steps of establishing context of analysis are:

- Determine who is the users of the results
- Determine which decisions are this analysis supporting
    - Milestones for design accidental collision loads and critical decision gates for design input shall be identified.
- Operational phases and operations that are covered

Describe the involved system; Installation, vessels and surroundings:

a) Describe installation: Location, layout and geometry, manning, operational limitations, structural information,
b) Describe vessels and vessel traffic:
    i. Visiting vessel: visit frequencies, types (bow, class, displacement) including consideration of future vessel development i.e. size of vessel and bow types
    ii. Vessel on passing course: Traffic surveillance (AIS and radar) data, displacement estimation
c) Vessel operations:
    i. Describe normal (visiting) vessel operations – offloading location, times, approaches
d) Identify and describe relevant barriers in place i.e. use the barrier maps (both visiting vessels and vessels on passing course)
e) Surroundings: Metocean data

3.2 Identification of critical system and barriers

Safety critical systems and barriers that shall withstand collision loads shall be identified. Safety critical systems and barriers that need to maintain function after collision, given as survivability requirements in NORSOK S-001 are typically:

a. Structures - main structures (load bearing, stability and floatability) and other critical structures such as derrick and flare tower
b. Marine systems and position keeping
c. Containment - Riser and topside equipment
d. Well integrity - Conductor

3.3 HAZAN and validity envelope

Through the HAZAN define the representative collision scenarios i.e. vessel types and phases:

- An appropriate set of representative operating scenarios must be established. Each representative scenario will have a unique set of initial conditions
- Identify visiting vessel types and size (displacement)
- Identify relevant barriers in place and discuss whether the RISP methodology is applicable within a validity envelope.

Based on experience from operations in the NCS, the following identified hazards (collision scenarios) should be considered, but not limited to:

- Passing vessels – vessel traffic with no relation to the specific facility
- Supply vessel
- Standby vessel
- Shuttle tanker – field specific
    - DP operation
    - Conventional
- W2W- vessel – for the facility
- Flotel
- Field-related
    - Installation vessel
    - Heavy-lift vessel
    - Pipe-laying vessel
    - Anchor handling vessel
    - Multi-purpose vessel
- Other – area and site-specific activities with floating vessels or barges

Scenario phases

For visiting vessel visit four phases should be addressed;

- Phase A - on arrival,
- Phase B - manoeuvring from standby position to operating position, and
    - when been allowed to enter the safety zone, with heading off facility and with steerageway (phase B1)
    - calibration and setup of DP systems, until it is positioned in its intended operating position (phase B2)
- Phase C - operating position.

In addition to the four phases, there is normally a phase where the vessel will be positioned in standby position, possibly for an extended duration, between on arrival and manoeuvring from Standby position to Operating position. It is however expected that the selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) and based on a careful consideration of the current weather conditions and with respect to the field layout and nearby installations. In this case it is assessed that the probability of collision can be efficiently mitigated by selecting this position such that the vessel is not exposing any nearby installations in case of a black out scenario. Being at a safe distance/location it is also assessed that the probability of not being able to respond to and correct a drive-off event (or other failure situations) is negligible.

Facility layout considerations (input to design)– to be discussed in HAZAN:

- Material handling - Laydown area – crane location – supply vessel loading position –> preferred downwind
- Riser location and protection – away from loading position (supply vessel)
- Offloading – location -> preferred downwind
- W2W – bridge landing area.

The RISP methodology is applicable within a validity envelope. This is relevant to address in the HAZAN i.e. separate validity envelopes are assessed per RISP model (hazard and area). In the table below a set of parameters to be discussed in the HAZAN is listed for the different collision scenarios.

Other vessel operations with other collision impact loads, which it is considered and decided not to be designed for, should be specifically addressed with respect to assessment of operational risks and compensating measures. The HAZAN shall document the reasoning not using the relevant scenarios for design input.

Table 3.1 Typical collision scenarios to be considered

Collision Hazard	Barriers and RISP envelope	Input to design load	RISP method
All passing vessels	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) Location away from traffic separation scheme (TSS), at least half of the width of TSS.	No	Perform vessel traffic survey (AIS data) Document degree of operational barriers
All visiting and attending vessels in waiting position	Selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) Weather conditions - vessel is not exposing any nearby installations in case of a black out scenario. Drive-off event fully recoverable	No	
Supply-vessel – on arrival (Phase A)	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure Vessels should set a course which is off set from it and at a tangent to the safety zone	No	
Supply-vessel – when been allowed to enter the safety zone, with heading off facility and with steerageway (Phase B1)	G-OMO-procedure Waiting position downwind facility (e.g. selection of station keeping method and pre-entry check list)	Yes	See section 3.5.1
Supply-vessel – Final approach, operated in full DP mode, from a distance of 150-200 m until operating position and	G-OMO-procedure Loading position down-wind	Yes	See section 3.5.2

operating position (Phase B2 and C)			
Shuttle tanker Conventional (No DP) – visiting	NA	Yes	Detailed assessment required. Outside RISP envelope.
Shuttle tanker – on arrival (Phase A)	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure	No	
Shuttle tanker vessel – Manoeuvring from standby position to operating position (Phase B)	G-OMO-procedure	Yes	See section 3.5.3
Shuttle tanker - Operating position (Phase C)	G-OMO-procedure Weather vaning FPSO 80-100 m offloading distance DP-operation	Yes	See section 3.5.3
W2W vessel	Minimum DP2 Preferred connected downwind Speed requirements Heading and hold time requirements	Yes	See section 3.5.2
Standby vessel	In downwind position	No	
Field-related	Separate risk evaluation	No	
Flotel	Separate risk evaluation	Yes	Use model from Ref. / 2/ and Ref. /3/, outside RISP

3.4 Evaluate the damage impact

Figure 3.1 presents the collision energy model used in this project including the terminology for describing (Ref. 2);

a) The total energy in the collision, equivalent to the kinetic energy of the colliding vessel (assuming the facility is not moving) – *Collision energy*.[2]

b) The energy absorbed by the deformation of the facility and the colliding vessel as a result of the collision – *Deformation energy.* This is further split into *Facility deformation energy* and *Vessel deformation energy*.

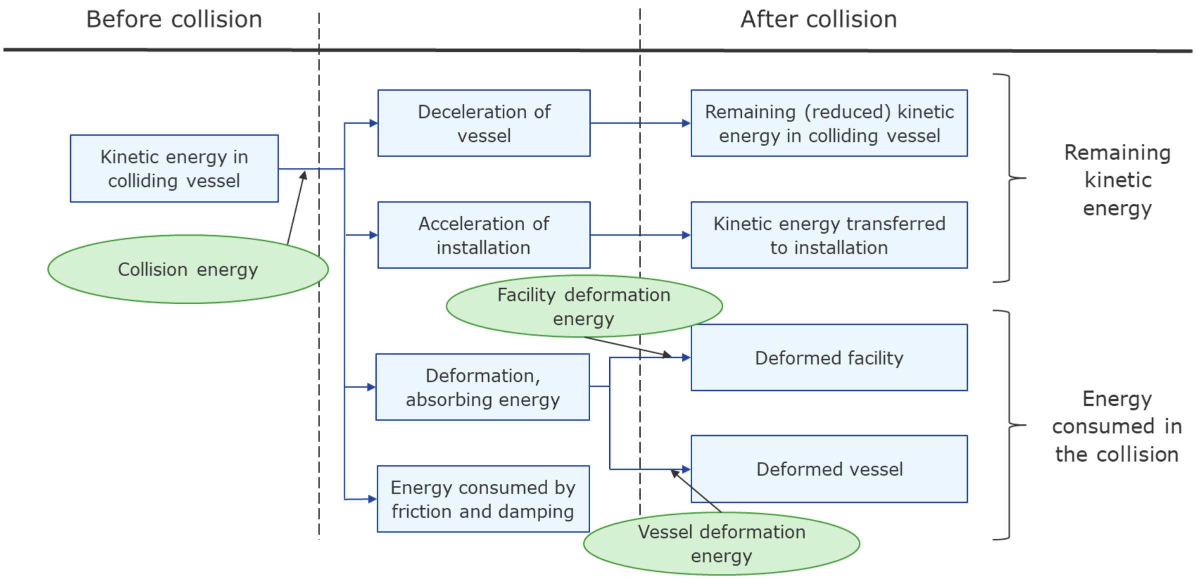

Figure 3.1: Collision energy model including terminology as recommended in this document.

The collision energy (E_s) can be calculated by the equation, by using the vessel mass (displacement in kg) (m_s), the vessel added mass (a_s) and its impact velocity (V_s):

$$E_s = \frac{1}{2}(m_s + a_s)V_s^2$$

The added mass accounts for the hydrodynamic forces that act on the ship during a collision. There are a number of factors that need to be considered when assessing the added mass for a vessel, such as the shape of the vessel, its draught and the duration of the impact. Frequently used added masses are 10% for stern/bow on collisions and 40% for broadside collisions.

[2] Prior to a collision scenario between a facility and a colliding vessel it is assumed that the vessel is the only moving part; i.e. that the facility is not moving, and thus that the kinetic energy of the facility prior to the collision is zero. If the facility has the potential to drift or drive-off of position, e.g. a floatel or drilling rig, this may be the colliding vessel, either colliding with another nearby facility or a nearby vessel. It is however assumed that only one of the colliding parties will have velocity prior to the impact.

With respect to the consequence modelling, the following factors are taken into consideration:

- Energy dissipation between the vessel and platform, i.e. not all initial kinetic energy will be transferred to the platform structure and lead to plastic deformation. In direct hits, all energy is absorbed by the vessel and the platform structures. Typically, in low energy impacts most of the energy will be taken up by the facility. For high energy impacts, most of the energy will be taken up by the vessel. Smaller vessels absorb more of the energy than large vessels.
- It is important to note that the energy distribution between vessel and facility depends on several factors such as type of bow, size of vessel, collision angle, point of contact(s) etc. Without a detailed structural analysis of the specific platform and relevant vessel it is challenging to conclude with certainty about the energy distribution.

In view of the above-mentioned uncertainties, it is difficult to obtain exact numbers for how much of the energy that is distributed between the platform and vessel. A guideline for establishing the energy distribution between vessel and installation has been developed. This guideline is outlined in Section 3.6.

Based on the work performed in Ref. 2 a set of recommended collision velocities were given (Ref. 3). The recommended collision velocity distributions (beta-distribution) for different event types are listed in Table 3.2.

Table 3.2 Recommended collision velocity distribution (beta-distribution) per event type (Ref. 3)

Operation phases	Min. velocity [m/s]	Max. velocity [m/s]	Alfa-factor	Beta-factor	Recommended collision frequencies [per visit]
Phase A, OSV	0	6.0	1.3	0.8	4.6E-07
Phase B1, OSV	0	5.0	1.3	0.8	1.2E-06
Phase B2, OSV	0	3.0	0.8	2.0	4.9E-06
Phase C, OSV	0	3.0	0.8	2.0	3.6E-05
Phase A, Shuttle tanker	0	6.0	1.3	0.8	4.6E-07
Phase B and C, Shuttle tanker	0	2.5	1.6	2.3	3.8E-05

3.5 RISP method to define protection towards collisions

The frequency for supply vessel collision is in the order of 4.3E-05 times per visit and should therefore be considered as a dimensioning event. Phase A constitute to about 1% of the total collision frequency and is not regarded as a dimensioning scenario. If we address all phases together, only 3% of the collisions is expected to be in Phase B1.

The proposed RISP method for protection of facilities for collision loads is independent of supply vessel visiting frequency. This means that the RISP method can be more readily applied earlier in a project development than traditional methods.

Both Phase B2 and C are dimension scenarios, even with only a few visits pr year, so the maximum collision velocity of 3 m/s in Table 3.2 should be used. For Phase B1 the highest collision velocity is 5 m/s. Using a collision velocity of 5 m/s will give sufficient robustness to cover all expected collisions.

3.5.1 Supply-vessel – when been allowed to enter the safety zone, with heading off facility and with steerageway – Phase B1

There may be a wide variation in impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact, dissipation of energy between installation and vessel. The corresponding speed in head-on collisions varies and can be up to 5 m/s. Considerations of procedures for field traffic surveillance, speed limitations, and improvements in the design of vessel control systems also play an important role in giving realistic impact scenarios. About 3% of the historical collisions have occurred in Phase B1. If an impact velocity of 3 m/s is used as input to design, the DAL corresponds to the 98% of the expected collision impacts.

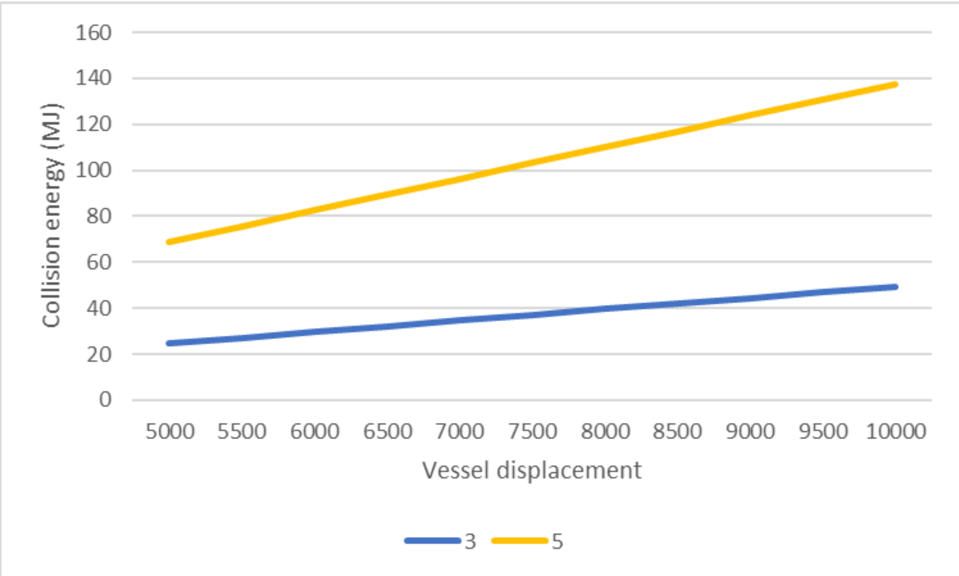

Figure 3.2 Collision energy for phase B1, impact velocity 3m/s and 5m/s respectively

3.5.2 Supply-vessel and W2W vessel – Final approach, calibration and setup of DP systems, until it is positioned in its intended operating position and in operating position (Phase B2 and C)

Due to the limited distance between the vessel and the installation during loading/offloading, the speed at impact given a drive-off is assessed to be low. If there are specific vulnerable collision targets, such as risers or living quarter, it might be necessary to apply a more detailed speed distribution. For a conservative approach, the speed distribution given in

NORSOK N-003 (2017) should be used. There may be a wide variation in impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact. From operating position, it is likely that in addition to head-on collision, the vessel may move sideways, in the aft direction, or even rotating when colliding with the installation. The corresponding speed in head-on collisions shall 3.0 m/s. A hydrodynamic (added) mass of 40% for sideways and 10% for bow and stern impact can be used.

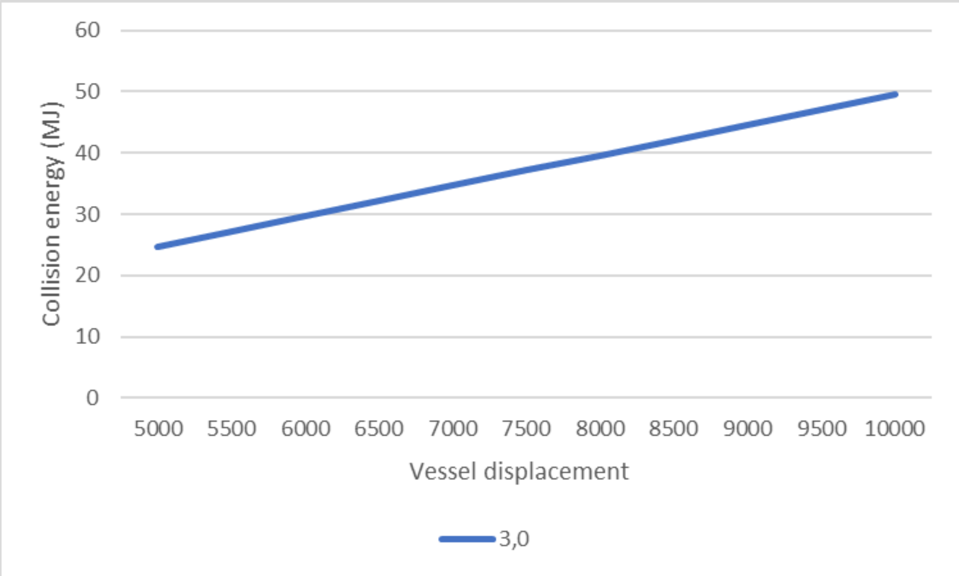

Figure 3.3 Collision energy for bow impact with impact speed of 3m/s

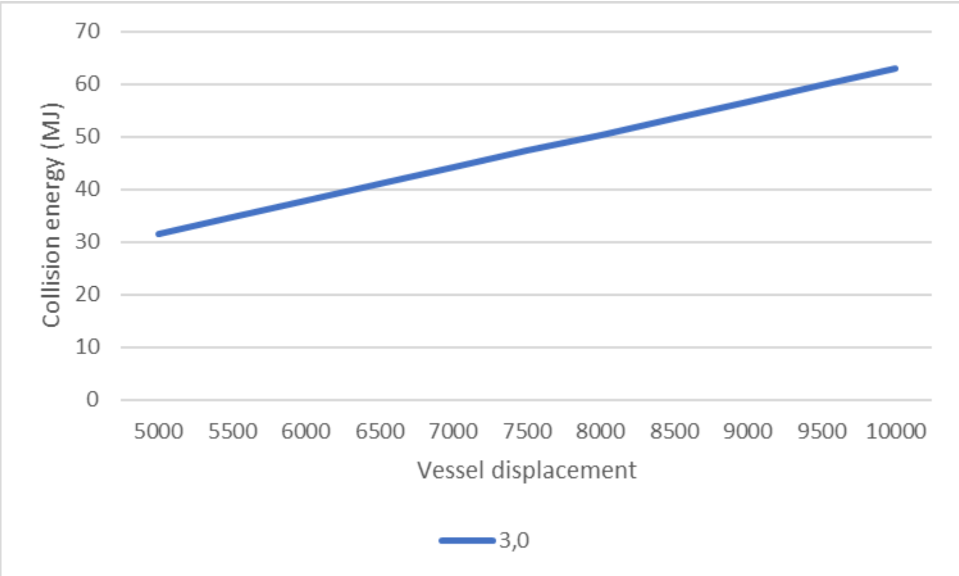

Figure 3.4 Collision energy for broadside impact with impact speed of 3m/s

3.5.3 Shuttle tanker vessel – Manoeuvring from standby position to operating position and operating position (Phase B and C)

NORSOK N-003 (2017) suggest using a minimum collision energy of 100 MJ for collision scenario involving shuttle tanker hitting the stern of a FPSO. According to Ref. 2 this can give too weak design. Head-on collision can have a impact speed of 2.5 m/s and that should be used as input to DAL. This is assessed valid both design scenarios i.e. for the maneuvering from standby position to operating position, and when in operating position.

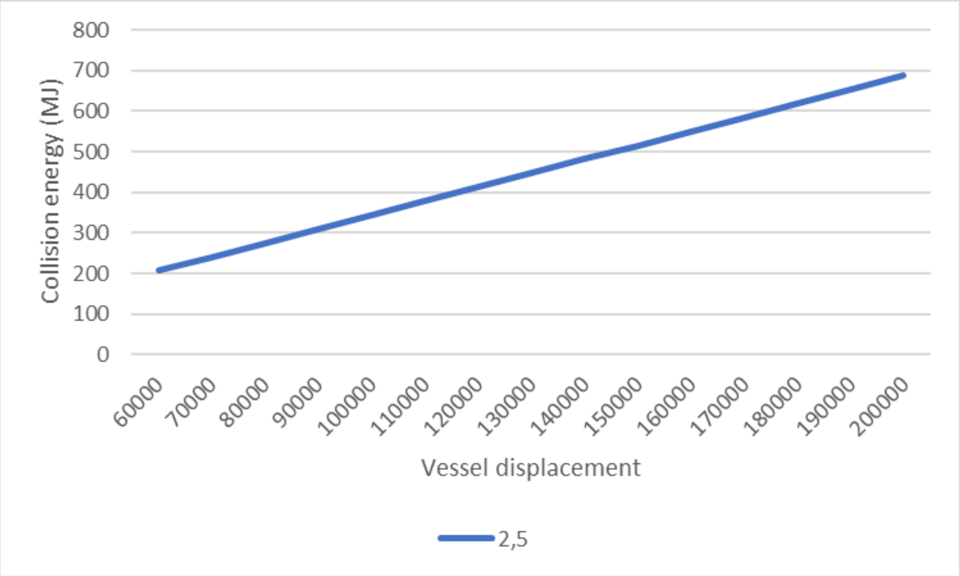

Figure 3.5 Collision energy for shuttle tanker bow impact for different impact speeds

3.6 Application of collision load energy

An important step in the consequence assessment is to evaluate damage of impact and the allocation of collision/impact energy between the vessel and facility. The following steps are proposed in Ref. 2 in order to establish a reliable allocation of collision energy for use in collision consequence modelling:

1. Establish the collision energy, as per section 3.5. This is the kinetic energy prior to impact.
2. Estimate the part of the collision energy that will remain as kinetic energy after the impact.
3. The remaining part of the collision energy is the deformation energy (strain energy) causing damages to the facility and the impacting vessel.
4. The allocation of deformation energy between the facility and impacting vessel and the structural damages to the facility are given by structural impact response analyses. The following steps are recommended:
    a. The analyses should normally be based on an assumed vessel type/stiffness
    b. Preferably the structural analyses should be carried out to find the limiting deformation energies (or contact pressures for strength design) of the facility, in order to provide info that could be reused at a later stage. The practice has been to stop when the (current) design criteria are fulfilled.

The distribution of energy shared by the facility and the vessel is different for different vessel types, impact locations and energy levels. Simplified estimates for allocation of energy for a range of vessel types and impact points (on vessels) may be calculated, provided the structural analyses also provide the capacity for ductile design (deformation energy capacity for the installation). These estimates will however be less accurate than supplementary structural analyses as the relative strength will change when another assumption is made with respect to the impacting vessel.

A method was developed in the industry project (Ref. 1). The method was developed as a guidance to us of DNVGL-RP-C204 "Design Against Accidental Loads" (Ref. 4) and DNVGL-RP-C208 "Determination of structural capacity by non-linear finite element analysis methods" (Ref. 5).

3.7 Consequence modelling

The summary of relevant collision scenarios, with relevant type of hit is shown in Table 3.3.

Table 3.3 Relevant collision scenarios to be considered

Vessel operating condition/phase	Type of hit to be considered
Passing vessel	Bow hit
Drifting vessel	Broadside
OSV – on arrival	Bow hit
OSV – Manoeuvring from standby position (after entering clearance)	Bow hit
OSV – Manoeuvring from standby position to operating position in DP-mode	Broadside
	Stern hit
OSV - Operation position	Broadside
	Bow hit
	Stern hit
Shuttle tanker – Manoeuvring from standby position to operating position	Bow hit
Shuttle tanker - Operation position	Bow hit
Floatel – operating position	Ponton hit
	Topside hit
General	Topside hit

For bow hit, both direct hit and glancing blow should be considered. For broadside hit, both midship hits and hits with rotation should be considered. For stern hits, both direct hit and stern corner hit should be considered.

The probabilistic distribution of the different collision scenarios is dependent on the vessel width and geometrical considerations of the facilities sub-structures (number of legs or columns, width of structures, height to topsides etc.). This can be set for each case specifically, but ref. 2 has given some guidance on how to set these probabilities.

Some general guidance for each phase is shown in Table 3.4. The probabilities given in table is based on a combination of knowledge from accidents and considerations of operational procedures.

Table 3.4 Hit types for each phase

Phase	Bow hit	Broadside hit	Stern
Passing vessel – powered	100 %	NA	NA
Passing vessel - drifting	Insignificant	100 %	Insignificant
Supply - Phase A	100 %	Insignificant	Insignificant
Supply - Phase B1	100 %	Insignificant	Insignificant
Supply - Phase B2	10 %	70 %	20 %
Supply - Phase C - drift off	Insignificant	70 %	30 %
Supply - Phase C - drive off	10 %	70 %	20 %
Shuttle tanker – phase B and C	100 %		

A more detailed distribution should be considered, see Table 3.5. For bow hit, both direct hit and glancing blow should be considered. The distribution of direct hit versus glancing blow is based on historical events. For broadside hit, both midship hits and hits with rotation should be considered. For stern hits, both direct hit and stern corner hit should be considered.

Table 3.5 Hit types for each phase with subcategories of hit types

Phase	Bow hit		Broadside hit		Stern	
	Direct hit	Glancing blow	Midship	Fore/aft with rotation	Direct hit	Stern corner
Passing vessel – powered	40 %	60 %				
Passing vessel - drifting			50 %	50 %		
Phase A	40 %	60 %				
Supply - Phase B1	40 %	60 %				
Supply - Phase B2	Insignificant	10 %	50 %	20 %	10 %	10 %
Supply - Phase C - drift off			35 %	35 %	15 %	15 %
Supply - Phase C - drive off	Insignificant	10 %	50 %	20 %	10 %	10 %
Shuttle tanker – phase B and C	40 %	60 %				

In addition, the scenario definition considers the facility layout and type of hit points, see Table 3.6.

Table 3.6 Relevant hit points to be considered

Facility type	Hit points to be considered
GBS structure	GBS structure Topside structure
Jacket	Leg Bracing Topside structure Riser
Jack-up	Tie-beam Bracing Topside structure Drill string/riser
Semi-sub	Column and pontoon Bar Diagonal bracing Topside structure (incl. any reserve buoyancy elements in the deck) Tethers/anchoring Drill string/riser
FPSO	Between bulkheads At bulkhead Tank with risers Tank with equipment Topside structures i.e. flare tower, crane pedestals Stern

An important step in the consequence assessment is to evaluate impact of damage. Given the different collision scenarios including the hit types, a set of structural deformation cases is defined. Such a set of structural deformation cases is defined for each facility type. The risk modelling considers that one collision scenario (hit type and hit point on facility) can lead to several cases of structural deformations depending on the energy distribution. The following main categories of structural deformation cases are:

- Global overload of the structure
- Loss of load carrying capacity or loss of stability
- Damages

It is also important to look at other consequences than damages to structures. Location of critical equipment (risers, support structure, etc.) is an important factor in evaluating the potential outcome of a collision. Low energy impact collisions may have serious consequences when damaging critical equipment.

To be able to fully understand the collision risk the industry project (Ref. 2) have chosen to define a set of damage impact cases. The intentions of defining damages cases are to look at possible outcomes of the structural damages. An important parameter for risk is the time frame for which evacuation is possible. Damage impacts cases can be:

- Immediate collapse or capsize i.e. no time for evacuation
- Deferred collapse or flooding (loss of integrity or stability) – some or limited possibility for evacuation before collapse/capsize
- Damage – sufficient time available for evacuation, typical 1 hour, but possible immediate fatalities
- Little/no damage – no fatalities
- Other damage impacts (riser leak, storage tank leak etc.)

Dependent on facility type, there are additional damage impacts that needs to be evaluated, such as:

- Riser or drill string leaks and possible explosion and fire consequences
- Storage tank leak
- Damage to topside equipment such as flare, tanks, structures and lifeboats

3.8 Application of methods in design

No specific input.

4 Summary of key results

Key results from the evaluation made for the various Major Accident Hazards (MAH) considered in Chapter 2 to 13, are summarised in Table 4.1. Further details can be found in the respective Chapters.

Table 4.1 Summary of key results for evaluated MAH.

Ref. (Chapter)	Hazard	Key RISP requirements	Validity envelope / premises	Comments
3	All passing vessels	Not a DeAE	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) Location away from traffic separation scheme (TSS), at least half of the width of TSS.	Important to do a Vessel traffic survey of AIS data and assess degree of operational barriers in place.
3	All visiting and attending vessels – on arrival	Not a DeAE	Traffic surveillance, alert and evacuation procedure (NORSOK S-001, section 25) G-OMO-procedure	
3	All visiting and attending vessels in waiting position	Not a DeAE	Selected standby position will be sufficiently far away from the installation (i.e. outside the safety zone) Weather conditions - vessel is not exposing any nearby installations in case of a black out scenario. Drive-off event fully recoverable	
3	Supply-vessel – when been allowed to enter the safety zone, with heading off facility and with steerageway (phase B1) W2W vessel	Head-on collision with larges vessel with impact speed of 3 m/s.	G-OMO-procedure Waiting position downwind facility	Consider impact scenarios, e.g. direct hit or glancing blows, and a varying degree of speed reduction prior to impact, dissipation of energy between installation and vessel.
3	Supply-vessel – Final approach, operated in full DP mode, from a distance of 150-200 m until operating position and operating position (Phase B2 and C)	The corresponding speed in head-on collisions with largest vessel shall be 3.0 m/s.	G-OMO-procedure Loading position down-wind	

	W2W vessel			
3	Shuttle tanker vessel - Manoeuvring from standby position to operating position and operating position (Phase B and C)	Head-on collision with impact speed of 2.5 m/s.	G-OMO-procedure Weather vaning FPSO 80-100 m offloading distance DP-operation	
3	Shuttle tanker Conventional (No DP) – visiting	Outside RISP		
3	Standby vessel	Not a DeAE		In downwind position
3	Flotel	Outside RISP		Use industry model in Ref. 1 and 2.

5 References

1 JIP report (LR/DNVGL/Safetec): “JIP visiting vessel collision risk assessment methodology”, Report no: 106074/R1, Rev. Final B, dated 07.05.2019.

2 JIP report (Safetec/LR/DNVGL/Lilleaker): “JIP Collision Consequences and Risk Modelling”, Report no.: ST-14833-2, Rev. 2.0, Date: 26.06.2020

3 JIP report (Safetec/LR/DNVGL/Lilleaker): “Updated visiting vessel collision frequency estimates and velocity distributions”, Report No.: 2020-0703, Rev. 1, Date: 2020-09-14

4 DNVGL-RP-C204: “Design Against Accidental Loads”.

5 DNVGL-RP-C208: “Determination of structural capacity by non-linear finite element analysis methods”.

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GEXCON

PROJECT REPORT

Addendum to "RISP Report: Work Group 4 - Other Accidents"

High Voltage Hazards

Client

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Addendum to "RISP Report: Work Group 4 - Other Accidents"

Summary

This report summarizes result from a JIP task on transformer hazards in offshore installations. A methodology for hazard identification of HV system has been developed. This report is written and formatted to replace Chapter 6 in RISP work group 4 report.

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1 RISP Report: Work Group 4 - Other Accidents

Transformer hazard was assessed by the RISP Work Group 4 with conclusions summarised in the original report. Since the original RISP report was issued in 2019 (ref [0]), additional efforts have been undertaken assessing transformer risk.

This report summarizes result from work done in 2022 on transformer hazards in offshore installations. A methodology for hazard identification of HV system has been developed. This report is written and formatted to replace Chapter 6 in RISP work group 4 report

1.1 Abbreviations

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AC - Alternating Current
CFD - Computational Fluid Dynamics
DC - Direct Current
HV - High Voltage
CFC - chlorofluorocarbons
LFL - Lower Flammability Limit
LV - Low voltage
LQ - Living Quarter
NMA - Norwegian Maritime Authority
UPS - Uninterrupted Power Supply
PRV - Pressure Relief Valve
RISP - Risk Informed decision Support in development Projects

1.2 Introduction

High voltage system transfers substantial amount of energy and during a fault this energy may be released to the surroundings. A sudden energy release from a HV system represents a potential hazard to the surroundings and these events fall into two main categories:

- Arc in air. When an arc occurs in air some of the energy is transformed into heat and inherent volume expansion. Similar effects may occur when arcs occur in other materials (i.e. some of the energy is released as heat). If the arc occurs in a confined environment the outcome will be overpressure. Such physical explosion may be sufficient to blow doors of their hinges but are generally not viewed to have major hazard potential.

- Arc in equipment insulated by mineral or synthetic/ester oil. When an arc occurs inside oil insulated equipment the insulating oil will decompose and produce flammable gases. Upon release to surroundings and mixing with air a secondary explosion may occur. In high voltage industry there are examples of such explosions generating overpressure of several bars and these events involve substantial hazard potential

Besides the events relating to sudden discharge of energy. i.e. an explosion, the oil insulated components also represent a fire hazard. Large transformers contain substantial quantities of hydrocarbons and although these oils have high flashpoints there is a potential for substantial fires. Fires may also occur in dry insulated transformers and cables, but the hazard potential for these events would be moderate.

As long as best available technology is applied (see section 6.3), transformer fires and explosions are not considered risk drivers for offshore production facilities. The risk of fatalities or escalation to the production systems or wells is low. As transformers are often located in utility areas and close to LQ they do represent some potential for blast loading and fires in areas normally shielded from this type of exposure. Consequently, transformer enclosures should be designed so as to minimise damage and hazard to surroundings.

The main safety function that may be influenced by transformer events is loss of escape/evacuation due to smoke production as well as smoke ingress into LQ and critical areas. Local blast loading may pose a threat to safety functions (UPS etc.) located nearby.

The focus for this text is HV hazards where there is major hazard potential. In practice this will be oil insulated equipment.

As part of RISP a methodology for load prediction has been developed. A key motivator for this task has been hazard prediction in early design stage where the goal is simplistic and generic load prediction or hazard identification. The method is based on a conservative approach which should limit the chance that a project sees higher loads in later design stages.

1.2.1 HV hazards and secondary explosion

Failure in oil filled HV equipment may result in a high voltage arc which will decompose oil into lighter components producing reactive and flammable gases. The main components are hydrogen and acetylene, with smaller amounts of methane, ethylene, ethane and propylene. With a large supply of heat, liquid oil turns to vapour and further contributes to pressure buildup.

When pressure in the transformer exceeds the strength of the tank or connections gas and oil mist is released to the surrounding area and mixes with air. Ignition of this atmosphere will cause a secondary explosion. As the amount of gas is limited, high pressures will not occur without a high degree of confinement. In closes spaces with limited possibilities for pressure venting, explosion overpressure may reach several bars.

1.3 Strength of knowledge

There is a very extensive experience with high voltage transformers in the power industry and in the last two decades there has been much attention on hazard relating to HV transformers. This focus has been spurred by deregulation of the power market (more dynamic loading to the HV systems), banning of CFC based explosion suppression systems and a general aging of transformers in the grid.

In early 2000 a publicly funded research project was initiated to address explosion safety in the power industry with a particular focus on transformers and oil filled HV equipment in subterranean facilities. Many of the power companies have also initiated research and test campaigns. There is also a history of serious transformer events fatalities and high pressure loads.

Since the 2000s it has become a common practice to perform CFD based explosion risk analyses in the power industry. For subterranean plants with poor escape possibilities, it is common to do probabilistic analyses with fatality predictions and 10^{-4}/year criteria for Design Accidental Loads. For above ground transformer stations, simpler consequence-oriented analyses are usually preferred. Break up of transformer tanks and release of flammable material is associated with inherent uncertainty, which adds a substantial degree of uncertainty to these analyses which are then strongly biased toward conservative assumptions. Frequency for serious transformer failure involving rupture of tanks is normally set to 10^{-3}/year. This frequency is based on general statistics of severe transformer failures [1], [2] [3] with a n assumption relating to failure of the transformer tank. Not all of these events with tank failure will lead to explosion overpressure.

10^{-4} /year pressure of transformer rooms in subterranean power stations range between a few 100 millibar to a few barg. These analyses (which count about 50 stations) often refer to facilities with very unfavourable conditions for managing overpressure, hence they are not directly comparable to offshore transformer stations. Experience from onshore industry do show that transformer explosion can be severe events with major hazard potential.

Transformer fires have received less focus onshore. For subterranean stations and built-in transformers the view has been that severe fires are hard to sustain and historically there have been no fires with hazard potential comparable to the worst explosion accidents. Fires in above ground transformers are frequent but generally receives lesser attention as risk to personnel is low (i.e., easy escape). Experience from fires in large transformers indicate that these can be very hard to extinguish even with substantial firefighting efforts. The prospect of severe transformer fires on an offshore installation merits concern.

The strength of knowledge associated with transformer fires and especially explosions must therefore be considered high. It should be emphasised that the breakup of transformer tanks is associated with inherent uncertainty and also that the statistical data are not solid.
Transformer fires and explosions must therefore be considered as design events for RISP development, even if the likelihood of fatalities and loss of main safety functions is low (see also Section 6.1). However it is quite possible to manage these hazards through good design and it is a far easier task than managing explosion hazards in the process areas.

1.4 Validity envelope for RISP

The applicability for RISP will be assessed in the HAZAN (see WG 1 report Section 2.2). During the HAZAN the barriers listed in Chapter 6.3.2 through 6.3.9should be assessed for high voltage systems. A summary of recommended safety safeguards, for HV systems are given in Chapter 6.3.6. The presented RISP methodology for load prediction and fire hazard assume these safeguards to be implemented, thus they constitute the validity envelope for the described methodology, together with the regulatory requirements listed in 6.3.1.

In this document the word "must" is used to define the validity envelope. In addition, guidance is provided for additional risk reduction, normally described with "should", "should be considered", or "recommended"

1.4.1 Regulatory requirements

If the use of high voltage transformers is to be considered within the RISP validity envelope it must as a minimum document compliance with the following regulatory and standard requirements:

- PSA (Management regulations & Facility regulations)
- NMA for floating facilities
- NORSOK E-001
- NORSOK S-001.

1.4.2 Layout

Transformers should only be located where proper venting of explosion overpressure can be achieved. For practical purposes, this implies that transformers should be located with one wall facing sea /open area. As with conventional pressure venting, vent panels should be as light as possible and release at low pressure (0.05 barg or similar)

Pressure venting is possible by large size duct arrangements, but it is often challenging to obtain cost effective and satisfactory solutions. The guidelines and load prediction methods given in this document is not adequate for facilities where pressure venting occur through long pressure vent paths or ducting. Pressure venting through duct arrangements (i.e longer than 2-3 meters) is outside the RISP validity envelope.

Transformers should be separated from the surroundings with fire divisions alternatively by adequate safety spacing. Fire divisions shall withstand the design accidental load (see Chapter 1.5.8).

Separation between the transformers and the surroundings must meet the requirement from NORSOK S-001:

In installations with multiple transformers there is potential for fire escalation or damage to neighbouring transformer unit. The recommended design is to separate transformers in separate fire rated cells. The recommendation is based on safety consideration and production maintenance. This recommendation may be waived if more detailed analysis show the risk to be acceptable

Onshore regulation [4] mandate HV rooms to have two escape options if the rooms are more than 10 m long. This requirement is not mandatory offshore, but is recommended

1.4.3 Structural integrity

Transformer enclosure shall be designed at least Class A-0 fire
divisions (ref S001). Explosion relief panels shall be located such that any pressure and flames are directed toward a safe area (preferential toward sea). With propriate pressure relief arrangement explosion loads will be moderate, and it is recommended to design transformer enclosures for blast resistance. A method for identification of design load is given in Chapter 1.5 . Transform enclosures and associated equipment should be designed in a manner that minimize projectiles to surrounding areas.

1.4.4 Containment and drain

Oil filled transformers shall have bunding and an open drain arrangement to limit environmental spills. When mineral oils are used the drain arrangement shall be designed so as to minimise fire hazard. The collection arrangement/pit shall be sized for full containment of the transformer content and be covered by grating arrangement preventing oil fire in the pit form burning.

There shall be an overflow line to sea sized for firewater & deluge capacity regardless of oil type.

1.4.5 Process safety and HV system barriers

The energy released by the arc will have a large impact on the potential for transformer tank rupture and explosion severity. Measures or safeguards limiting arc duration will greatly impact on the released energy and quick and reliable disconnection will be among the most important safeguards. There are various means to achieve such a safeguarding function. The below sections describe the main principles along with other transformer related safeguards.

Electrical protection
Electrical protection includes methods for reducing the clearing time for internal arcing faults. This can be achieved also by current limiting fuses. Also, the fault current can be reduced by appropriate design of the electrical system of which the transformer is a part. This can be achieved by current limiting reactors, high impedance cable of upstream transformers.

All transformers must have fast reacting electrical protection, and for serious faults like short-circuit at the HV terminal, the reaction time must be in milliseconds. However, if the failure is in the windings, in particular if they are located at LV side, there is a risk of the safety system not reacting so fast, allowing the failure to develop. The impedance in the windings limits the short-circuit current, making it harder to detect for the overcurrent protection system. At the same time, since the impedance limits the short-circuit capacity of the transformer, is also limits the energy in the arc.

Power disconnection
The primary explosion in a transformer will normally be strongly limited if there are good mechanisms installed to quickly disconnect the power in the event of an arc. Buchholz-relay is standard protection in transformers which may stop an arc quite efficiently, and this will limit the energy in the primary explosion (which produce the fuel to the secondary explosion). Pressure sensor inside the transformer will detect pressure from an arc even faster.

Condition monitoring
Online condition monitoring includes dissolved gas monitoring and other indicators of increased likelihood of an arcing fault. Condition monitoring will allow for operational intervention of an event before it develops to be large and potentially fatal.

Online condition monitoring must be applied for RISP projects

Type of cooling agent
Choice of transformer oil will impact on risk. Mineral oil typically has a flashpoint ~130-140 °C while ester or silicon-based oils typically are in the range ~250-300 °C. The flashpoint is a relevant parameter for the propensity of fires but may be less relevant in a situation where an arc transfers MJs of energy into the oil and where the thermodynamic conditions will be far from ambient.

The effect of oil type is expected to have limited impact on explosion although some research [5] suggest beneficial effects especially for AC systems.

Flashpoint is a more relevant parameter for fire and high flashpoint oils can be expected to have both a reduced likelihood of fire and a reduced intensity if fire occur. A high flashpoint will not eliminate the potential for a severe fire.

High flashpoints oils are recommended and should be considered in RISP developments. If mineral oil is used, the combined integrity of all fire barriers needs to be robust.

Pressure Relief Valve (PRV)
Oil-filled transformers are commonly equipped with pressure relief valves that are mounted directly at the tank. The valve will open at high pressure. The set-point for a PRV could typically be 0.35 barg, and the diameter up to 150mm. The PRV can be equipped with a switch that could trip the power supply for the transformer. A pressure-relief device shall be fitted in the cover of all transformers 2 500 kVA and larger or with insulation levels 200 kV and higher [6]

It is normal for onshore applications that gas or oil released through the PRV is released in the transformer room rather than being vented to a safe location. This could represent a hazard for personnel in the area, possibly also representing a fire and explosion risk.

The PRV can be too slow to respond to fast pressure increase from a short circuit but will protect the transformer tank in scenarios with gradual pressure build-up and low-energy arching faults. This could be the case with fire exposure, oil filling operation or other maintenance operations or transformer malfunction scenarios.

PRV is not mandatory in RISP developments but should be considered.

Pressure relief through use of rupture disc
Tank rupture can be prevented by relieving the pressure developed as result of an internal arc. A pressure relief valve will in many scenarios respond too late and with insufficient capacity to prevent rupture.

A “transformer protector” is a protective system comprised of a large rupture disc mounted on the transformer tank, an oil/gas separation tank and a vent. Such a system is activated within milliseconds, and static pressure build-up can be prevented in scenarios with too fast pressure build-up for the PRV or Buchholz relay.

Note that for large transformers the arc may be located at a distance from the rupture disc, and in these cases the effect of the rupture disc is limited (since the pressure increase is too rapid for the disc to be able to vent out a larger column of oil).

Rupture discs shall be considered in RISP developments

Enhanced transformer tank construction
A transformer tank can be designed to have greater tolerance for internal pressure build up and thereby reduce the probability for tank rupture. This is typically achieved by increasing tank strength and by designing the tank to plastic deformation. Such a design will not eliminate tank rupture and it may be argued that some fault events may worsen. Overall enhanced tank construction is viewed beneficial for safety, but the effect is viewed to be moderate

Enhanced transformer tank construction is beneficial but is not a requirement in RISP developments

1.4.6 Fire detection

Transformer rooms shall have fire detection

1.4.7 Passive fire Protection

Beyond fire rating of compartment wall there will normally be no need for passive fire protection. If load bearing structure go through the transform cell /area of transformers, passive fire protection needs to be considered based on the heat rates given in Chapter 1.5.8

1.4.8 Active fire protection

The transformer rooms shall be protected with active fire protection.

Water mist function with automatic initialization upon fire detection is the recommended solution for transformer enclosures. The water mist systems shall provide a quick and reliable discharge of water mist at a sufficient density and at sufficient duration for adequate fire suppression and control. General requirements for water mist systems are covered in ISO 13702. NFPA 750 should be used as guideline for design of water mist systems. System should provide protection for long duration fires.

For transformers with low flashpoint oils additional firefighting arrangement with foam capacity should be considered. Experience for onshore transformer fires is that they are hard to extinguish and that it is difficult to provide foam /extinguishing capacity at the right spots.

The ventilation should cease and dampers close on fire alarm. Shutting off air supply to the transformer cell will limit fire intensity.

1.4.9 Escape and evacuation

Transformer fires and explosions are likely to remain local events with low likelihood of impairment of exposure escape and evacuation.

Escape chute s, life rafts and similar functions should not be located near the vent area of transformer cells. Chapter 1.5 gives indication for blast loads and heat loading to nearby targets.

Impairment of rescue due to smoke is the main impairment hazard and must be considered.

1.5 Proposed RISP methodology

1.5.1 RISP Transformer Hazard: Pressure Loading

As part of RISP a methodology has been developed for load prediction of transformer hazards. A key motivator for this work has been hazard prediction in early design stage where the goal is simplistic and generic load prediction or hazard identification. The method is based on a conservative approach which should limit the chance that a project sees higher loads in later design stages.

The proposed methodology may be used for existing installation to the degree the installation is similar to those presented in this report.

Transformer explosion hazards are not of the same magnitude as conventional explosion hazards in offshore installations. In contrast to conventional process explosions, it is quite possible to design against the worst credible transformer explosion and to do so without substantial cost penalties. The concept of designing for the worst credible events gives a greater margin of safety compared to the conventional risk approach, i.e. designing for 10^{-4} /year criteria. Moreover, it avoids the topic of event frequencies and associated uncertainty.

In the event a project falls outside the envelop of the RISP methodology a more comprehensive method may be chosen. For these situations an alternative would be to follow a probabilistic methodology similar to that adopted in the onshore hydro power plants. Chapter 1.5.3 gives a brief summary and some recommendation for such a situation

The RISP methodology is based on two main elements:

- Properties of the electrical system. Arc energy is a critical factor and is derived directly from properties of the electrical system. There are several factors that will impact on arc energy including type of system (AC or DC), rated power and disconnection functions.

- Physical characteristics of transformer cell and surroundings. The severity of a transformer explosion is strongly tied to the degree of confinement, the volume of the transformer enclosure and conditions for pressure venting.

The RISP methodology involves a simplistic characterisation of the above factors which is then used as the basis for identifying blast load through the use of a look up function. The method incorporates a wide parameter range both for electrical characteristics and physical characteristics of transformer cells. The blast load predictions are based on FLACS simulations. Chapter 1.5.3 gives more background on this methodology along with adaptations made for the SEBK project [7].

The RISP methodology also includes a chapter on transformer fire hazard. It is challenging to quantify the fire hazard associated with a transformer in a similar fashion to that done for explosions. Major hazard potential from a severe transformer fire would normally require failure of several barriers and is affected by mitigation initiated after fire onset. The suggested approach is to adopt a “worst credible fire event”. The event considered is a transformer fire following an explosion where panels are open and active fire protection is not working.

A severe transformer fire can give substantial heat loads with long duration. Heat loading will be local and contained but smoke may expose larger sections and part of LQ. Smoke exposure will be very dependent on the geometry of the installation and may have substantial safety implications. The hazard cannot easily be quantified or formulated in specific design recommendations. Smoke exposure from transformer fires must be considered qualitatively and particular focus should be given to the relative relation between transformer vent openings and targets sensitive to smoke

1.5.2 RISP Explosion methodology

The mains steps of the RISP methodology for transformer explosion is outlined in the below figure. If a design comes out with higher than desirable loads the recommended approach is to increase the pressure vent area. If this is not possible an increase in transformer cell volume or improved electrical protection should be assessed. The concept is illustrated below.

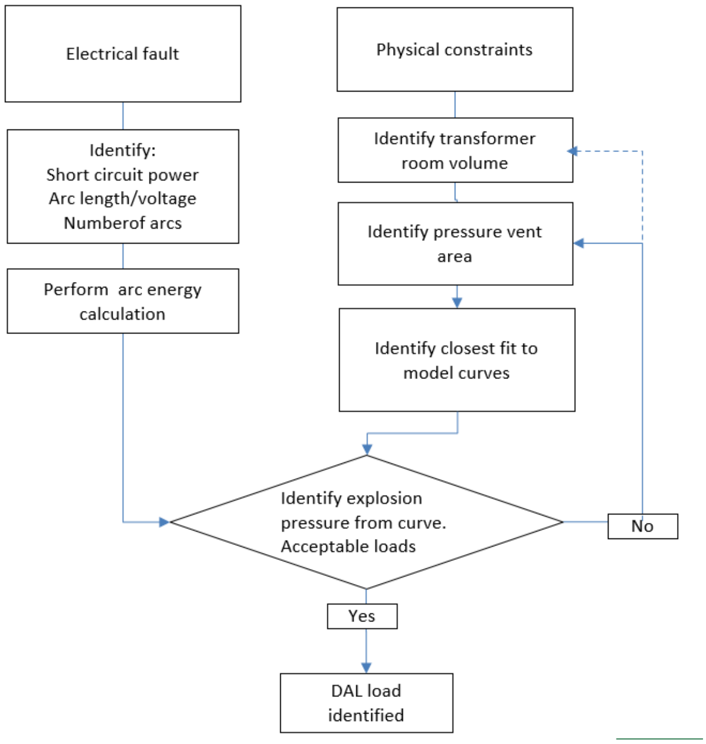


Figure 1: Method overview

1.5.3 Basis for methodology

Since 2000 probabilistic explosion analyses has become an established practice for subterranean transformer installations where pressure venting isn’t an option. The methods were developed as part of the SEBK project [7] funded by the Norwegian Research Council and the power industry.

Key features in the SEBK methodology are:

- Arc energy is calculated by simple correlations and used to determine the amount of decomposed oil. One MJ of energy will produce 0.093 m3 of gas [8] [9]
- Composition of thermally decomposed insulation oil is based on experimental data with main components being hydrogen (74%) and acetylene (21%). [9] The established practice does not assume that ester oils will produce less gas or a notably different composition. The argument is that the heat and energy near the arc will be plentiful and that break up of long chained hydrocarbon (the bulk of insulation oil being C13-C36) would produce similar composition in spite of the additional oxygen (i.e. the ester group). This is a conservative approach as some experimental data suggest reduced gas formation for ester oils.
- The term “oil mist” is used for the mixture of small droplets produced by mechanical break up and evaporated oil. The amount of oil mist is assumed to vary greatly with how the transformer tank breaks up and is associated with substantial uncertainty. In the established probabilistic methodology this is addressed by assuming a wide range of outcomes: the amount of oil mist is set to vary from zero up until 8 times the combustion energy of the decomposed oil. The extreme values are assigned a low probability with the most likely scenarios containing 2-4 times the amount of oil mist. These oil mist estimates are also supported by other sources [10] Butane is normally used to represent oil mist.

- The gas cloud is assumed to either ignite at worst possible time (i.e. where gas is mixed with air in optimal ratio) or at a late time where gas is completely mixed with air. For most events this latter assumption gives concentration below LFL, and in practice the overall ignition probability will be close to 50%. The basis for assessing ignition probability is poor. The arc is an extremely potent ignition source but may not come in direct contact with flammable atmosphere (i.e submerged in oil). Electrical discharge produces temperatures high enough for metals to evaporate and ultimately cause ignition through hot surfaces. Consensus is that ignition is very likely but there are also several examples of severe transformer failure where cells have been sprayed down with oil mist without ignition occurring.
- Gas clouds are assumed to form above the transformer with central ignition and a strong ignition source.
- The established probabilistic methodology take account of whatever electrical fault scenarios are identified and also accommodate scenarios where barriers fail (failure of protective devices)
- The methodology assumes causes for transformer breakdown to be independent events i.e. event probability is multiplied with the number of transformers/oil-filled units.

The established methodology has been focused on AC systems with less attention being focused on DC systems. The fundamental mechanisms should be the same but there are some discrepancies between AC and DC with regard to break down of isolation oils [5]. Generally, loss of insulation capacity occurs more easily with DC than AC, but the general view is that the effect is accounted for by transformer designers. Experimental data on oils [5] also indicates that synthetic or ester oil make less of a difference in DC systems.

In the power industry there is also an established practice for doing simpler consequence-oriented analyses. These are routinely done for above ground transformer stations where pressure venting is possible. The approach can be labelled as “worst credible event” and disregards event probability. The approach assumes a conservative electrical fault scenario but where protective devices work as intended, i.e. worst credible. Furthermore, it is assumed that the amount of oil mist will be large: typically 4 times the combustion energy of decomposed oil. This will produce a large cloud but of moderate reactivity. This type of cloud will generally give a high-pressure load when the degree of confinement is high. Ignition probability is implicitly assumed as unity. The identified scenario is used as a dimensioning event and typically used for sizing of pressure vent arrangement. With a single scenario, alternative design options can easily be assessed through simulations.

The method adopted in the RISP approach is comparable to the “credible worst case” approach described above. The simulated scenario is viewed to be the worst credible event. Protective devices are assumed to work as intended and probability of occurrence factors are disregarded altogether.

1.5.4 Electrical faults

As part of the methodology, simplistic calculation procedures for arc energy are provided. Arc energy may be calculated in alternative ways with varying degree of detail. Although the methods presented here are viewed as appropriate for early-stage generic loads, characteristics of the electrical system may merit some adjustment. It is hence advisable to have arc energy provided or verified by the electrical discipline.

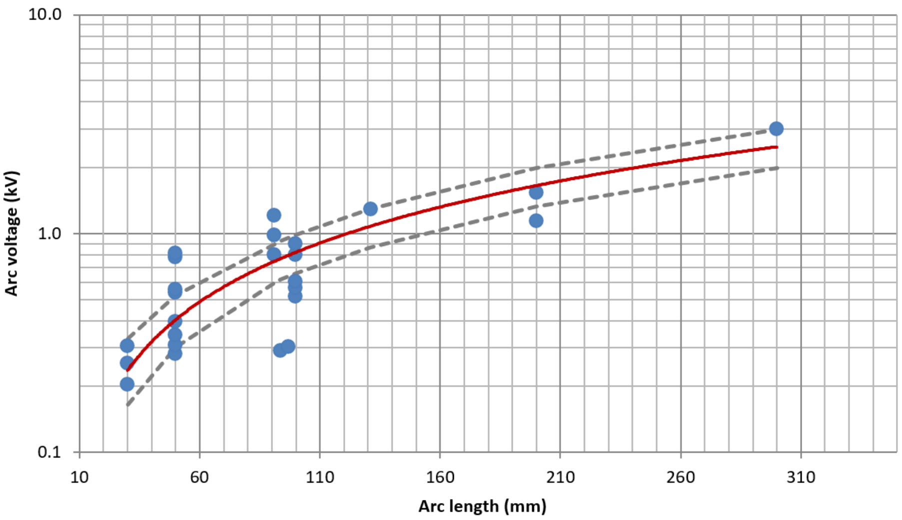
Arc energy is a critical parameter as it scales directly with the amount of gas.

The arc energy can be calculated based on arc-voltage, arc-current and arc-duration:

arc-energy = arc-voltage x arc-current x arc-duration time

Arc-voltage

The arc-voltage depend on the length of the arc in the oil. For oil-filled transformers, arc length can be derived from experimental data as shown in Figure 2. The experimental data show considerable spread an arc voltage are occasionally set to 1.5 KV for HV systems above 11kV. An alternative and better approach is to calculate arc voltage as a function of isolation gap. The value of 5V/mm is commonly used. As and arc may not form as a straight line a factor of 50% is often assumed. The red line in Figure 2 corresponds to a 5V/mm plus a 50% margin. For a given power rating, the arc length can be read off the below figure.



Transformers- insultating distance		
Rated voltage (kV)	Insulating distance (mm)	
36	70	80
52	80	80
72.5	90	100
100	105	120
123	110	140
145	125	160
170	140	180
245	155	200
245	165	220
245	185	240
362	205	260
420	220	260
420	235	280
550	260	280

Figure 2: Experimental values for arc voltage [9]

Arc Current

The arc-current is mainly determined by the short circuit level of the system and is a property of the system rather than the transformer. The arc-current can be calculated based on the apparent power Sk [MVA] and other system properties. Faults may occur at HV or LV side and the highest arc current is used in the analysis.

Arc Duration

The arc-duration time is given by the time the protective devices and circuit breaker will need to disconnect the faulty circuit. Arc duration is a system property and need to be defined by the electrical discipline. Typical values are 70-200 ms. but disconnection times can in some systems be substantially longer.

1.5.5 Characteristics of transformer cell

Characteristics of the transformer cell will have a decisive impact on overpressure. The most critical characteristics are cell volume and pressure vent area. These parameters are used as main criteria in the RISP methodology when selecting appropriate pressure / energy curve.

Explosion loads prediction in the RISP methodology is based on FLACS simulations using three sizes of transformer cells. Volumes are 500, 1250 and 2000 m^3. All cells have length:width:height ratio of 4:2:3 with pressure vent opening placed on the smallest wall (i.e. the least favourable location). For each cell volume 3 different pressure vent areas can be chosen. Figure 3 show the geometry models with panel areas.

Vent area to volume ratio is the same for all cell volumes and the smallest vent area. (Vent area/volume equal 0.015). When vent areas become bigger, the ratio can no longer be upheld without adding vent areas to multiple walls of the larger cells.

When assessing transformer cell characteristics the following points should be noted:

- The simulated cells are based on typical cells with minimal amount of congestion inside the cell. Although the explosion will be confinement driven, an increased amount of obstructions inside the cell - and in particular in the area between clouds and vent panels, will increase pressure.

- If a room has proportions deviating from those listed above and with longer distance to vent opening pressure will be somewhat worsened. The effect will be small as long as the deviation is not extreme

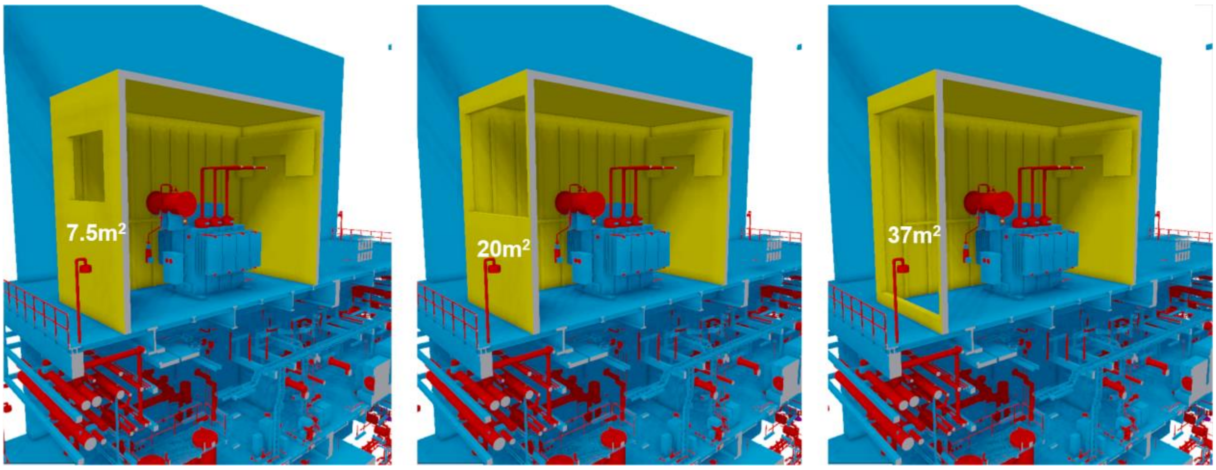
- Vent openings are most effective when they are close to the explosive cloud. If a vent opening is located at a side wall or in the roof pressure vent condition will be improved. The effect will be small.

- Stated explosion loads refer to cells with one (1) vent opening. Multiple openings in different parts of the room will typically give a small reduction in overpressure.

- Pressure vent openings should be design with the least possible opening pressure and a weight as low as possible. The loads given in this document assumes relief panels of 0.05 barg and 20 kg/m^3 weight. Panels with higher opening pressure and/or higher weight will result in higher pressure. Indicatively, doubling opening pressure and weight give about 40% increase in pressure.

- It is recommended to locate pressure vent openings high on the walls as it lessens direct exposure to personnel on the outside (pressure /projectiles and flame exposure). This will also be beneficial in a fire event

- In the event of a transformer fire, the vent openings are the most likely exit point for smoke. Proximity to sensitive targets for smoke exposure should be considered



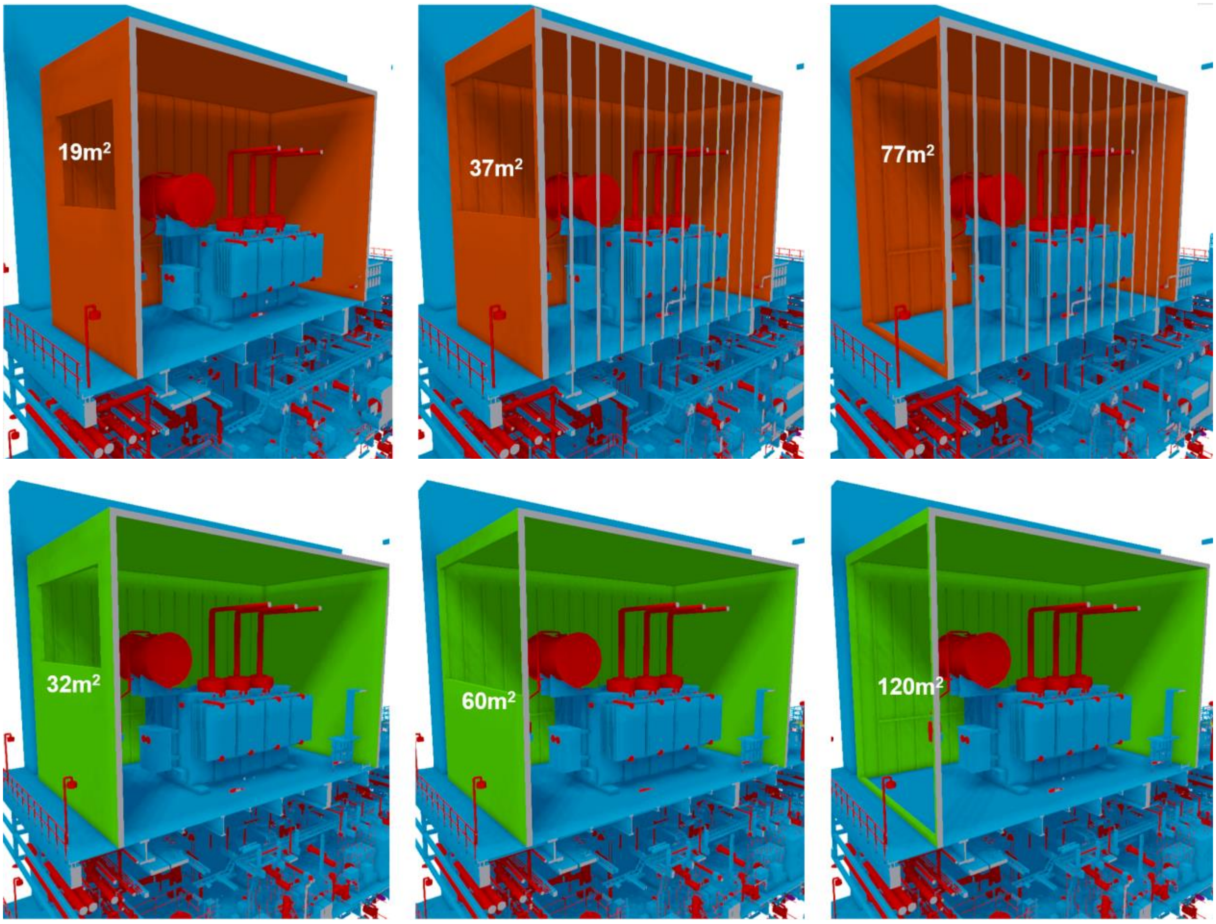


Figure 3: Transformer cells used in the study, Volumes are 500 m^3 (top), 1250m^3 and 2000m^3 (bottom)

1.5.6 Pressure load prediction

Pressure loads are derived on the basis of three main parameters: arc energy, cell volume and vent area. With these quantities determined the dimensioning event inside the transformer cell can be read directly off the below figures. Volume of transformer room determine which figure to be used. Based on arc energy pressure can then be determined for alternative pressure vent arrangements. An example is shown in Figure 4 (an arc energy of 120MJ and medium size pressure venting will give a load of 0.2 barg. These predictions are conservative, and the load can hence be recommended used as Design Accidental Load (DeAL).

The stated loads refer to explosion overpressure inside the transformer room and apply to all walls and roof. Identical load to all parts is typical when the vent opening is restricting pressure. When the vent opening is large, spatial variance can be pronounced with somewhat elevated loads to the wall furthest away from the vent opening. For design purposes, identical loads on all parts are practical. The larger the transformer room, the more spatial variance in load. In situations with large transformer rooms and notable pressure there may be cost savings in differentiating design loads to the different parts (walls).

It may be noted that curves for the 500m^3 cell (Figure 6) shows greater deviation. This is caused by this small room having relatively large clouds and scaling effects: The figure illustrates that when vent area becomes insufficient (as is the case for the 7.5m^2 curve), very high pressure loads will occur.

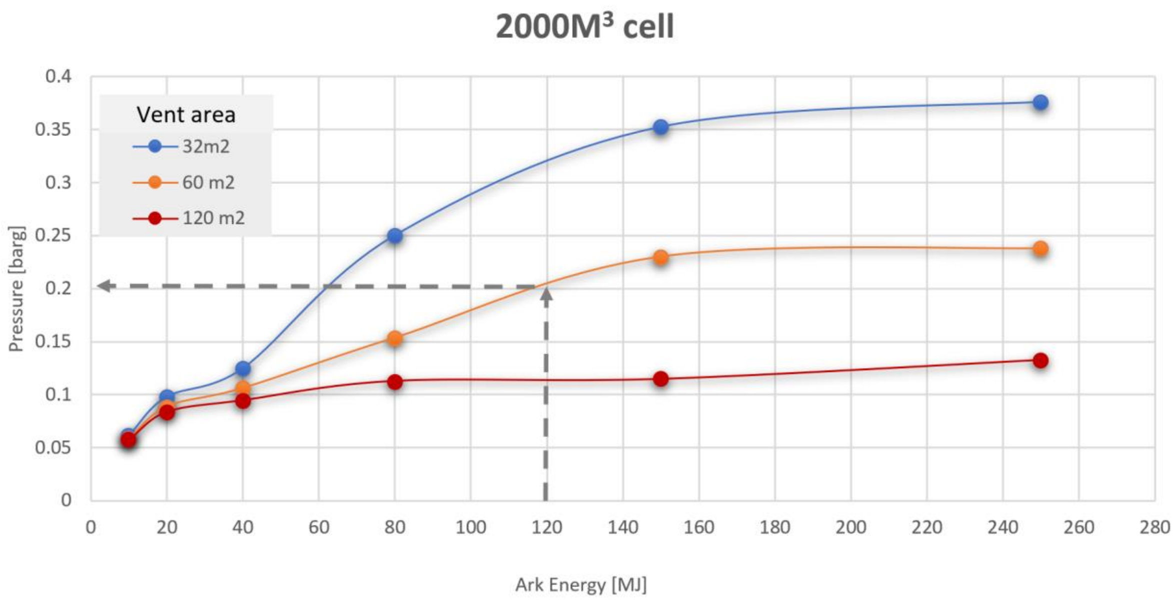


Figure 4: Pressure/arc energy curves for 2000m^3 transformer cells

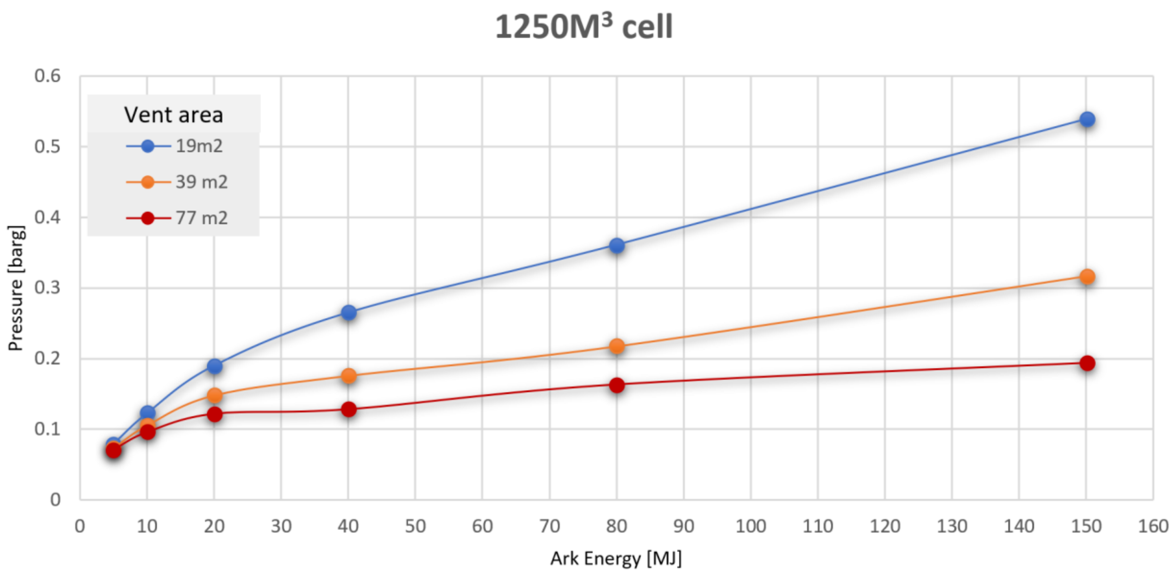


Figure 5: Pressure/arc energy curves for 1250m^3 transformer cells

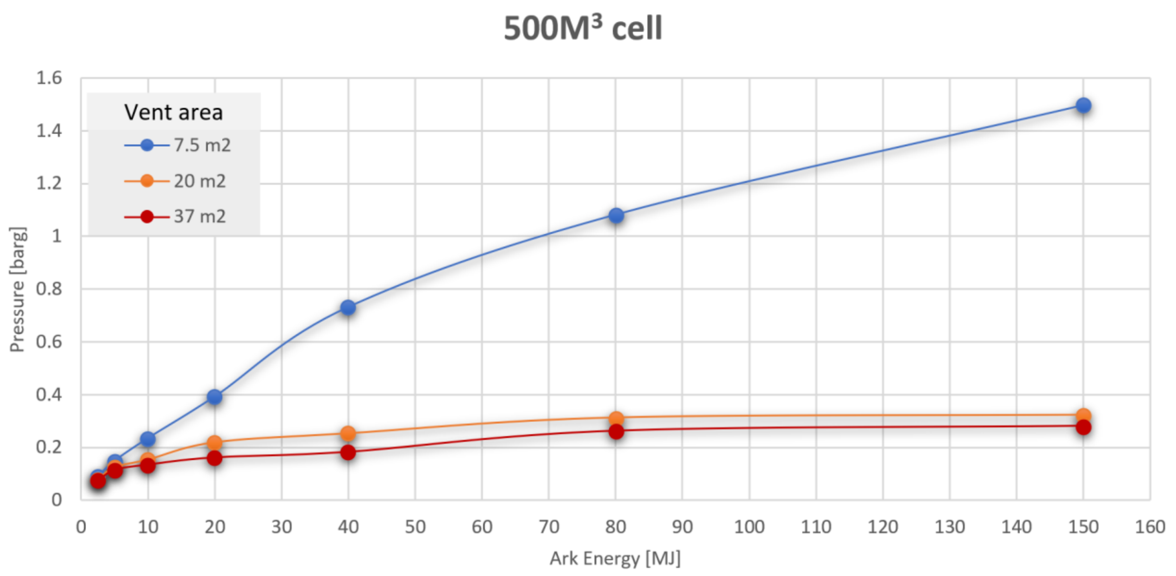


Figure 6: Pressure/arc energy curves for 500m^3 transformer cells

1.5.7 External pressure loads

Pressure escaping out through vent openings will propagate radially out to surroundings. Pressure loads outside the transformer cells will in most situations be low with moderate potential for causing damage to surrounding targets. With transformers typically located in the utility module - an area normally shielded from explosion loading, there may be targets with low resistance to pressure loads.

A simple prediction of external pressure loads is not easily obtained as overpressure is not solely governed by the internal pressure but also by the restrictive effect of the vent opening. A typical pattern for external loading is shown in figure. The below section outlines a coarse method for assessing external loads it should be viewed only as an indicative prediction of external pressure loads.

Indicative external loads can be derived from the following simple volume considerations: adding a sphere outside the vent opening with volume equal to the transformer cell implies that the expanded gas would occupy twice its original volume and hence have half the pressure. With internal pressure of 0.2 barg in the 1250m^3 cell, external load of 0.1 barg would extend about 7 m out from the center of the vent area. Distance to the 0.05 barg load would be about 11 meters. This type of simple correlation is reasonably aligned with the simulation results but appear to overpredict loading when vent areas are very large.

The above estimates and the simulations are based on venting into a completely unrestricted area. External loading will be considerably increased by obstruction in the vicinity of the vent area.

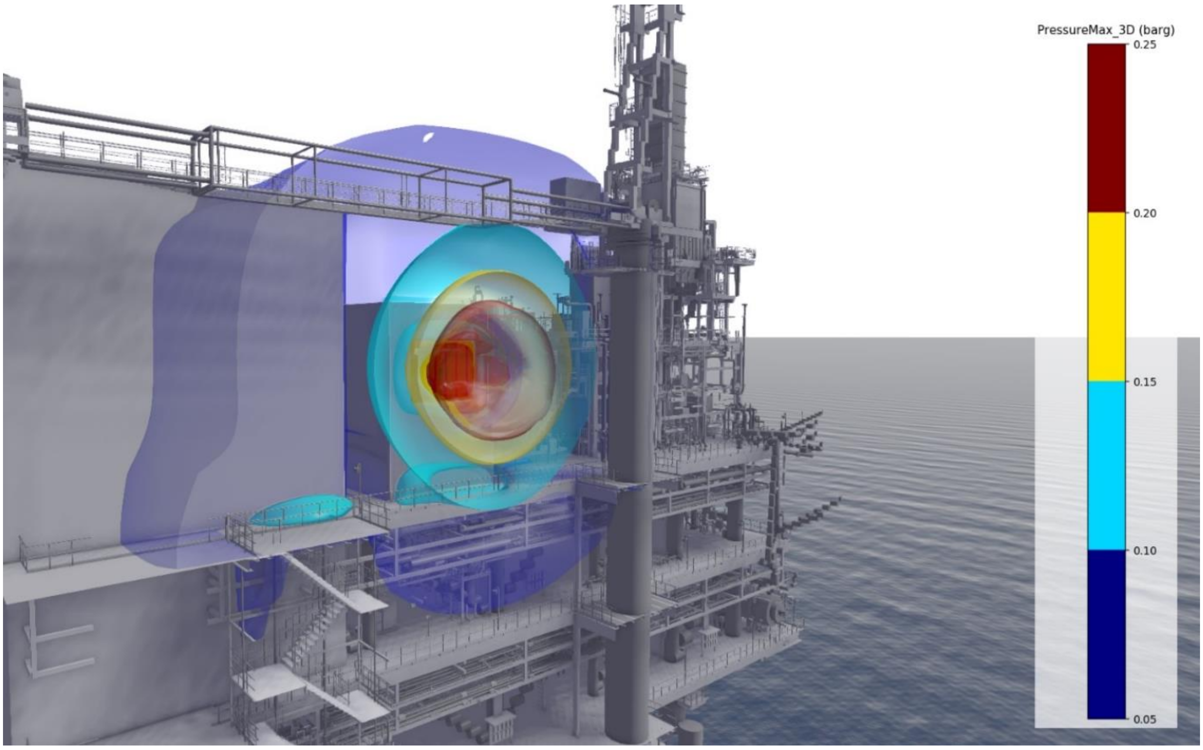


Figure 7: External pressure wave propagation (1250m³ cell, 37m² vet and internal pressure of 0.25 barg).

1.5.8 RISP Transformer Hazard: Fire Loading

Transformer fires typically involve partial rupture of casing or bushing and oil burning as it seeps out through cracks and openings. The combustion zone typically may reside inside the broken transformer. Oil reaching the deck should be collected by the oil containment system limiting the potential for a larger pool fire. With proper grating arrangement, oil shall not be able to burn once inside the pit.

The above fire scenario cannot easily be simulated but as the fire will be oxygen restricted, heat output can be approximated by looking at what fire size can be sustained given the oxygen supply. Simulations have been performed with the objective to identify fire intensity given credible air supply to the combustion zone. Fires has been modelled as a pool fire on the deck.

Designing the transformer encloser in a way that restrict oxygen supply is a good strategy. In the event of a conventional fire, dampers on HVAC inlets and outlets should effectively restrict air supply. In the event the fire is preceded by an explosion, the pressure relief panels will be released with fresh air entering through the panel area. The latter will have potential for more severe fires and is assumed to be the worst credible fire.

A handful FLACS simulations have been performed to assess de potential fire loading and design features impact on the fire. Simulations were performed for the 1250 cell with multiple release rates. Figure 8 show heat and smoke exposure of scenarios were highest sustainable fire intensity. Note that the simulations assume that the only access point for fresh air would be the panel vent area.

Additional entry points for air may have substantial impact on the outcome and the heat load prediction are sensitive to presents of additional sources of air supply.

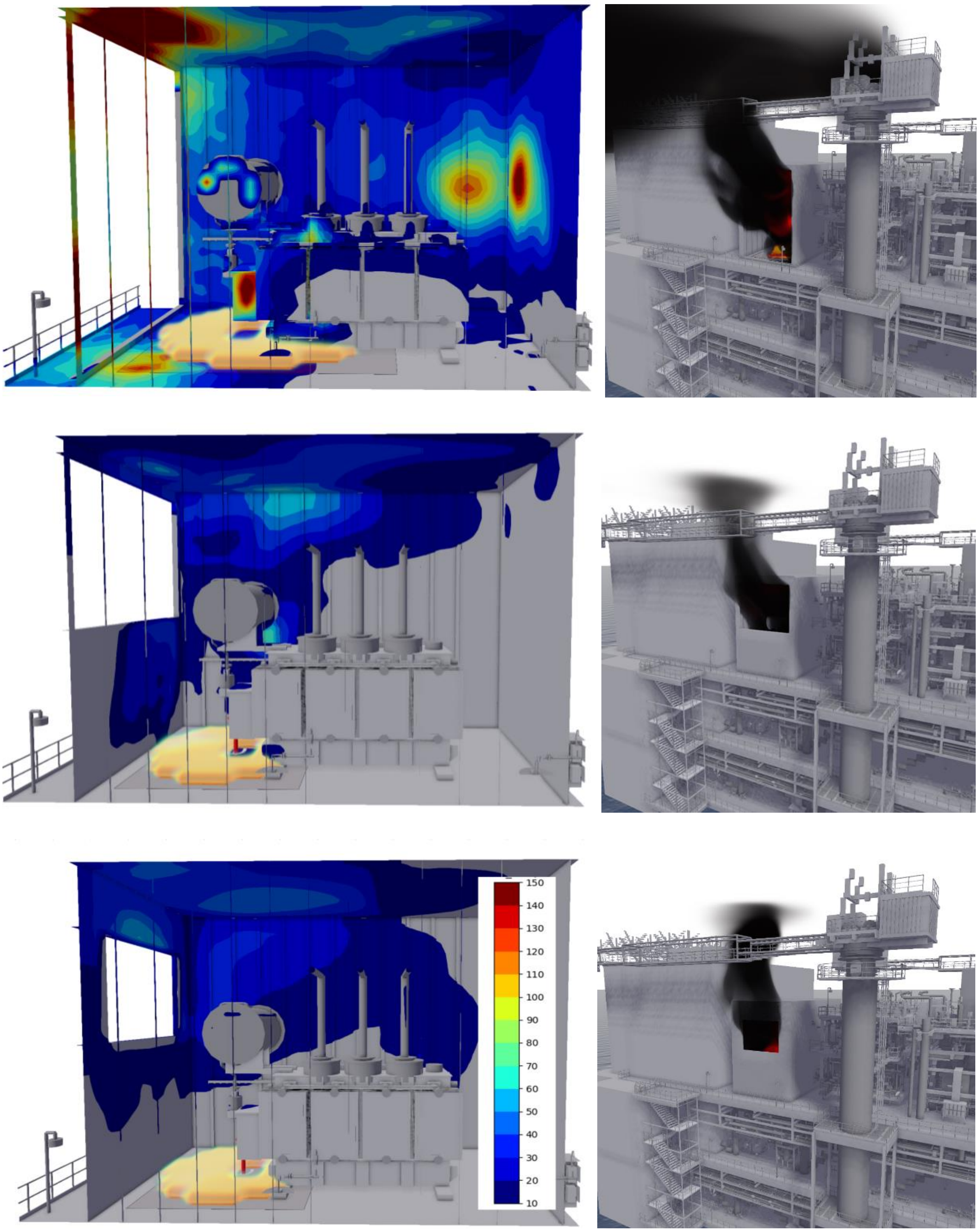


Figure 8: Heat loading and smoke exposure with various panel sizes.

Based on the performed simulations the following observations/recommendation are made:

- Pressure vent area are assumed to be the only access path for fresh air into the transform cell. Inflow of air is severely restricted when the cell only has one opening i.e. when smoke have to exit the same opening as air comes in. Alternative openings– especially if located in lower sections, should be avoided. The fire intensity may be substantially increased if there is a chimney effect. Doors should be designed to remain closed during and after a severe transformer failure.
- Simulations with small or moderate vent panel area show distinct effect of oxygen depletion. Radiative heat output is severely restricted and so is smoke generation.
- Simulations with fully open wall sustain a considerably higher fuel consumption rate giving higher radiative loads and greater smoke exposure.
- Location of vent area should be aligned with the presence of targets sensitive to smoke

Pressure vent area are assumed to be the only access path for fresh air into the transform cell. Inflow of air is severely restricted when the cell only has one opening i.e. when smoke have to exit the same opening as air comes in. Alternative openings– especially if located in lower sections, should be avoided. The fire intensity may be substantially increased if there is a chimney effect. Doors should be designed to remain closed during and after a severe transformer failure.

Simulations with small or moderate vent panel area show distinct effect of oxygen depletion. Radiative heat output is severely restricted and so is smoke generation.

Simulations with fully open wall sustain a considerably higher fuel consumption rate giving higher radiative loads and greater smoke exposure.

Location of vent area should be aligned with the presence of targets sensitive to smoke.

To the degree practical, the above recommendations may also be considered for naturally ventilated transformer bays. (i.e preventing chimney effects and easy access of fresh air).

Table 1: Summary fire characteristics

Panel area	Expected burn rate (kg/s)	Totalt heat output [mW]	Equivalent pool fire size [m^2]	Simulated heat load [kW/m^2]
Small (19m2)	0.5	20	10	50
Medium (37m2)	0.7	30	14	70
Large(77m2)	2	60	40	150

Table 2: Recommended DeAL requirement for transformer enclosure

Panel area	DeAL Heat load [kW/m^2]	Duration
Small and medium	100	1h
Large(77m2)	200	1h

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

RispEx-decision support for explosion load design

Main Report

Report for:
RISP Participants, att: Equinor Energy AS

Summary

JIP: Risk informed decision support in development projects (RISP)		
RispEx-decision support for explosion design loads – Main Report		
Security classification of this report:	Distribute only after client's acceptance	
Report no: DNV report no 2020-0628	**Revision:** Rev 03	**Report date:** 22 September 2023
Prepared by: Sjur Helland, DNV	**Reviewed by:** Jens Johansson Garstad, DNV	**Approved by:** Unni Nord Samdal, Equinor
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Document history

Revision	Date	Description/changes	Changes made by
Rev A	19.06.2020	Draft A, issued for comments	Linda Fløttum, Aker Solutions Jens Garstad, DNV Asmund Huser, DNV
Rev 0	17.08.2020	Updated based on comments. First issue	Linda Fløttum, Aker Solutions Jens Garstad, DNV Asmund Huser, DNV
Rev 1A	19.10.2021	Draft. Update with process area types and large areas	Sjur Helland, DNV Jens Garstad, DNV
Rev 01	15.11.2021	Updated based on comments. First revision	Sjur Helland, DNV Jens Garstad, DNV
Rev 02A	15.12.2022	Draft. Updated with updated model for explosion loads on decks.	Sjur Helland, DNV Petter Vollestad, DNV
Rev 03A	04.07.2023	Draft. Updated with updated drag explosion model.	Sjur Helland, DNV Jens Garstad, DNV
Rev 03	22.09.2023	Updated based on comments. Third revision.	Sjur Helland, DNV Jens Garstad, DNV

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1 Executive Summary

DNV (then DNV GL) and Aker Solutions were awarded the RispEx project in September 2019. RispEx is carried out as a separate activity in the JIP Risk Informed decision Support in development Projects (RISP), with project leader from DNV and participation from DNV and Aker Solutions.

The overall objective of RispEx is to develop a digitalized tool that can provide explosion related decision support in offshore oil and gas development projects. RispEx is developed as a digitalized “look-up approach” based on known risk profiles.

RispEx shall provide recommended design explosion loads, based on the project information available at DG2 stage. In addition, RispEx shall provide typical accidental events to be used in risk management context (e.g. management of change, ALARP).

The main work process in the RispEx development has been as follows:

- Selection of representative geometries
- CFD simulations for each representative geometry
- Probabilistic explosion analysis for each representative geometry
- Model development (based on interpolation), including recommendation for DeAL and accident scenarios and validity envelope
- Testing, validation and comparison
- Digitalization

A summary of RispEx is provided in section 3. This section describes the objectives and main features of RispEx as well as the use of the tool in a development project. A validity envelope has been defined, deciding whether RispEx can be used for the specific project/module in question.

With the release of RispEx version 2.0, RispEx is considered sufficiently mature to be used as basis for setting design accidental loads for fixed facilities. RispEx may be used as basis for design accidental loads for ship shaped FPSOs as well, however RispEx has undergone less extensive validation for ship shaped FPSOs, and it is therefore recommended to exercise caution by verifying key RispEx intermittent results when using the tool for ship shaped FPSOs. This is further described in section 3.11 and the user manual.

The RispEx user manual is enclosed in Appendix A.

The technical basis of RispEx is described in detail in section 4.

2 Introduction

2.1 Overall project description

DNV (then DNV GL) and Aker Solutions were awarded the RispEx project in September 2019. RispEx is carried out as a separate activity in RISP, with project leader from DNV and participation from DNV and Aker Solutions. DNV/Aker Solutions reports directly to the leader of the steering committee in RispEx.

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The main work process in the RispEx development has been as follows:

- Selection of representative geometries
- CFD simulations for each representative geometry
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- Model development (based on interpolation), including recommendation for DeAL and accident scenarios and validity envelope
- Testing, validation and comparison
- Digitalization

The work process is illustrated in Figure 2-1: .

The project started up in September 2019 and the draft report and digitalized tool was issued in June 2020.

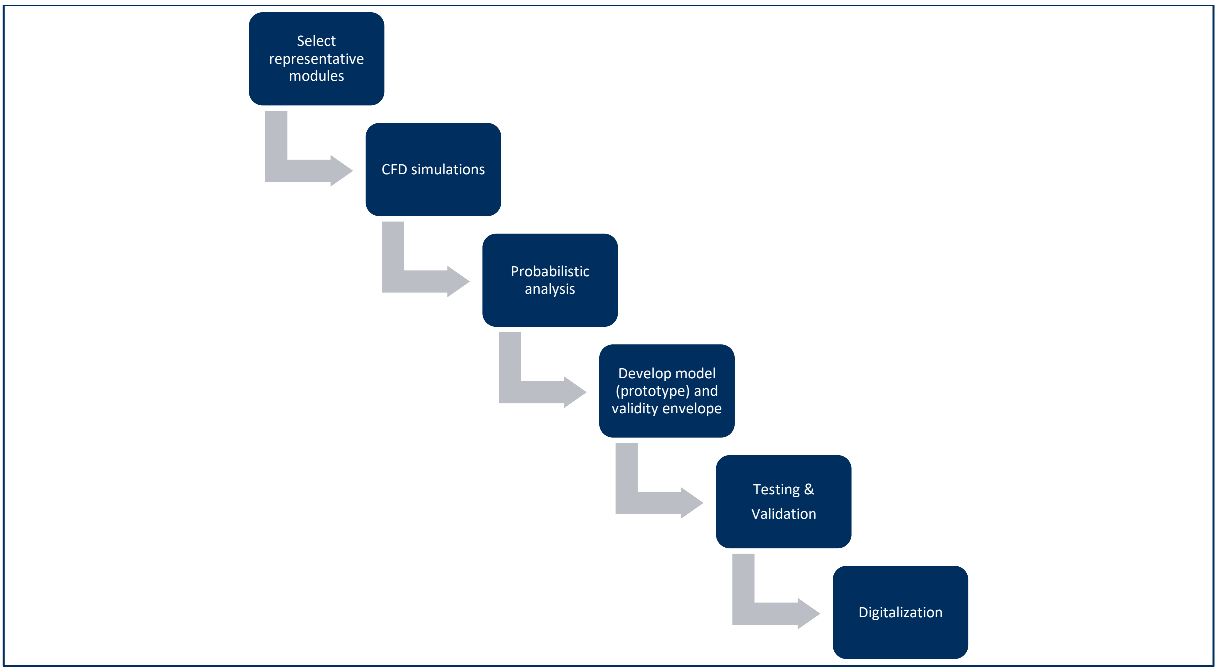


Figure 2-1: RispEx work process

2.2 Background

2.2.1 RISP project

The project "Formålstjenlige risikoanalyser" ("Expedient Risk Analyses") was run until spring 2017 by Norwegian Oil and Gas, NOROG (Ref. /1/). The project (hereafter called the NOROG project), with results and proposals for further work, was presented in the Operations Committee meeting in NOROG and received full support. The authorities (Petroleum Safety Authority) have also expressed a strong wish to see the project being continued.

The RISP joint industry project described in this document is a continuation of the NOROG work and the recommendations it led to. The outcome of RISP is likely to form a significant part of the fundament for the upcoming update of NORSOK Z-013. RISP has focused on risk management in project development of topside facilities (in a broad meaning), including subsea accidents that may affect the facility.

Seven offshore operator companies have initiated and sponsored the RISP work; Equinor, ConocoPhillips, Total E&P, Vår Energi (ENI), Lundin (now part of AkerBP), Wintershall and AkerBP.

The JIP consists of two Sub-Projects. Sub-Project 1 has been carried out in 2018 (includes WG 1 and WG 2). Sub-Project 2 has been carried out in 2019 and includes WG 3 (fire), WG 4 (other accidents) and WG 5 (regulatory framework). The five workgroups are undertaken by vendors nominated by the sponsors, and different work packages are defined for the different workgroups. The vendors are: Lilleaker Consulting (now part of Proactima), Gexcon, DNV GL (now DNV), Lloyd's Register (now Vysus Group), Aker Solutions, Proactima and Safetec.

Both sponsors and vendors are participants in the JIP. The PSA has been involved as observer in the RISP project.

2.2.2 RispEx

The background for the industry's request to develop a new approach to specify design explosion loads in development projects is the challenges experienced with current practice of probabilistic explosion risk analysis.

Normally, the design accidental explosion loads need to be "frozen" in FEED phase. At this stage the input with the right level of detail required to perform probabilistic explosion analysis according to current practice is not available, e.g. the 3D models lack a lot of details and the leak picture is not known in detail. Hence, the results from a probabilistic explosion analysis performed at an early stage are associated with significant uncertainties.

Further, the already developed probabilistic explosion models have become quite complex with many user-influenced input parameters. In many cases, transparency and traceability of the probabilistic models can be poor.

Often experienced challenges with the use of probabilistic explosion analysis, as described above, are:

- Late design changes, that can be costly and time-consuming for a project
- Too late decision support
- Difficulty to understand the results from the probabilistic analysis due to poor transparency and traceability
- Much effort and money are 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.

RISP workgroup 2 delivered a report in March 2019, ref. /2/. The report describes alternative approaches to explosion modelling and proposes some simplifications and a simple look-up table. However, the work does not provide ready-to-use methods for specification of explosion loads. Based on this, it was decided by the Steering Committee to develop RispEx.

2.3 RispEx program version history

The initial version of RispEx was published in August 2020. An overview of the program version history is presented in Table 2-1. Aker Solutions was involved in the initial version of RispEx, but subsequent updates have been performed by DNV and the RISP steering committee.

Table 2-1: Version history

Version	Period	Changes
1.0	2019 - 2020	Initial version.
1.1	Spring 2021	Inclusion of access control.
1.2	Summer 2021	Support for different types of process areas.
1.3	Fall 2021	Support for very large process areas for fixed installations.
1.4	Fall 2021	Bug fix for external ignition with different area types.
1.5	Fall 2021	Adjusted explosion model for very large or very open areas. Bug fixes for FPSO and wellhead areas. Adjusted user warnings.
1.6	Summer 2022	Introduced a new model of horizontal divisions.
1.7	Winter 2022	Corrected a bug related to cloud volume in cases below the lower threshold of explosion pressures.
2.0	Summer 2023	Implemented drag model

2.4 Abbreviations

ACH	Air Changes per Hour
ALARP	As Low As Reasonable Practicable
BOP	Blow Out Preventer
CFD	Computational Fluid Dynamics
DeAL	Design Accidental Load
DG	Decision Gate
ESD	Emergency Shutdown
FPSO	Floating, Production, Storage and Offloading (platform)
FWD	Forward
HC	Hydrocarbon
HPHT	High Pressure, High Temperature
LEL	Lower Explosion Limit
NCS	Norwegian Continental Shelf
NOROG	Norsk olje og gass
PSA	Petroleum Safety Authority
RISP	Risk informed decision support in development projects
SC	Steering Committee
TRA	Total Risk Analysis
ToR	Terms of Reference
WG	Work Group

3 RispEx Summary

3.1 Introduction

This section gives a summary of RispEx: the objective and overall description of the model and the development, as well as the intended use of RispEx.

For detailed technical description of RispEx, reference is made to Section 4.

3.2 Objective of RispEx

The overall objective of RispEx is to develop a digitalized tool that can provide explosion related decision support in offshore oil and gas development projects.

RispEx shall provide recommended design explosion loads, based on the project information available at DG2 stage. In addition, RispEx shall provide typical accidental scenarios to be used in risk management context (e.g. management of change, ALARP).

The design explosion loads shall be robust enough to sustain throughout all project phases, but without being unnecessary cost drivers. The same safety level shall be achieved by using this tool as the current safety level for existing designs on NCS (based on probabilistic explosion analysis). By "the same safety level" it is understood that the recommended design loads for a specific module produced by RispEx shall be at the same level as actual/historical design loads for the same module.

The intention is that the explosion loads will be specified in concept or FEED phase by use of RispEx, followed up during FEED and detail engineering, and finally verified at "as built". The follow-up and verification of the DeALs shall be done with RISP approach, i.e. without doing detailed probabilistic explosion analysis. This approach is described further in section 3.9. A validity envelope has been defined, deciding whether RispEx can be used for the specific project/module in question.

RispEx has been developed as a digitalized "look-up approach" based on known risk profiles, somewhat more advanced than the "look-up table approach" proposed in ref. /2/. The proposed method is aimed at being transparent, reproducible, and professionally sound, and may be made openly available through an internet portal, as required for the RISP methods.

3.3 RispEx overall basis and architecture

RispEx is developed as a look-up tool, based on known risk profiles.

The known risk profiles are developed from CFD and probabilistic analysis of selected representative modules that are considered modern and typical future modules. RispEx is based on total 38 representative areas distributed as follows:

- 26 process areas on conventional integrated platforms
- 7 wellhead areas on conventional integrated platforms
- 5 representative FPSO process areas (weather vaning FPSOs)

The basis of the tool consists of pre-calculated cloud exceedance curves (ignited cloud size vs. probability given leak) and cloud volume vs overpressure relations for the 38 representative areas.

RispEx explosion load results for an area is calculated based on interpolation on the predefined curves. The interpolation is based on **module volume** and **total openness.** It has been a goal to keep the interpolation logic relatively simple but at the same time being able to reflect the main physical phenomena.

The total leak frequency is estimated based on the volume of the module, i.e. based on relation between module volume and leak frequency, as well as the leak rate distribution proposed in ref. /2/. For wellhead areas, the leak frequency is estimated based on the number of wells (as user input).

3.4 RispEx user interface

The RispEx user interface, input and output fields is described in the sections below.

3.4.1 User input

The RispEx user interface, input fields are shown in Figure 3-1.

The following input to the tool needs to be provided by the user: (i) Module dimensions; (ii) Type of concept/area; (iii) Data for process/wellhead area; (iv) Openness; (v) External ignition, and; (vi) Scaling factor target frequency.

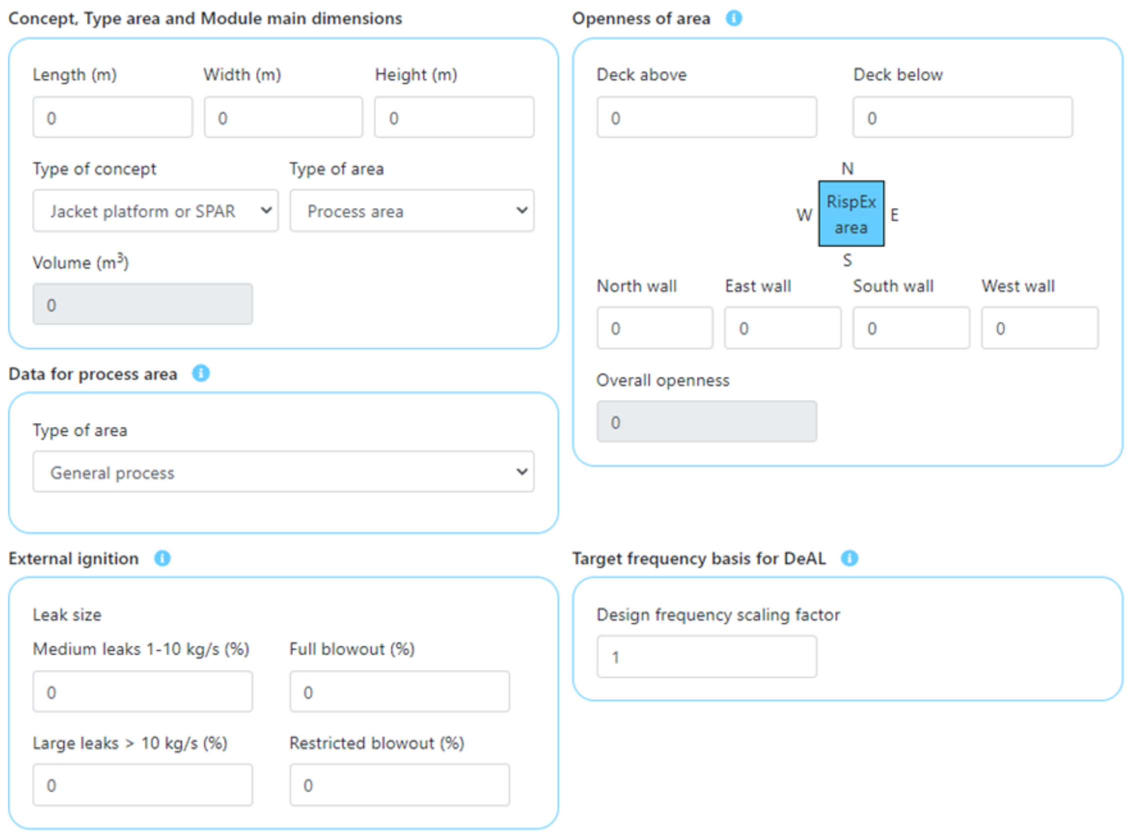
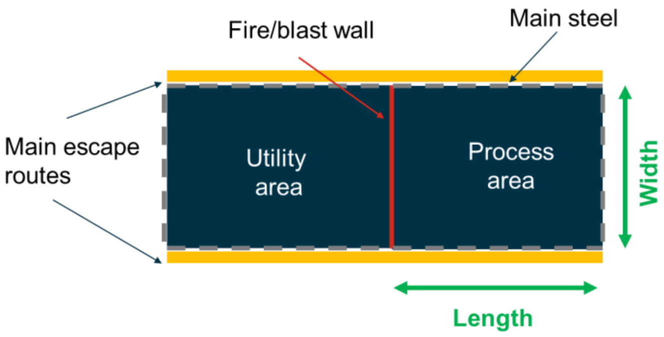


Figure 3-1: RispEx user interface – input fields

Module dimensions: Module length, width and height in meters. The width of the platform is in the longitude direction of the firewall, normally in the north-south direction. The length is normally in the east-west direction. The dimensions are defined by the congested region typically limited by main structural elements, as shown in the illustration below. Escape routes etc. outside the congested region shall not be included in the module volume.



Type of concept/area: The RispEx model is different for FPSO process areas, integrated platforms process areas and wellhead areas, and therefore this need to be provided as input.

Other input process area: For a process area the user in addition need to give the input the type of process area. This is used to estimate the fraction of liquid leaks. Liquid leaks constitute a lower explosion risk than gas leaks as they tend to produce smaller gas clouds for a given total release rate.

Other input wellhead area: For a wellhead area the user in addition need to give the input the total number of well slots. This is used in the leak frequency estimation. Note that also future wells shall be included, in order to get a robust estimate. Water injection wells shall not be included in this. In addition, the user needs to define whether the blowout potential from the producing wells is <15 kg/s blowout rate or >15 kg/s blowout rate).

Openness: The degree of openness needs to be specified for each boundary of the module/area, where 1 is fully open and 0 is closed. Openness per boundary is defined by the fraction of the area covered by walls, weather cladding, panels etc. Firewalls and fully plated decks/walls will have a degree of «openness» of 0. By this definition, the degree of «openness» for a ventilated side differ slightly from the effective openness as main structural members, piping and other units blocking the ventilation area is not defined as openness.

The total openness of the module will be calculated based on the user input for each boundary. The total openness level is used in the interpolation scheme (i.e. not the openness for each boundary).

External ignition: The user has the possibility to do an evaluation of external ignition probability and include this as input to RispEx. Reference is made to user manual, appendix A, for further details.

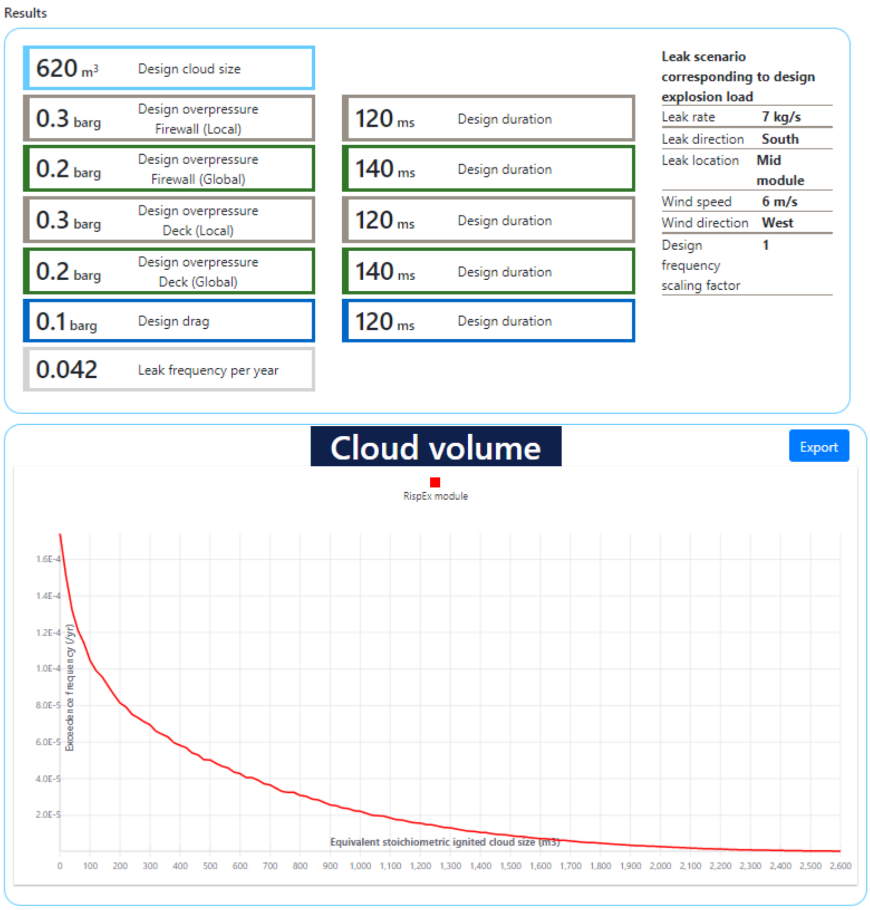
Scaling factor Target frequency: The target frequency that gives the recommended design accidental loads is hard coded in RispEx. The target frequency in the draft version of RispEx is $7 \cdot 10^{-5}$ per year. The user has the possibility to use a scaling factor to investigate the sensitivity of the results if the target frequency is changed. The default scaling factor is 1. When 1 is applied as the scaling factor, the results show loads in line with the fixed target frequency (not visible to the user). If the user wants to see how sensitive the loads are with respect to changes to the return frequency relative to the target frequency a user defined scaling factor is applied. i.e. If the fixed target frequency is 7E-5 per year, then a scaling factor of 0.9 shows explosion loads corresponding to a return frequency of 6.3E-5 per year. (however, these frequencies are not visible to the user).

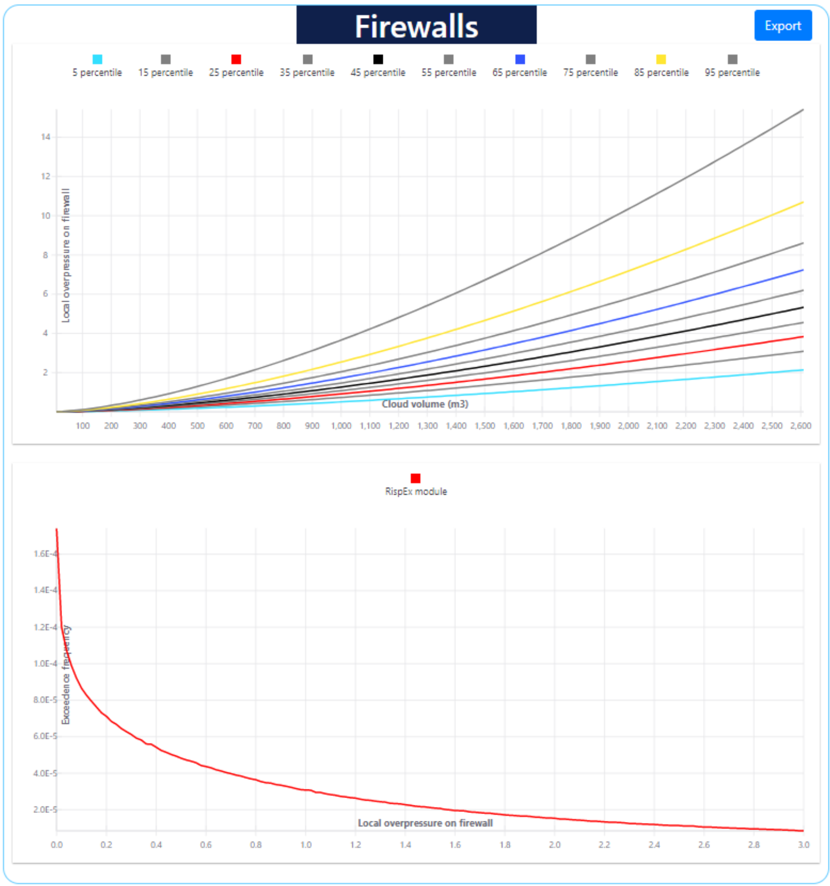
Two alternative applications of the scaling factor may be

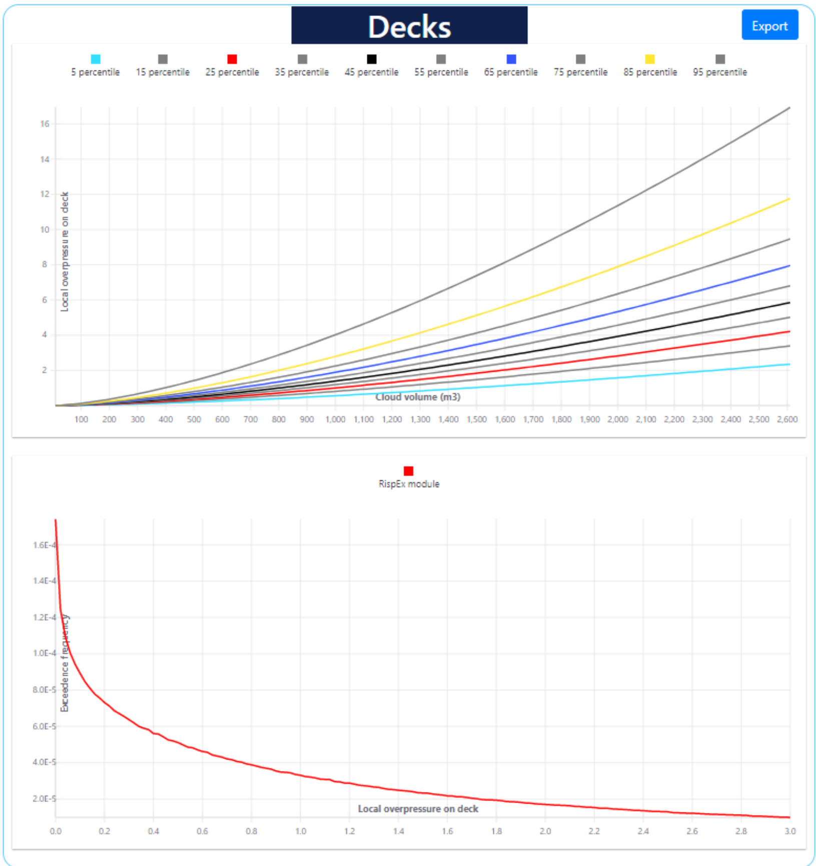
- If design explosion load is defined as total frequency of N areas sharing a common main area boundary, then a Design frequency scaling factor 1/N may be used per area. See section 3.5.
- If the project wish to include a frequency based contingency on the Design explosion load, this can be achieved by applying a design frequency scaling factor below 1. A scaling factor of 1 provides the minimum DeAL value (dimensioning load + a margin defined by the RISP steering committee), and a scaling factor below 1 will add additional margin.

3.4.2 Output

The user interface, output fields are shown in Figure 3-2.




Firewalls
Export
5 percentile
15 percentile
25 percentile
35 percentile
45 percentile
55 percentile
65 percentile
75 percentile
85 percentile
95 percentile
Local overpressure on firewall
Cloud volume (m3)
RispEx module
Exceedence frequency
Local overpressure on firewall


Decks
Export
5 percentile
15 percentile
25 percentile
35 percentile
45 percentile
55 percentile
65 percentile
75 percentile
85 percentile
95 percentile
Local overpressure on deck
Cloud volume (m3)
RispEx module
Exceedence frequency
Local overpressure on deck

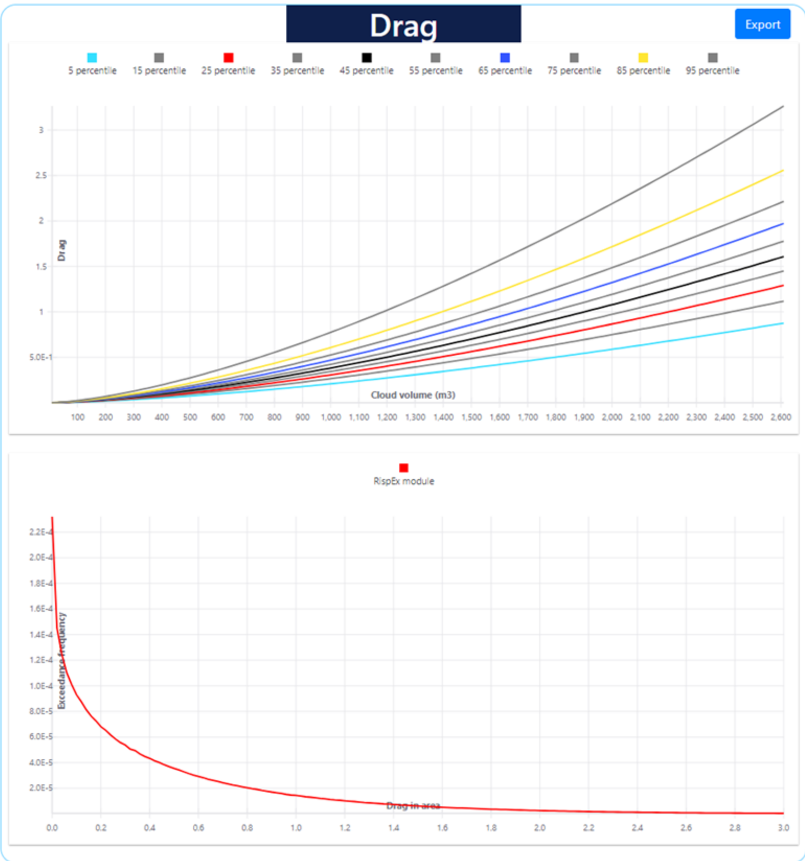


Figure 3-2 RispEx user interface, output fields

The output from the tool will be:

- Recommended design ignited cloud size
- Recommended design accidental loads with typical associated durations:
    - Area local overpressure load (4m × 4m panels) for firewalls and large equipment
    - Area local overpressure load (4m × 4m panels) for decks
    - Global overpressure load to be applied for firewalls and decks
    - Area drag that can be applied for smaller equipment, structures and piping systems
- Corresponding leak scenario/accidental event to be used in development projects e.g. as part of Risk Management process. The leak scenario representing the design pressure is defined by leak rate, leak direction, leak location, wind speed and direction. Note that the leak scenario is expressed in "Equivalent gas rate" terms.
- Curves to support the understanding of the estimated explosion risk picture, e.g.:
    - Ignited cloud exceedance
    - Overpressure vs cloud size
    - Pressure exceedance

3.5 Recommendation for DeAL

RispEx will calculate the recommended DeAL directly. The DeAL has been based on a target frequency of $7 \cdot 10^{-5}$ per year. Comparing to an acceptance criterion of $1 \cdot 10^{-4}$ per year, this means a margin of 30%. When performing traditional probabilistic explosion analysis as basis for design explosion loads, margins of this magnitude is typically used between dimensioning and design accident loads. In addition, another robustness in RispEx, is that the tool returns a minimum local design load of 0.3 barg. This will ensure that small and minimum sized modules always get a design load, even if the frequency of ignited leak in the module is less than $7 \cdot 10^{-5}$.

It will be up to the user to add additionally contingency, e.g. to account for uncertainty in the input to the tool (module dimensions, openness). This can be done e.g. by doing sensitivity analysis varying the input parameters to RispEx.

RispEx has been developed for calculation of <u>one module</u> at a time, and assuming that the acceptance criterion of 10^{-4} per year applies for escalation from the module. In case there are several modules that share explosion barrier to the same neighbouring main area (see Figure 3-3), and the acceptance criterion applies for the shared barrier[1], RispEx is currently not set up to handle this directly.

However, it is still possible to use RispEx for these cases by manipulating the scaling factor for the target frequency. For this case a scaling factor 1/N may be used per area when N areas within the same main area are sharing a common main area barrier. Note that this applies for the DeAL load for the main barrier and not for drag loads.

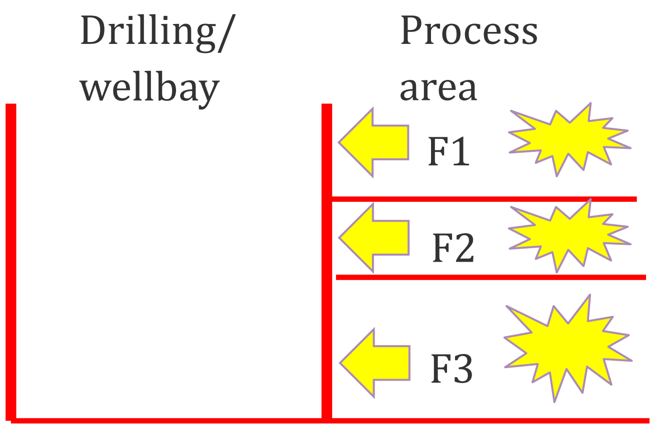


Figure 3-3: Several modules sharing the same explosion barrier (example)

3.6 Validity Envelope

In principle the RispEx tool will be valid for all types of concepts, if the criteria in the validity envelope is fulfilled. The choice of representative modules will influence the validity envelope. The representative geometries have been chosen from the following concepts:

- Ship-shaped FPSOs
- Process areas on jacket platforms / SPARs
- Wellhead areas

The ship-shaped FPSO concepts included are turret-moored, with and without fire division in the process area. Currently, wellhead platforms and large process areas on e.g. SEMIs and circular FPSOs have not been included in the representative areas.

RispEx has been developed for greenfield projects but can also be used for modification projects if the validity envelope is fulfilled.

The tool can be extended with additional concepts at a later stage.

A validity envelope, defining the criteria for when the tool is valid for a specific design, are developed as part of RispEx. The validity envelope has three categories:

1 Historically there has been somewhat different practices as to how the acceptance criteria for escalation due to explosion shall be implemented. One interpretation is that the 10-4 criterion applies per fire area for escalation towards one neighboring main area, one other is that it applies for escalation from one main area to another main area. One main area may consist of several fire areas. As per 2023-01-01 the facilities regulations defines escalation as across fire areas.

1. **Overall concept and design**, e.g. regulatory requirements and standards basis for design.
2. **RispEx user input parameters**, i.e. module dimensions and openness.
3. **RispEx fixed input parameters**, i.e. predefined input such as segment inventories, blowdown time, congestion etc.

The validity envelope defined for RispEx is tabulated in Table 3-1.

Table 3-1: Validity envelope

Validity envelope dimension	Requirements
Overall concept and design	Design according to PSA requirements and NORSOK S-001 Design according to ISO 13702 Naturally ventilated areas Areas that does not contain HPHT equipment. Concepts with natural gas only. RispEx is not valid for concepts with more reactive or heavy gases such as hydrogen or LPG/LNG. Minimum 2-ways ventilated areas (Minimum two naturally ventilated sides of the area. In areas with only two ventilated sides, they should be located on opposite sides, i.e. not an area with L-shaped configuration of blast walls) Wind speed distribution similar to Norwegian Continental Shelf (typical)
RispEx user input parameters	Dimensions, Process areas - FPSO concepts: Module volume: *30 000 - 70 000 m*^{3} Module length: *30 - 120 m* Module width: *30 – 60 m* Module height: *8 – 25 m*
	Dimensions, Process areas - other concepts: Module volume: *3 000 - 28 000 m*^{3} Module length: *18 - 70 m* Module width: *18 – 50 m* Module height: *5 – 20 m*
	Dimensions, Wellhead areas - other concepts: Module volume: *3 500 - 15 000 m*^{3} Module length: *20 - 25 m* Module width: *25– 44 m* Module height: *7– 15 m*

	Non-rectangular areas can be reflected based on representative dimensions Length, Width, Height which give the volume corresponding to the L shaped area, as long as the length and width do not deviate from the projected length and height of the L shape area with more than10 %.
	Openness: Firewalls: Openness 0 Lower deck: Openness 0- 0.1 Open/partly open sides: Openness 0-1 Top deck/roof: Openness 0-1 Note that some restrictions to the confinement levels per side in RispEx is that the floor deck needs to be 0-10% open, and two adjacent vertical sides (e.g. both the North and South sides) both needs to have openness > 0.35. Confinement level overall for FPSO concept: >0.18 Confinement level overall for other concepts: >0.07
RispEx fixed input parameters	Minimum blowdown time; 15 min to 6.9 barg
	Gas detector design/density according to NORSOK S-001
	Design of ESD system according to NORSOK S-001
	Reliability of safety systems according to NORSOK S-001
	Max closing time ESD valves: 30 sec
	Maximum number of hot work hours: 100 hours hot work class A in habitat.
	Congestion within “Normal” levels *

* RispEx is not valid for very congested areas or special geometries that will give high explosion loads. This should be a part of the assessment in HAZAN and need to be followed up throughout the development project

There are concepts/type of design where RispEx can be used but will provide conservative results. Examples of this are:

- Modules containing substantial amounts of utility equipment (low gas/oil leak frequency)
- Concept with no firewall towards prevailing wind direction

3.7 Benchmark and validation of RispEx

3.7.1 Introduction

As part of the testing and validation process of RispEx, a comparison with available PLOFAM2/MISOF2 analysis has been performed.

When comparing explosion analysis performed by different consultant companies with RispEx, it is expected to see a variance in the results. Similarly, a variance would be expected if two different consultant companies (with two different tools) performed an explosion analysis of the same module. Since the complex methods for calculating explosion loads includes subjective evaluations deviations are expected also on individual level independent of tools etc.

The goal of the comparison is to investigate whether there are systematic overestimation or underestimation in the different steps of RispEx when comparing to the available PLOFAM/MISOF analysis.

The comparison has been performed for the different steps in the explosion analysis (if they were available):

- Leak frequency
- Frequency – ignited cloud relation
- Ignited cloud – pressure relation
- Overpressure – frequency relation

Modules from 5 different installations have been included, and in addition the MISOF test modules are included. For confidentiality reasons, the installations have been anonymized.

The comparison with the PLOFAM/MISOF analysis is documented in Appendix D.

3.7.2 Summary of comparison

In short, and perhaps as expected, RispEx will in some cases overpredict dimensioning explosion loads and in other cases underpredict them. There are three models in the tool that are more or less independent of each other. These are:

- Leak frequency model
- Probabilistic model to produce probabilities for ignited cloud volumes given leak.
- Model for explosion overpressure as a function of ignited cloud volumes

For **process areas**, the established relationship between generated overpressure and ignited cloud volumes agrees relatively well with values computed in TRAs. The model for ignited cloud-volume also appear to behave as desired in the sense that when the leak frequency is adjusted to TRA levels, it tends to approach the TRA cloud-frequency results. At least this is the case when applied to modules with a relatively high fraction of gas leaks compared to liquid leaks.

The RispEx tool is best suited for modules with an overweight of potential gas leaks (e.g. gas compression areas). Hence, caution should be exercised when using the tool to predict loads in areas where one would expect a high liquid leak fraction. As input to further work one could consider refining the tool to be able to distinguish between different types of process modules. As an extension of this a more thorough approach to the leak frequency model could be taken.

For **wellhead areas** RispEx overpredicts the explosion loads for most of the modules tested. The reasons for this have not been investigated in detail, but this could be related to a relatively robust activity level defined in RispEx, refer to 4.3.2.3 . Comparison with more modules is recommended to make a conclusion on this.

The **FPSO** model has only been tested with one area, and it is difficult to draw conclusions based on this. For the FPSO tested, the RispEx results are on the conservative side.

In general, only a few PLOFAM/MISOF analysis have been available for benchmark, and it is recommended to more extensive testing /comparison as part of the future maturing of RispEx. Based on the testing/benchmark performed it has not been identified systematic over/underprediction that recommends adjustment of the RispEx model.

3.8 Uncertainty assessment

An uncertainty assessment for RispEx has been performed based on Equinor method for qualitative uncertainty assessment (ref. /3/). The uncertainty assessment is documented in Appendix E.

Uncertainty related to the following main elements has been considered:

- Leak frequency modelling in RispEx
- CFD analysis of representative modules
- Probabilistic analysis used to establish risk curves for representative modules
- Interpolation scheme

A total of 22 uncertainty assessment elements has been included. In the assessment, each of the elements are described with respect to sensitivity and knowledge/competency, as illustrated in the matrix in Figure 3-4 and the criticality/robustness rating as shown in Figure 3-5.

Sensitivity	**Competency**		
	Low	Medium	High
High			
Medium			
Low			

Figure 3-4 Uncertainty matrix

	High criticality	Low robustness
	Medium criticality	Medium robustness
	Low criticality	High robustness

Figure 3-5 Criticality / robustness

Based on the classification of Sensitivity and Knowledge/Competency, each element gets a total uncertainty result.

The elements are found to have a dark score, i.e. high criticality and low robustness, are presented in Table 3-2. Proposed management of these uncertainty element is included. The complete uncertainty assessment is included in Appendix E.

Table 3-2: RispEx, Identified high criticality /low robustness uncertainty elements

ID	Uncertainty element	Sensitivity	Competency	Handling of uncertainty element
10	Congestion and detailed geometry of module	High	Medium	Validity envelope to restrict use for very congested areas or special geometries that will give high explosion loads. Highlight this in user manual.
13	Variance between different probabilistic explosion models/tools	High	Low	RispEx is based on DNVs probabilistic explosion tool, Express, which is an acknowledged tool.
15	Total leak frequency estimation	High	Medium	The leak frequency model in RispEx will be robust for most designs. Further work is also proposed on leak frequency.
17	Ignition model	High	Medium	RispEx is based on MISOF2 which represents the best available knowledge

3.9 Application of RispEx

The application of RispEx throughout a development project is illustrated in Figure 3-6.

In concept phase, RispEx can be used to estimate DeALs for various concepts and design. Effects of changes in module dimensions or openness can be assessed. Reference is also made to Section 3.4 in RISP main report regarding use of specialized studies (ref. /4/)

The design explosion loads are normally frozen in FEED phase, for the purpose of specification of explosion loads to equipment purchase orders as well as for cost and weigh estimate of topside facilities. RispEx will be used to specify the loads in FEED phase. During FEED and detail engineering, it must be followed up and confirmed that the design is within the validity envelope, and that the input parameters have not changed. The accidental events provided by RispEx can be used by development project for e.g. ALARP assessment, design optimizing and management of change purposes. For certain assessments/required decision support it might not be sufficient with the accidental scenarios provided, and other analysis or methods may be required. This will need to be assessed on a case-by-case basis for the relevant project. Reference is also made to Section 3.4 in RISP main report (ref. /4/).

At “as built” it shall be sufficient to verify that the input to RispEx has not changed, and that the design still is within the validity envelope, i.e. probabilistic explosion analysis is not required for the “as built” verification purpose.

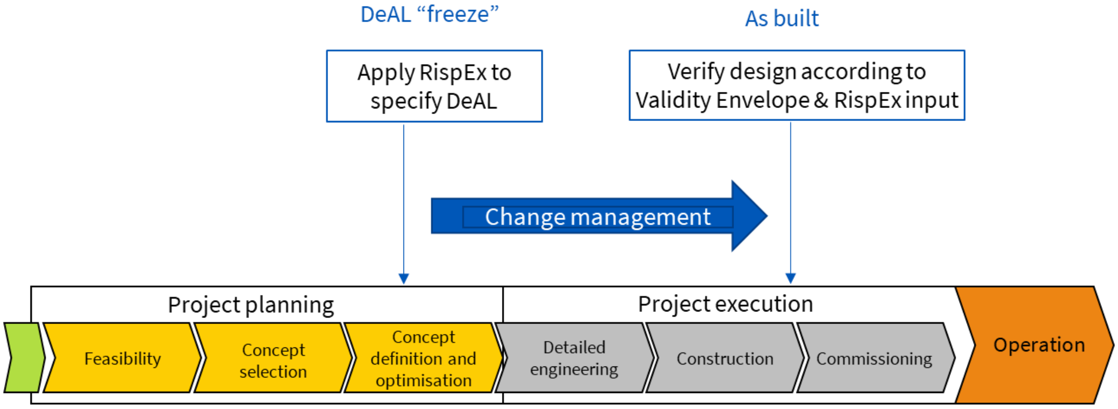


Figure 3-6: Application of RispEx throughout a project development.

3.10 RispEx User Manual

The RispEx user manual is attached in Appendix A. The user manual explains the input / output from RispEx in detail, as well as the limitations of the code (validity envelope). RispEx will also provide results outside the validity envelope, but with a warning for the user. It is the user's responsibility to ensure that RispEx only is used within the validity envelope.

3.11 Limitations

1. The limitations of the use of the RispEx tool is described in the validity envelope, refer to section 3.6 and user manual (Appendix A)
2. In some cases the boundaries of an area are not well defined, and several potential area boundaries may be selected as input to RispEx. This is further described in Appendix A.
3. The RispEx explosion model depends on the volume of the explosive cloud, the openness of the area and the volume of the area. It has been observed that the RispEx model may in some cases underestimate the explosion overpressure for very open areas, where congestion is the primary driver of explosion overpressure. This is further described in Appendix A.
4. Due to sparsity of models of as-built modern FPSOs, the RispEx model for FPSOs is based on fewer areas than the models for fixed facilities Furthermore, the FPSO RispEx model has undergone less extensive validation process. It is therefore recommended to verify some intermittent results when the model is used for FPSOs. This is further described in Appendix A.
5. The method will give general drag/overpressure loads with typical associated durations for an area, to be applied for physical area divisions (walls/decks), equipment, piping and structures. DeALs for specific equipment/targets are not covered by the method but could be implemented at a later stage.
6. The focus in this project has been on developing the RispEx tool, including validity envelope and documentation. Description of the risk management process from FEED to As built has not been covered (in detail), e.g.:
   - The potential need for additional type of analysis as decision support in FEED and detail engineering, e.g. detailing of design accidental loads for a specific package, understanding of risk picture etc.
   - Follow up of Design Accidental Loads, including validation at as-built

3.12 Potential future extensions

As part of the RispEx method and tool development, the following possible improvement points been identified:

1. Implement a system to systematically manage RispEx in the future, including necessary maintenance, gathering and evaluating feedback from users and potential updates to the model based on such feedback.
2. Further development of the leak frequency estimation method in RispEx.
3. Refine the resolution of points for interpolation within the validity envelope. It may be relevant to include additional representative areas with openness levels and volumes that will close gaps where the interpolation needs to take data from relatively distant data points. It may also be relevant to expand the validity envelope to include datapoints outside the region where the model interpolates today.

Other functionality or improvements that may be considered:

- Expand functionality to specify target cloud size as input.

- Functionality to reflect different wind conditions such as different wind speed distribution which may in particular be relevant for facilities with other geographical locations than the NCS. Another option is to reflect different wind rose distribution.
- Improvement of the dynamic calculation tools in terms of improved coding or functionality:
  - Optimize the code for faster run time. This may also allow higher resolution of the graphs without resulting in too long run time.
  - Minor updates such as
    - Order of notation of Walls in tool. Evaluate if West – North – East – South is a more intuitive order.
    - Consider if Y-axis on Exceedance curves should have logarithmic scale.
    - If an error message is given (as in Figure 2-3 in the manual), the Calculate button should be removed or deactivated
    - Consider de-activate the Data for wellhead areas if Process area is chosen. Possibly also external ignition for blowouts.
    - Default value for representative blow out rate should be marked, or no blowout rate should give an error message.

4 Technical basis of RispEx

4.1 Overall model architecture

The basis of the tool consists of pre-calculated cloud exceedance curves (ignited cloud size vs. probability given leak, exceedance curves) and cloud volume vs overpressure relations for 38 representative areas. A flow diagram of the tool is included in Figure 4-1.

Initially, explosion analysis results for 21 representative traditional process areas (i.e. on jackets and SPARs), five representative FPSO process areas and the additional seven representative wellhead areas are included in the RispEx model. The volume and openness level of the representative areas varies, while other parameters, e.g. wind rose, performance of safety systems, and inventories are assigned with typical values kept identical for all areas. The layout and congestion of the geometries are selected based on typical areas. Geometries are cut and pasted from the approximately ten FLACS geometry models available from the explosion analysis for the facilities most recently set in operations, or still in detailed design development in the Norwegian industry.

RispEx explosion load results for an area are calculated based on interpolation on the predefined curves.

The key explosion results given as output from the tool are returned based on the area-specific cloud exceedance curves, as well as a few other user-defined parameters. This results in pressure exceedance curves established by interpolation, which are used to calculate the DeAL pressure. Input and output are further described in Section 3.3.

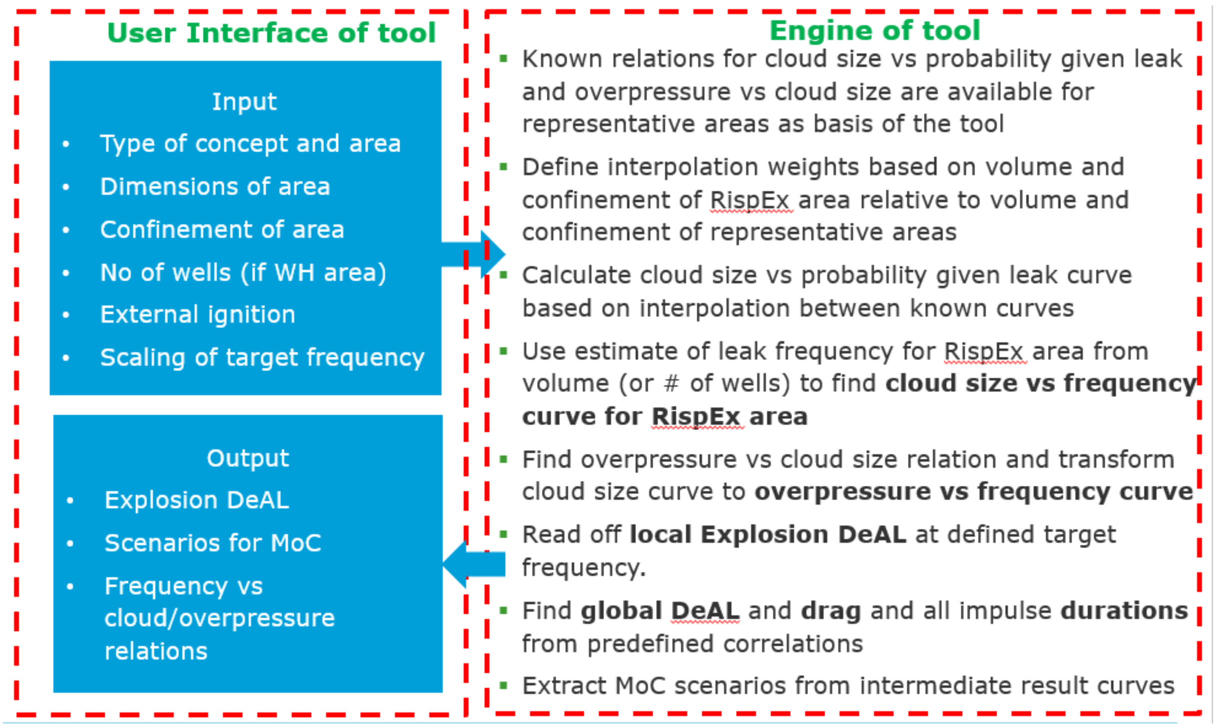


Figure 4-1 Simplified illustration of how the RispEx tool works

Note that the cloud-size exceedance curve (ignited cloud exceedance probability given leak) of the representative areas form the basis of the method/tool.

The way the cloud size exceedance curves are calculated for all representative areas are relatively complex, since it is performed in line with the approach described in NORSOK Z-013.

The cloud size exceedance curves are calculated using FLACS Computational Fluid Dynamics (CFD) consequence modelling and the probabilistic tool Express version 5.2, ref. /5/. Express is an internal DNV tool, but it is implemented as an integrated part of Safeti Offshore risk analysis tool, ref. /6/, hence the tool is also indirectly commercially available.

To make the Express interpretation of NORSOK Z-013 more transparent, a detailed description is given in Sections 4.3 and 4.4 on how explosion analysis results are calculated based on the defined input of a representative area. Some representative intermediate and final results are also provided. A record of modelling parameters for all representative areas is provided in Appendix B. All intermediate and final results are available in the input files for the digital RispEx tool. See Appendix C for details.

Since the method is relatively complex, the description of Express is quite technical. It is reproduceable by running Express v5.2 with the input given in this document. It is also traceable and reproduceable in the sense that all input, as well as intermediate and final output is given, and it will be possible to rerun the explosion analysis in all different tools for which a version of the NORSOK Z-013 method is implemented, to compare how the results correspond with the defined input.

The aim of the interpolation logic described in Section 4.5 is to show that the method by which the actual cloud exceedance curves and the overpressure vs cloud size relations are established are transparent, intuitive and relatively easily to reproduce. This way, the results produced when using the RispEx method will be easily traceable, as intended.

4.2 Representative areas

CFD ventilation, dispersion and explosion simulations, as well as probabilistic explosion analysis have been carried out for 38 representative areas as part of the RispEx tool development process. The purpose has been to provide a well-documented and consistent collection explosion analysis results based on probabilistic modelling of a fixed set of representative areas. This provides the possibility to interpolate between the results when key results are required for a given module with an arbitrary set of input parameters within the valid input range.

4.2.1 Representative modules and main parameters

Representative modules that have been subject to the probabilistic analysis was selected based on:

- Modern and assumed typical future modules
- Sufficient technical basis for interpolation
- The selected parameters defined in the above chapter also guides the selection of areas. Three main types of areas are assessed in terms of function of area:
    - Process area on conventional integrated oil and gas facility (25 areas)
    - Process area on weather-vaned FPSO (5 areas)
    - Wellhead area on conventional integrated oil and gas facility (7 areas)

Small wellhead platforms have not been assessed. Turret areas on FPSOs have not been assessed.

The specification of an area is limited to four different input parameters. These are considered the key drivers of the explosion risk in an area. These area parameters (defined as described in Section 3.3) are:

- Length – L [m]
- Width – W [m]
- Height – H [m]
- Total openness parameter - A_v / A [-]
    - Based on O_W, O_E, O_N, O_S, O_{Up}, O_{Down}

Where O_X denotes the openness, i.e. how open the area is on the surface side of the area toward direction X. Note that this parameter was named Porosity in earlier revisions of the report and in earlier version of the program the program. This name is consistent with the meaning of the parameter. The name of the parameter has been changed from Porosity to Openness since Rev 0 of the report. The mathematical definition remains the same.

A visualization of the parameters, and illustration on how L, W and H relates to Platform North are given in Figure 4-2

The parameters A_v and A are the sums of the total *open* areas, and the total areas around the 6 sides of the RispEX area, respectively. The Total openness parameter is 0 for a fully closed room and 1 for an area with no solid borders.

The total openness parameter is hence reflecting both the solid/open wall configuration, and wind protection along the wall as described in the following two chapters.

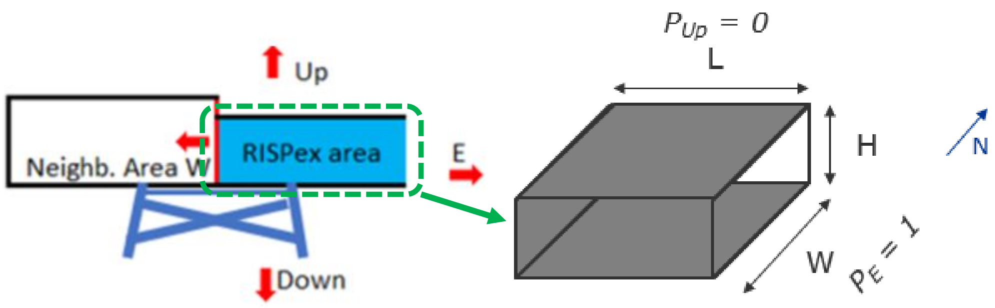


Figure 4-2 An offshore area, illustrating what sides are denoted L, W and H relative to platform North.

4.2.2 Principles for how areas are defined

This section describes the principles for how to define representative areas to have an adequate variety and range of the three parameters defining the dimensions of the area, and the six parameters defining the porosity/openness level, in order to cover the most relevant area configurations within the validity envelope, and to have a good basis for interpolation throughout the range of the validity envelope.

Physical and representative parameters are derived from the basic input parameters when applied in the model. These are typically the volume, the aspect ratio and total openness parameter of the area.

Three main types of area configurations are assessed:

- 2-ways ventilated area
- 3-ways ventilated area
- 4-ways ventilated area

2- and 3-ways ventilated areas are assessed for all types of areas, i.e. both for process area in integrated facility, process area on FPSO and for wellhead area. However, for the 3-ways ventilated area on FPSOs, the open sides are the North surface side of the area (port side), South side (starboard) and upwards. For areas on an integrated facility, the open sides for a 3-ways ventilated area are North, South and East.

4-ways ventilated area are only considered for process areas on integrated facilities and process areas on FPSO. Here, the fourth side that is open is always up.

In this context, 2-ways ventilated area refer to an area where 4 of the sides are fully enclosed by plated, non-porous wall or deck (with a openness of 0), while 2 of the sides contain openings for natural ventilation.

The open sides may be partly covered by weather cladding, louvers, grating, pop-out panels, walls, decks or other solid or porous plates covering some of the opening. In the model, this is reflected by selecting an openness between 0 and 1, where 0 is fully closed and 1 is fully open. Obstacles caused by structural elements, piping or equipment units should for simplicity not be reflected by the openness. For this reason, a openness of 1 will have effective openness somewhat below 1 (meaning the typical openness is already represented in the model).

Representative configuration of 2-ways, 3-ways and 4-ways ventilated areas for the different types of areas included in the RispEx model are illustrated in Figure 4-3 to Figure 4-7 below.

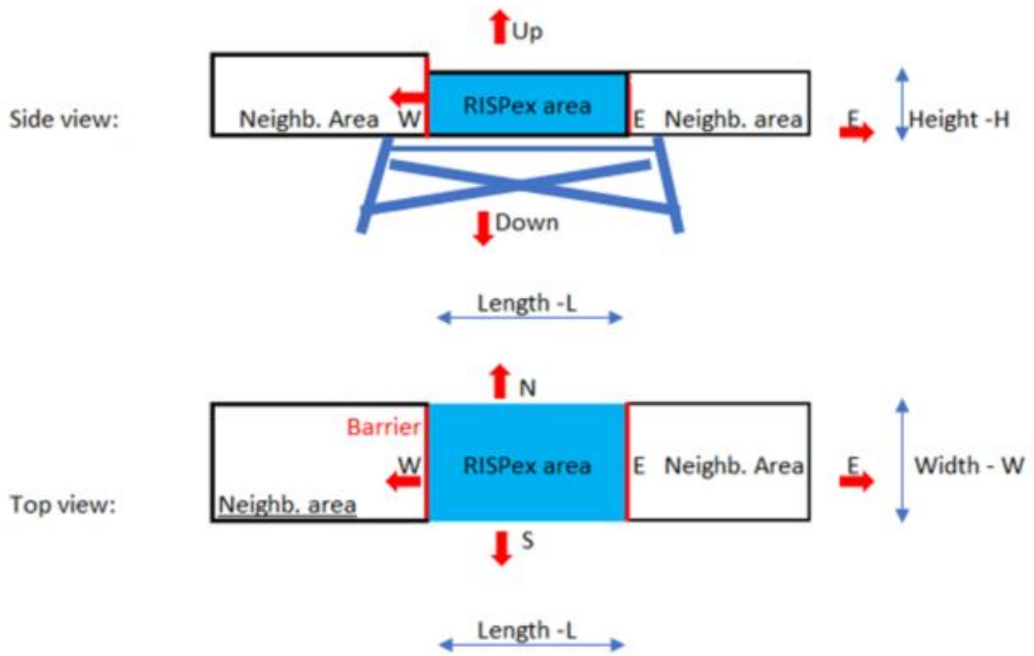


Figure 4-3 Representative configuration of a 2-ways ventilated area for conventional process area and wellhead area (open towards Platform North and Platform South). Despite not shown in the illustration, there may be deck levels above and/or below the RispEx area.

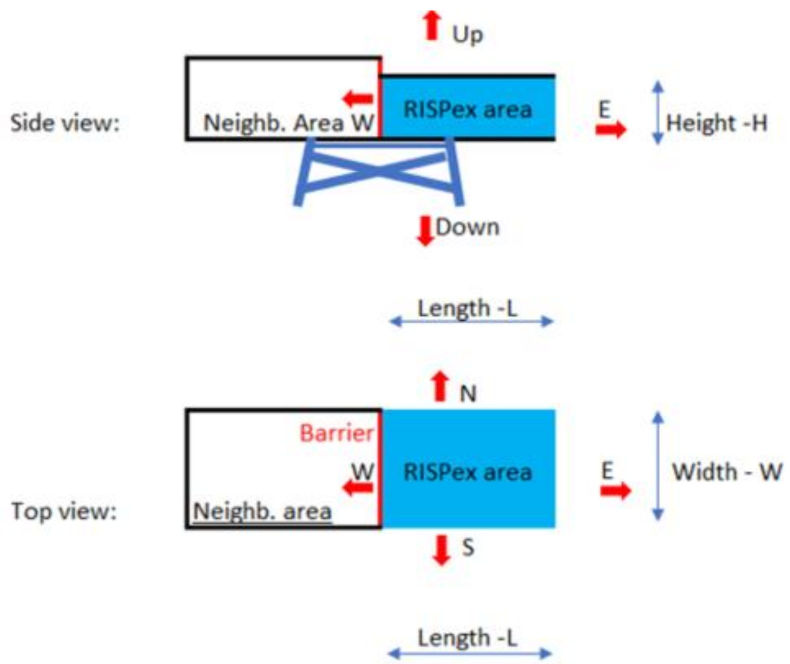


Figure 4-4 Representative configuration of a 3-ways ventilated area for conventional process area and wellhead area (open towards Platform North, Platform South and East). Despite not shown in the illustration, there may be deck levels above and/or below the RispEx area.

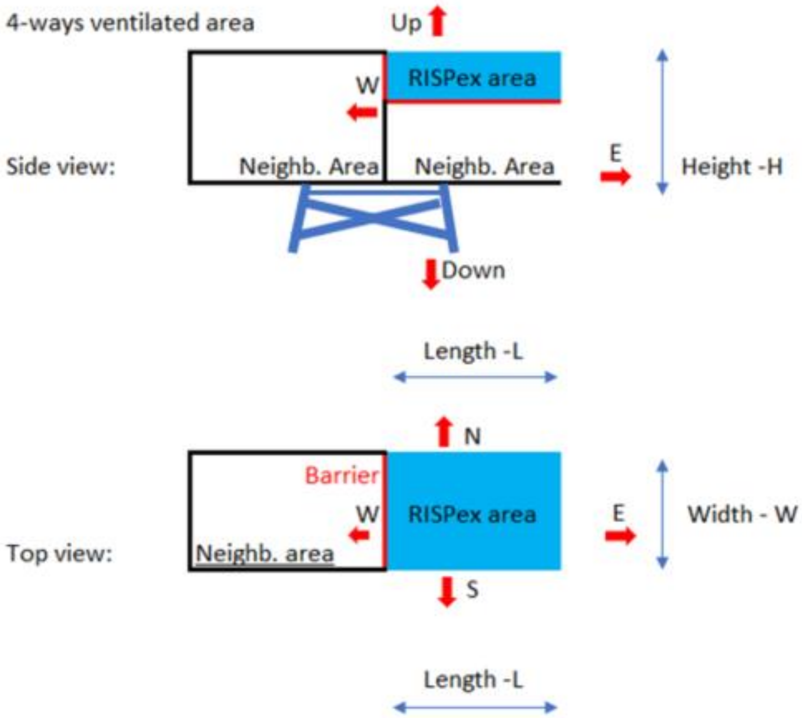


Figure 4-5 Representative configuration of a 4-ways ventilated area for conventional process area and wellhead area (open towards Platform North, Platform South, Platform East and upwards). The open/ventilated sides may be partly covered with decks and or cladding/panels/louvers, this must be reflected as an openness below 1 as input (but above 0 which is fully plated).

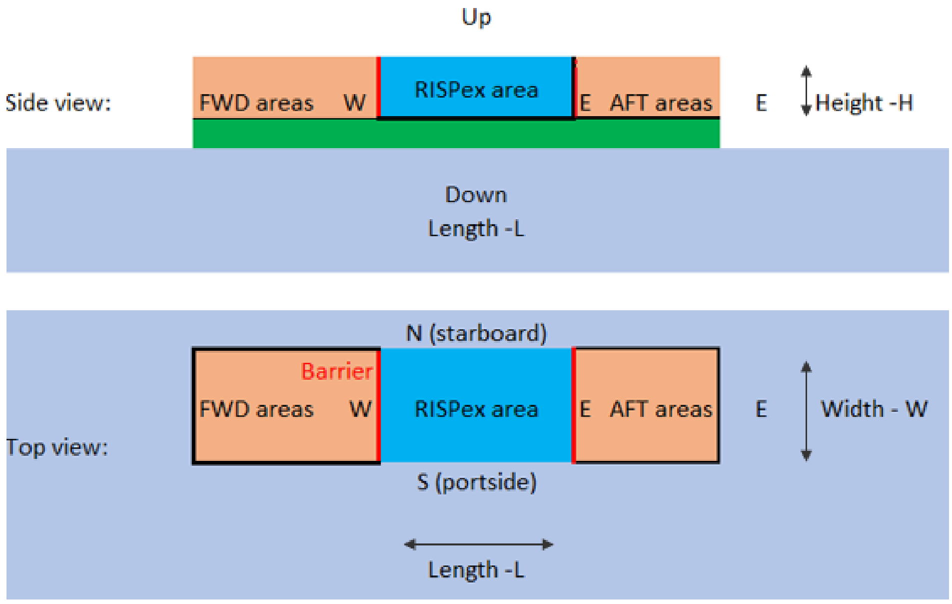


Figure 4-6 Representative configuration of a 3-ways ventilated area on an FPSO (open towards Starboard, portside and up). On this drawing, the turret is to the left (not shown).

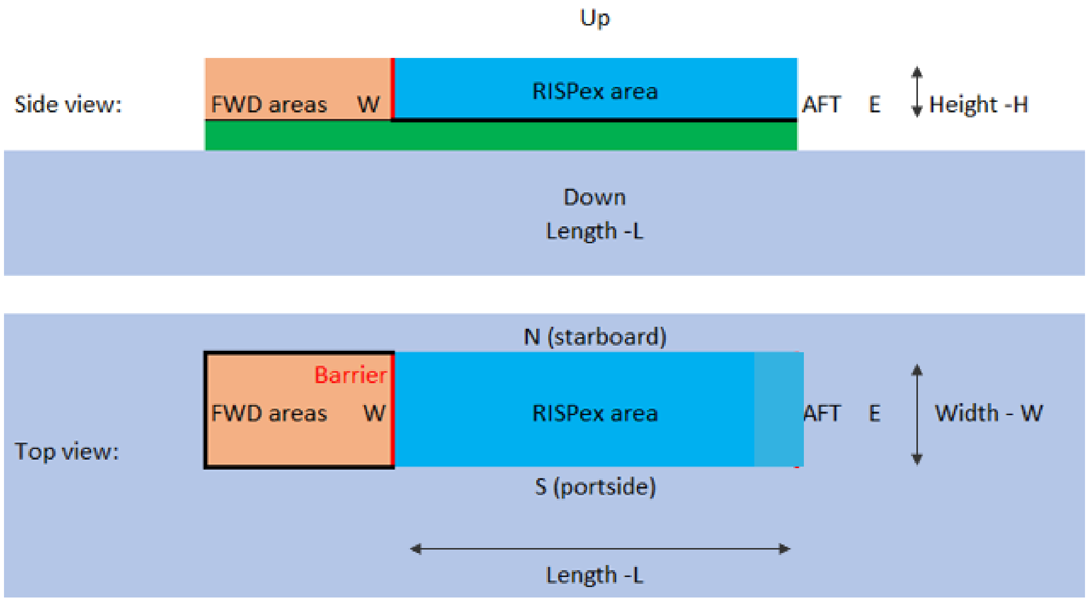


Figure 4-7 Representative configuration of a 4-ways ventilated area on an FPSO (open towards Starboard, portside, AFT and up). For the representative areas, a wind rose is selected so that the prevailing wind is from FWD most of the time, resulting in process area most of the time in the wake of the wind (lower ventilation conditions)

4.2.3 Input openness and effective openness

The user input openness (O_x) should only consider additional covers such as wind protection and decks when larger than 25% of the top area. If there are no such additional covers, O_x = 1 should be used.

In order to obtain realistic openness of the "open" sides with input openness 1, these will be set equal to/reused from the real as-built FLACS geometries, so that the level of natural obstacles beyond walls and weather cladding will be realistic in the representative areas. It is expected that the typical openness value for a realistic open side with no walls or cladding will be around 0.9-0.95 due to obstructions caused by e.g. load carrying structures, piping, cable gates, equipment units. Based on the way the openness parameter is defined in RispEx, this will correspond to a Openness degree of 1 (fully open). A typical openness value as defined as input parameter in RispEx may be 0.7-0.8 (2-meter wind wall across the entire side for a module with height 8 meters result in Openness of 0.75). Note that based on this, the total openness caused by all obstructions will be lower than the openness specified as input to the tool. In the representative geometries it is important to capture the total blockage caused by all obstructions. Hence, the efficient openness in the geometry model would be ~0.75 in cases where the defined (and interpolated) Openness is ~0.85. For open (ventilated) sides of the RispEx representative geometries the Openness will typically be set to 0.8-1 (corresponding to an effective openness of 0.7-0.9) based on:

- For North and South side of the area, as well as for East side for 3- and 4-ways ventilated areas, perforated/porous weather cladding from an elevation ~0.3 meter above deck level is typically included, extending ~2.7 meters upwards to provide weather protection/shielding for personnel inside the module (causing obstructions that need to be defined in the input). Additionally, the main load bearing members of the module, as well as various cable gates, piping, and equipment units, will cover some of the ventilation opening (causing additional obstructions reducing the effective openness but should not be reflected in the RispEx input).
- For a 4-ways ventilated process area, it is not realistic that the area is fully open upwards. A common configuration is that there is plated or grated access decks, such as laydown area or cooler decks etc above the area. To reflect the 4-ways ventilated configuration, a grated deck with a size that is 25% (0.5 L × 0.5 W) of the footprint of the

area is included above the process area for the representative areas to have representative modules that have some predefined openness in order to ensure interpolation points that do not tend to be higher than the region the tool is most likely going to be used for. In addition, there will be the natural obstructions caused by various types of structural members and piping/equipment. These will be included in the representative geometries based on the way the representative areas are constructed; i.e. based on cutting region from relevant as-built geometries and put together to construct representative areas with the preferred dimensions.

4.2.4 Common area dimensions and openness configurations

When selecting dimensions and openness of the representative areas in terms of what are the most typical length, width, height and openness configuration for offshore process and wellhead areas, some observations are made below. these are based on evaluations of eight recent as-built geometry models, as well as the areas relevant for explosion analysis database collected as part of RISP Work Group 2. These common values are reflected in the selection process and can be summarized as follows.

For “conventional” process areas on jacket platform, SPARs, etc:

- Dimensions, size and shape
    - Length: Usually above 20 meters. 25-40 meters are a common range. The length may extend to 70 meters but limited by length of platform.
    - Width: 28 meters are the most common as the width extend across the platform within the main steel frame. 40-45 meters are also seen for several facilities.
    - Height: 8 and 10 meters are the most typical height per deck level.
    - Footprint shape: Typically, relatively close to 1. L/W in the range 0.5 – 1.6 is common.
    - Module volume: The typical range is between 4000 m^3 - 28 000 m^3
- Openness
    - 2-ways or 3-ways ventilated. Weather deck type process areas may be 4-ways ventilated. The high ventilation for these areas results in reduced explosion risks, but some 4-ways ventilated process areas for some newer designs are very large, with partly plated decks above containing laydown areas or upper weather decks. Hence 4-ways ventilated areas are included as representative areas for larger process areas.
    - The openness levels of 2-ways, 3-ways and 4-ways ventilated modules varies, both based on how confined the ventilated sides are, but also based on the shape of the module. For the representative conventional process areas selected for RispEx, the range in the total porosity/openness level per type of ventilation configuration can be summarized as follows:
        - 2-ways ventilated modules, A_v/A = 0.07- 0.16
        - 3-ways ventilated modules, A_v/A = 0.14-0.23
        - 4-ways ventilated modules, A_v/A = 0.37-0.48

        Openness level is here defined as described in Section 3.3 as well as in previous parts of this section.

For process areas on FPSOs, the following applies:

- Dimensions, size and shape
    - Length: FPSO process areas may be very large if there is no firewall dividing the process areas into more than one large area. For the initial version of RispEx, it is anticipated that future Norwegian FPSO designs will have process areas that is divided into 2 areas by physical firewall, hence reducing the length of the area to maximum 60-80 meters

- Width: The span across the width of the FPSO may typically be ~50 meters.
- Height: When modules are located at the process decks, there may be intermediate deck levels but only covering minor parts of the full area footprint. Hence the most likely configuration is 3-ways ventilated areas, with ventilated sides starboard, portside and upwards. Total height of process area may then be up to 20 meters.
- Module volume: When considering FPSO process areas divided to more than one area by firewall, the typical range is between 30 000 m^3 - 70 000 m^3

- Openness
  - Some weather cladding, typically along walkways, at each side. Typically an escape tunnel is along one of the sides. Upwards there is not likely to be a deck covering the full footprint, but various decks for some of the modules located in the FPSO process area.
  - For the representative FPSO process areas selected for RispEx the range in the openness level per type of ventilation configuration can be summarized as follows
    - 3-ways ventilated modules, A_v/A = 0.36-0.41
    - 4-ways ventilated modules, A_v/A = 0.37-0.48

  Openness level is here defined as described in Section 3.3 as well as in previous parts of this section.

For wellhead areas on integrated facilities, such as jacket platforms, the following applies:

- Dimensions, size and shape
  - Length: 20-24 meters long.
  - Width: The typical width on wellhead areas are similar to the conventional process areas on jacket platform, i.e. in the range 28-44 meters, stretching from across platform in N-S direction. 28 meters is most common for recent facilities put in operations, but up to 42-44 meters realistic for platforms with wide footprint across platform.
  - Height: 7-15 meters high, between plated cellar deck and plated hatch deck (below well intervention deck / BOP deck) with grated intermediate decks (X-mas tree access deck, choke valve balconies etc). 13-15 meters height is expected, but example of 7 meters are found among the wellhead areas included in the set of eight most recent facility geometries. Footprint of grated deck ranging from several decks covering 50-100% of footprint in total, or one large mostly grated X-mas tree deck covering ~80-100% of footprint
  - Resulting typical volume range is then 4000-15000 m^3, with grated deck “in the middle”
- Openness
  - The wellhead area may be located in the middle of integrated facility (between Utility/LQ and Process – i.e. 2-ways ventilated with firewalls on both sides) or in the end/platform East side (Next to Process - i.e. 3-ways ventilated areas). 4-ways ventilated is not considered relevant, as cellar deck assumed plated, and ceiling assumed plated hatch deck below well intervention deck.
  - For the representative wellhead areas selected for RispEx the range in the openness level per type of ventilation configuration can be summarized as follows
    - 2-ways ventilated modules, A_v/A = 0.14-0.2
    - 3-ways ventilated modules, A_v/A = 0.2-0.31

Openness level is here defined as described in Section 3.3 as well as in previous parts of this section.

4.2.5 Representative CFD area definitions

The dimensions and openness configuration applied for the representative areas are listed in Table 4-1 for process areas on integrated facilities, Table 4-2 for process areas on FPSO and Table 4-3 for wellhead areas on integrated facilities. The openness level per side of the area is specifically defined in Appendix B.

A_v/A is then calculated as the total ventilated area of all 6 sides of the area, divided by the total surface area of all six sides of the area.

Table 4-1 Areas used with shapes, dimensions and openness configuration for representative RispEx process areas on integrated facilities

ID	Shape desc.	Length (m)	Width (m)	Height (m)	Ventilated sides	Volume (m³)	Av / A [-]
03	Square - high	23	24.5	8	2-ways	4508	0.16
04	Square - low	30	28	5	2-ways	4200	0.11
01	Square - low	30	28	5	2-ways	4200	0.07
05	Square - low	30	28	5	3-ways	4200	0.16
02	Square - low	30	28	5	3-ways	4200	0.14
08	Square - low	32	32	8	2-ways	8192	0.13
09	Square - low	32	32	8	3-ways	8192	0.20
10	Square - low	32	32	8	4-ways	8192	0.47
11	Square - high	28.5	28	10	2-ways	7980	0.17
06	Square - high	28.5	28	10	2-ways	7980	0.10
12	Square - high	28.5	28	10	4-ways	7980	0.48
07	Square - high	28.5	28	10	4-ways	7980	0.37
13	Long - low	40	28	7	3-ways	7840	0.19
14	Long - low	40	28	7	4-ways	7840	0.47
16	Square - low	46.5	46	8	3-ways	17112	0.15
17	Square - low	46.5	46	8	4-ways	17112	0.45
18	Square - high	41	41	10	2-ways	16810	0.13
15	Square - high	41	41	10	2-ways	16810	0.08
19	Square - high	41	41	10	3-ways	16810	0.20
21	Square - high	41	41	10	3-ways	16810	0.16
20	Square - high	41	41	10	4-ways	16810	0.47
22	Long - high	57	28	10	3-ways	15960	0.23
23	Long – high	60	40	10	3-ways	24805	0.16
24	Long – high	60	40	10	3-ways	24805	0.19
25	Long - high	60	40	10	2-ways	24805	0.13
26	Long - high	60	40	10	4-ways	24805	0.47

- NOTE The areas tabulated with blue font has the identical layout, dimensions and ventilation category (i.e. 2/3/4-ways ventilated) as the area tabulated above, but the openness configuration of the open/ventilated sides are adjusted

Table 4-2 Dimensions and openness configurations for representative RispEx process areas on FPSOs

ID	Shape desc.	Length (m)	Width (m)	Height (m)	Ventilated sides	Volume (m³)	Av / A [-]
51	Narrow - high	32	53	19	3-ways	31800	0.35
52	Narrow - high	32	53	19	4-ways	31800	0.47
53	Square - low	60	53	10	3-ways	31800	0.41

54	Square - high	60	53	19	3-ways	60420	0.41
55	Square - high	60	53	19	4-ways	60420	0.49

Table 4-3 Dimensions and openness configurations for representative RispEx wellhead areas on integrated facilities

ID	Shape desc.	Length (m)	Width (m)	Height (m)	Ventilated sides	Volume (m³)	Av / A [-]
71	Narrow - low	21	26	7.5	2-ways	4095	0.14
72	Narrow – low	21	26	7.5	3-ways	4095	0.23
73	Narrow – high	20	28	13	2-ways	7280	0.18
74	Square/narrow – high	24	28	15	2-ways	10080	0.20
75	Square/narrow – high	24	28	15	3-ways	10080	0.31
76	Narrow - high	24	43	13	3-ways	13416	0.23
76	Narrow - high	24	43	13	2-ways	13416	0.13

4.3 Probabilistic analysis of representative modules

The basis of the tool consists of defined cloud exceedance curves and overpressure vs ignited cloud size curves for a fixed number of representative areas. This section describes the approach for calculation of these basis data.

The explosion analysis performed for the 38 representative process and wellhead areas initially included in the RispEx basis has been carried out in line with the approach specified in NORSOK Z-013, Annex F. The overall methodology is illustrated in Figure 4-8, below. The probabilistic analysis is carried out using the probabilistic tool EXPRESS. Further details on the probabilistic methodology can be found in several papers, including ref /7/ and /8/. The probabilistic calculation approach presented in this section should be considered together with the CFD calculation approach presented in Section 4.4, as the CFD simulations are an integrated part of the probabilistic analysis. CFD simulation results provides input to the probabilistic analysis.

Note that the cloud exceedance and overpressure vs ignited cloud size curves for a new area corresponding to the type, dimensions, and openness of what is defined as input in the tool is calculated based on interpolation between the predefined curves. The proposed principles of the interpolation logic are presented in Section 4.5. Based on an estimate of the leak frequency depending on the volume of the process area or the number of wells in the wellhead area, the pressure exceedance curve can then be provided as output.

4.3.1 Consequence Modelling

The consequence modelling is described in detail in Section 4.4. This involves a series of steps including the development of a 3D geometry model, and performing CFD ventilation, dispersion and explosion simulations, where the key objective of each step is as follows:

- **Geometry modelling**: Develop a 3D model of the asset which includes all the major structural elements that are typical for a conventional offshore process or wellhead area. The process of developing representative geometries is based on a high degree of reuse of as-built FLACS geometry models from the most recent Norwegian Oil and Gas development projects, as described in Section 4.4.1. No additional anticipated congestion is added to the model to account for small sized items, since the geometries used as basis should reflect anticipated congestion of as-built models. A summary of the key layout data per representative area are given in Table 4-1 through Table 4-3. The congestion levels of the models are summarized in Section 4.4.1.

- **Ventilation simulations**: Determine the fluid flow pattern within the relevant areas and obtain the ventilation rates in areas of interest. This is further described, and results presented in Section 4.4.2.
- **Dispersion simulations**: Determine the representative gas cloud sizes for each leak scenario considered. The variation in cloud size as a function of various dependent variables such as leak rate, leak direction, wind direction, wind speed is also obtained. Cloud sizes are defined as Q9 cloud size (i.e. equivalent stoichiometric cloud that is equivalent to the inhomogeneous cloud from the dispersion simulations). This is further described in Section 4.4.3
- **Explosion simulations**: Calculate the explosion overpressure as a function of dependent variables such as cloud size, cloud location, cloud shape, fill fraction, and ignition location. This is further described in Section 4.4.4.

The typical output from each of these steps is illustrated in Figure 4-8.

All ventilation, dispersion and explosion CFD calculations are performed with FLACS software, developed by GEXCON (Norway).

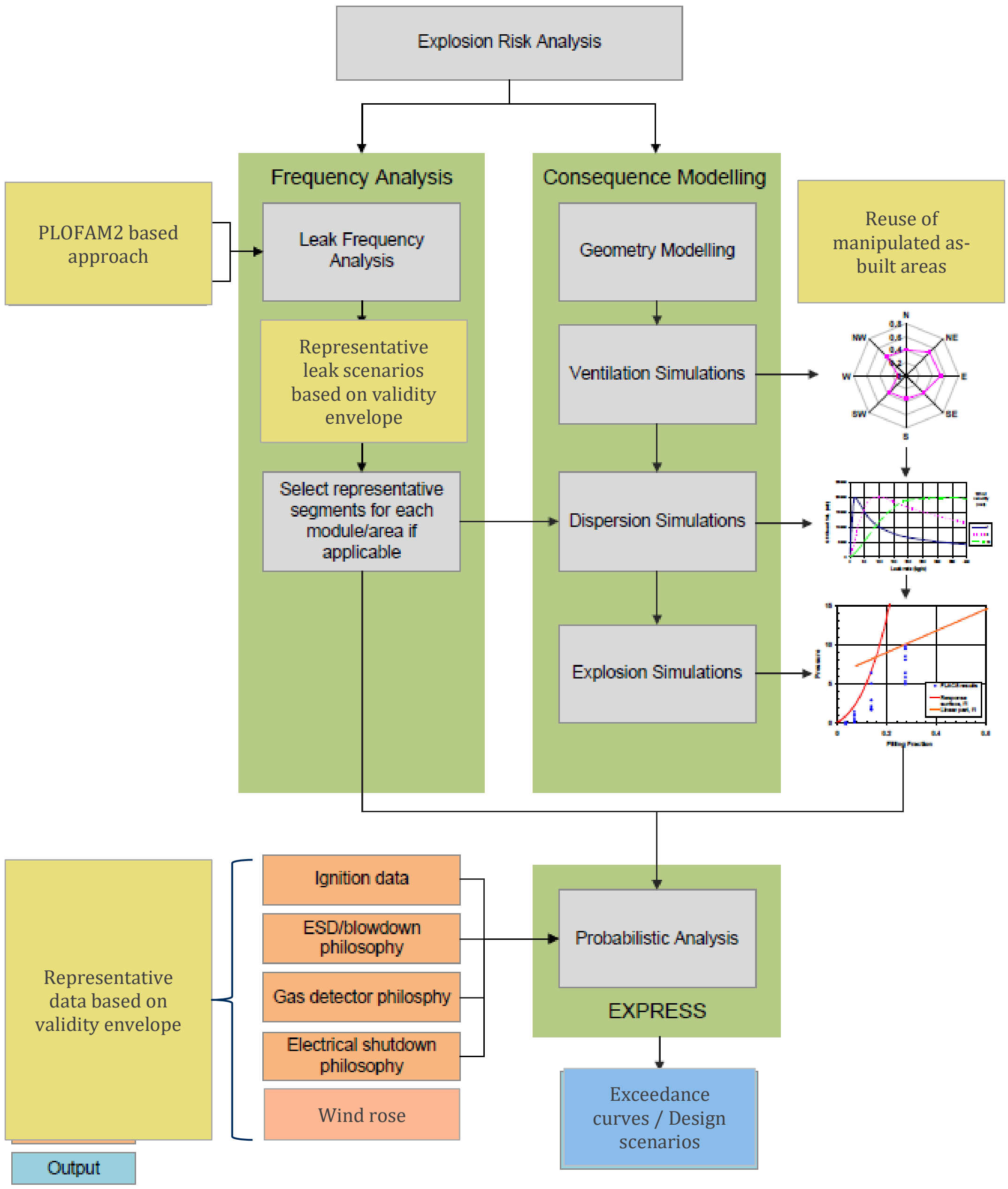


Figure 4-8: Schematic of the methodology applied for probabilistic explosion analysis

4.3.2 Frequency Analysis

The basis of the leak frequency estimation is PLOFAM2.

There are two key elements in the estimated leak frequency for a representative area;

1. The total frequency of gas leaks and volatile liquid leaks exceeding 0.1 kg/s
2. The shape of curve showing the conditional probability of exceeding certain leak size given leak has occurred

The probabilistic analysis is run with a leak frequency of 1 leak per year exceeding 0.1 kg/s, and with a "standard" leak size distribution (described in the following). This produces cloud exceedance curves for small, medium and large leaks individually. The three cloud size exceedance curves are later combined to reflect the total leak frequency, and the distribution of small, medium and large leaks for the relevant Rispex module.

The shape of the curve showing the conditional probability of exceeding certain leak size given a leak is based upon the relation given in ref. /2/. The complementary cumulative leak frequency fraction distribution, denoted *A(Q)*, is in line with ref. /2/ approximated by the following function:

$$A(Q) = C \cdot Q^{-k}$$

The following parameters are used:

Parameter	Value
k	For Q <= 1 kg/s: -0.50
	For Q > 1 kg/s: -0.70
C	For Q <= 1 kg/s: 0.3162
	For Q > 1 kg/s: 0.3162

For the probabilistic analysis, in line with ref. /2/, 60% of the leaks are pure gas leaks, while 40% are liquid leaks. For the liquid leaks, 10% of the fluid is assumed to flash off instantaneously.

The resulting curve for gas leaks is given in Figure 4-9. The curve is discretised in order to be applied in the Monte Carlo simulations performed by Express. The leak size distribution used in EXPRESS is tabulated in Table 4-4.

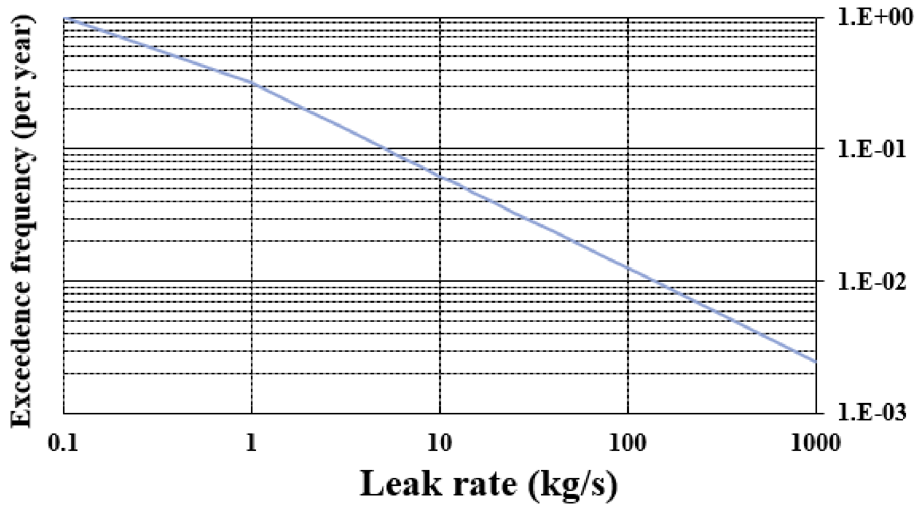


Figure 4-9 Leak rate vs conditional exceedance probability

Table 4-4: Leak categories used in the probabilistic explosion risk analysis (adjusted for flash fraction of liquid releases and allocated to leak categories)

Representative leak rate (kg/s)	Fraction of leak with this rate
0.3	0.69
0.7	0.09
2	0.11
4	0.04
8	0.03
16	0.01
32	1E-02
64	3E-03
100	3E-03
250	5E-03

The leak frequency size distribution presented in Table 4-4 is used for process leaks within wellhead areas directly in rispex.

For process areas on platforms and FPSO's it is possible to indirectly provide a liquid leak fraction based on the type of process area under investigation. This will re-calculate the distribution of small, medium and large leaks based on the associated fraction of liquid leaks within the area, and the assumed flash fraction of 0.1.

Four different areas process areas, with different liquid leak fractions are possible to specify:

- General process
- Gas processing
- Oil separation
- Oil processing

'General process' uses the default liquid leak fraction of 40%, as applied in ref. /2/ and the EXPRESS calculations, resulting in the same small/medium/large distribution as in Table 4-4. The liquid fraction applied and the resulting distribution between small, medium and large leaks for the other process area types are presented in Table 4-5.

Table 4-5: Main leak categories used in rispex calculations (adjusted for liquid leak fraction and flash fraction of liquid releases and allocated to main leak categories)

Type of process area	Liquid leak fraction	Fraction of leaks within leak category		
		Small	Medium	Large
General process	0.4	0.785	0.172	0.043
Gas processing	0.2	0.734	0.213	0.053
Oil separation	0.6	0.837	0.132	0.033
Oil processing	1.0	0.937	0.051	0.013

The small/medium/large distribution presented in Table 4-5 is used to weight the contribution from the small/medium/large cloud exceedance curves which are output from express.

The total leak frequency is calculated per area as summarized in the following subsections.

4.3.2.1 Leak frequency for conventional process area

For conventional process modules, the leak frequency applied in RispEx is estimated based on the volume of the module. Larger modules contain more leak sources, and consequently a higher estimated leak frequency would be estimated by traditional methods. In line with the simplified PLOFAM2 model provided in ref. /2/ the leak frequency for hydrocarbon leaks exceeding 0.1 kg/s in a conventional process area are estimated based on

$$f = k \cdot V$$

In this equation, f is the frequency of hydrocarbon leaks exceeding 0.1 kg/s, V is volume of the process area, and k is a constant giving information on how much leak sources there are per volume unit within the process area.

For process areas, no updated estimate of k has been performed as part of RispEx, hence the parameter value k=4.7E-6 per m^3*yr provided from ref. /2/ is used.

k = 4.7E-6 per m^3*yr, for conventional process areas

4.3.2.2 Leak frequency for process area on FPSO

The FPSO is not as constrained on space to the same degree as fixed installations. The estimated leak frequency for process leak is evaluated to be conservative when calculated in line with the coarse model parameter provided in Section 4.3.2.1, above. PLOFAM2 leak frequency estimates are available for two Norwegian FPSOs. Based on these two, the following k can be derived from the equation $f = kV$:

- FPSO 1, frequency of gas leaks + oil leaks >0.1 kg/s: k = 4.2E-6 /m^3 year (2.7E-6 when only gas leaks are included)
- FPSO 2: k = 8.0E-7 /m^3 year

FPSO 2 is a more modern design than FPSO 1, but as the statistical basis is limited, a value closer to the k value for FPSO 2 may be optimistic estimates on a too weak basis.

For FPSO type process areas, the following k value is applied in the RispEx model:

k = 2.0E-6 /m^3 year, for FPSO type process areas.

4.3.2.3 Leak frequency for conventional wellhead area on integrated facility

The following types of hydrocarbon releases may occur in a wellhead area:

- Process leakages
- Blowouts
- Well releases

For process areas, the volume of the area is evaluated to be the best possible indicator of leak frequency when selecting the main driver for a simplified leak frequency estimate.

Functionally, the wellhead area is simpler than the process area, as it contains mainly wellheads, X-mas trees and manifolds. The complexity of these systems in terms of number of leak sources is likely to be much more depending on the number of wells than with volume. For the process area, there is a larger range of equipment types, with various factors driving the number of leak sources per equipment unit. Hence, it is considered that for wellhead areas the number of wells is a better indicator of estimated leak frequency than the area volume.

The number of wells in RispEx is defined as the sum of producers and gas injectors. Water injection wells have a much lower hydrocarbon leak frequency and are therefore not included.

Process leakages

Process leakages is estimated based on previous equipment counts for wellhead areas, resulting in a typical number of leak sources for a production manifold segment. Leak frequency are calculated with PLOFAM 2. When considering a segment that includes one production line from master/wing valve, chokes and production manifold, a reference leak frequency can be estimated for this system/segment. The leak frequency applied to RispEx (upstream the production manifold) are then scaled with the number of wells (production lines). The pressure and density downstream choke for the reference segment which the leak frequency is calculated upon are assumed to 21 bara and 129 kg/m^3.

To account for potential gas lift/injection/test manifold in the area, the leak frequency for the manifold has been multiplied with a factor of 3. To account for potential gas lift lines, the leak frequency for the production line has been multiplied with 2.

The basis and resulting frequencies are presented in Table 4-6.

Table 4-6 RispEx Leak frequency basis for process leaks, Wellhead area, per well.

Description	Leak frequency > 0.1 kg/s per year	
	Per production line	Manifold
Calculated leak frequency production manifold (PLOFAM2)	1.6 · 10-3	3.9 · 10-4
Scaling factor	2	3
Leak frequency basis used in RispEx	**3.1 · 10-3**	**1.2 · 10-3**

Based on this method the following equation is used for calculation of leak frequency related to process events in RispEx

$$f = 3.1 \cdot 10^{-3} \cdot N_{wells} + 1.2 \cdot 10^{-3},$$

where

f = Annual frequency of process leakages > 0.1 kg/s and N_{wells} = Number of wells.

As the equation shows, the process leak frequency is a function of the number of the wells in the wellhead area. I.e. if the number of wells is 15, the resulting leak frequency in RispEx (contribution from process leakages) will be

$$f = 3.1 \cdot 10^{-3} \cdot 15 + 1.2 \cdot 10\text{-}3 = 4.8 \cdot 10^{-2} \text{ per year}$$

The leak rate distribution is assumed similar as for other process leakages in RispEx.

Blowouts and well releases

The blowout and well release frequencies are dependent on the activity level in addition to the number of wells.

The following activity level is used as basis for the RispEx wellhead leak frequency estimation. The activity level will vary for different installations and depending on many factors such as e.g. reservoir conditions. This activity level is considered typical to estimate a blowout and well release frequency in a wellhead area for the purpose of calculating design explosion loads and other decision support.

Table 4-7 Activity level

Operation	Number/activity level
Producing wells	Number of wells × 2/3
Gas injection wells	Number of wells × 1/3
Drilling	0
Completion	0
Wireline	1 per well per year

Coiled tubing	0.1 per well per year
Snubbing	0
Workover	0.1 per well per year

Blowout and well release frequencies are given in LRC report “Blowout and well release frequencies – SINTEF Offshore Blowout Database”, ref. /14/.

The following blowout frequencies with release in the wellhead area are calculated per well based on the activity level in combination with the blowout frequencies and flow path distribution suggested in ref. /14/.

Table 4-8 Estimated Blowout frequencies (per well)

Operation	Base freq blowout	Per yr per well	Fraction full - release in WH area	Fraction restr. - release in WH area	Frequency per well - full	Frequency per well – restr.
Producing wells	3.59E-05	0.67	0.16	0.57	3.85E-06	1.37E-05
Prod wells ex causes	2.74E-05	0.67	0.16	0.57	2.94E-06	1.05E-05
Wire line	5.87E-06	1.00	0.25	0.5	1.47E-06	2.94E-06
Coil tubing	7.28E-05	0.10		0.5	0	3.64E-06
Workover	2.50E-04	0.10	0.09	0.36	2.25E-06	9.00E-06
Gas injection wells	6.65E-05	0.33	0.16	0.57	3.51E-06	1.25E-05

The following well release frequencies with release in the wellhead area are calculated per well based on the activity level in combination with the well release frequencies and flow path distribution suggested in ref. /14/. The number of wells is assumed distributed as follows: 1/3 gas injection wells and 2/3 producing wells.

Table 4-9 Estimated Well release frequencies (per well).

Operation	Base freq. blowout Per yr per well	Freq. scale factor Per yr per well	Fraction full - release in WH area	Fraction restr. - release in WH area	Frequency per well – full pr yr	Frequency per well – restr. pr yr
Producing wells	6.65E-05	0.67	0	0.74	0	3.30E-05
Wire line	2.20E-05	1.00	0.09	0.64	1.98E-06	1.41E-05
Coil tubing	7.10E-05	0.10	0.5	0.5	3.55E-06	3.55E-06
Workover	5.48E-05	0.10	0.04	0.25	2.19E-07	1.37E-06
Gas injection wells	1.36E-04	0.33	0	0.74	0	3.32E-05

The following assumptions are applied to arrive at the blowout frequency per well as applied in the RispEx model:

- Fraction of blowouts and well releases with release point in wellhead/X-mas tree/BOP on platform assumed corresponding to Table 4-9.
- All releases specified in wellhead/X-mas tree/BOP on platform assumed contributing to explosion risk for RispEx wellhead area.
- All releases with release location specified Subsea or Drill floor/Upper deck area - on platform assumed not contributing to explosion risk for RispEx wellhead area.
- Representative blowout rate used for blowout rate category.
    - <15 kg/s: 10 kg/s,
    - >15 kg/s: 50 kg/s

- Restricted blowout and well release rates are assumed 20% of full rate.
    - Blowout rate category <15 kg/s: 2 kg/s,
    - Blowout rate category >15 kg/s: 10 kg/s
- In terms of the explosion consequences upon ignition, well releases are modelled as having similar consequences as blowouts.
- Ignition probabilities of well releases is set to 4%, ref. /14/.
- Ignition probabilities of blowouts is set to 5%, ref. /14/.
- In addition, the user has the option to include user specified external ignition probability both for process leaks and for full and restricted blowouts. Note that the ignition probability for blowouts is only applied for wellhead areas.

With the assumptions listed above combined with the tables listing the blowout frequencies and release locations suggested in ref. /14/.

Table 4-10 Blowout frequency pr well for RispEx wellhead area when representative blowout rate is set to <15 kg/s

Release case	Release frequency wellhead area /yr	Ignition probability	Representative rate modelled (kg/s)
Per well per yr full blowout	2.0E-05	4.7 %	10
Per well pr yr restricted	1.4E-04	4.4 %	2

Table 4-11 Blowout frequency pr well for RispEx wellhead area when representative blowout rate is set to >=15 kg/s

Release case	Release frequency wellhead area /yr	Ignition probability	Representative rate modelled (kg/s)
Per well per yr full blowout	2.0E-05	4.7 %	50
Per well pr yr restricted	1.4E-04	4.4 %	10

4.3.3 Probabilistic analysis Simulation Tool

The probabilistic analysis combines the detailed CFD simulation results and the frequency analysis results as well as other key input data in an integrated Monte Carlo simulation model to produce the exceedance curves from which the explosion Dimensioning Accidental Loads (DALs) for specific targets are derived for the representative modules.

The Monte Carlo simulations are performed using DNVs probabilistic explosion analysis tool EXPRESS which accounts for transient cloud development and ignition as well as all relevant weather and leak conditions, cloud location and ignition location.

4.3.4 Explosion targets in probabilistic analysis

In the explosion simulations for the representative area, the explosion load targets that are calculated in detail is the local 4×4 m^2 overpressure to decks and walls in the area including its pressure impulse and duration. Here, the maximum panel pressure on the wall considering all 4×4 m^2 panels is used as representative.

Drag loads and global panel overpressures (including its impulse and durations) to decks and walls are also monitored in the explosion simulations. Like the local panel pressures, the representative drag load is selected as the maximum drag (averaged over a representative volume) load in the area.

4.3.5 Key assumptions and study basis applied in the Probabilistic analysis

There is a very large number of factors believed to affect the explosion risk picture in a hazardous area at an offshore facility. The NORSOK Z-013 approach is based on quite complex modelling of the explosion risk in the area, where a lot of input is potentially reflected in the calculated explosion risk results.

The EXPRESS tool calculates the explosion risk in line with the NORSOK Z-013 approach. For this reason, all the input reflected in the calculation of the explosion risk in a representative area must have representative values applied in the calculations. This section lists all these values which is assumed applicable for a representative area.

The validity envelope defined for the model will partly be based on the assumptions and data provided in this section.

Some of the selected parameters can give lower/higher pressures than what would be the case if more/less adverse conditions would apply, respectively. Hence, the current selection is on average assessed to be representative.

Leak and release modelling

- The leak, release and dispersion modelling are based upon a leak from a gas inventory with the following characteristics and conditions. This corresponds to relatively light natural gas. Hence, the tool must be used with caution when applied to areas containing a lot of liquid hydrocarbons or heavier gas. Dispersion will differ as heavy gas will create gas clouds along the deck floor rather than the ceiling, and explosion overpressures will differ. In many areas the ventilation along the upper parts of an area is better than the lower part due to less windwall protection, and less large pieces of equipment. The energy mass content and explosion effects are also higher for heavier components than methane. Hence, overpressure may increase with introduction of heavier hydrocarbon components.

  The following are used as representative for the probabilistic analysis in RispEx:

  - Mole weight of 20.3.
  - 60 bara pressure and 70°C temperature at operational conditions before the leak occur
  - C_p/C_v 1.3
  - Compressibility factor Z=0.7
  - Density of leaked gas after expansion 0.84 kg/m^3,
  - Leak velocity used in simulations 196 m/s

Performance of safety systems and barriers limiting leak rate and leak duration, as well as reducing ignition probability:

- Confirmed detection when two 2 detectors are exposed to 0.2 LEL. Time from leak initiation until confirmed gas detection has been modelled in EXPRESS based on transient flammable cloud development as well as probability of exposure of gas detectors, with a typical gas detector density of 0.0055 detectors per m^3 assumed in the process module. This corresponds to a point detector every 180 m^3. The results are not considered very sensitive with respect to detector density, unless detector density deviates significantly from 0.0055 detectors per m^3.

- Time to isolation and fully closed ESD valves upon confirmed gas detection is assumed to be 30 seconds.
- The leak profile of gas leaks after ESD isolation is calculated based on an ESD isolatable inventory of gas and volatile condensate of 20 000 kg. It is unlikely that pure gas inventories are as large as this. However, the relatively large inventory is used to account for both large gas inventories as well as inventories with a considerable amount of volatile liquids, which will contribute with gas flashing from the liquid when the segment is depressurized due to leak and blowdown.
- Time to blowdown valves fully open from confirmed gas detection 45 seconds.
- Depressurization to 6.9 barg 15 minutes upon initiation of blowdown.
- To reflect possible failure of activation of safety systems or poor performance in terms of limiting the explosion potential upon an accidental event, a combined 5% failure probability of any safety system that are limiting the explosion consequences upon a HC process leak is assumed. The 5% account for both failures of automatic detection, ESD activation and/or blowdown. Effect of barrier failure is that the release is modelled as a leak from a 40 000 kg gas and volatile gas inventory with no blowdown. If the 5% failure probability is too conservative, this will be evaluated in the validation phase, possibly supported by sensitivity assessments to quantify the effect of a reduction in the failure probability.

Ignition modelling

- Standard parameters from MISOF2 ignition model are applied, ref. /9/. The key parameters from the MISOF2 model is the ignition intensity for continuous ignition sources of 6.1E-5 per m^3 and ignition intensity for discrete ignition sources of 1.5E-7 per m^3 per second. For further details as well as other parameters used for ignition source modelling, see the MISOF2 report.
- Some ignition source modelling parameters are area specific when applying the MISOF2 ignition model. The following parameters are used as representative
    - Hot work hours: 10 hours per years of hot work with ignition intensity 1 is assumed. For leak sizes 1 kg/s to 10 kg/s, a probability of 20% for gas ingress to the habitat is suggested in the MISOF2 report. By this, 10 hours per years of hot work with ignition intensity 1 correspond to 50 hours per year class A hot work in the area. Not that this is just a representative value of the number of hot work hours. The number of hot work hours in a particular area may increase by a factor 2 from this without being considered outside the validity envelope.
    - According to MISOF2, external ignition such as ignition upon exposure of gas turbine air intakes or combustion air intake to diesel driven firewater pumps should be assessed separately. For the purpose of RispEx, external ignition probability is assumed negligible unless added as a standalone input. In practice, this would require combustion air intakes not to be present at the facility or to be placed in a location that is very unlikely that will be exposed in case of a gas leak in the process area. Possibility to include external ignition sources (MISOF2) as a user interface parameter has been included.

Wind distribution

The wind rose used in the probabilistic analysis for the fixed type platforms is presented in Figure 4-10 and Table 4-12. The wind rose is typical for the North Sea. This is relevant for conventional process area and wellhead areas.

The wind rose used for FPSO is based on a typical weather-vaned orientation, with distribution of wind relative to FWD based on a FPSO project from the Norwegian sector.

For all representative geometries of conventional process areas and wellhead areas (all non-weather-vaned areas), it is assumed that a firewall is located at the western side of the module. It is assumed that this firewall separates the process area from the LQ, possibly with Utility area and/or wellhead area in between. The common design is to ensure that the prevailing wind direction is from LQ towards process area, to minimize the probability of gas and smoke from the process area to reach the safe side of the facility. Additionally, the wind rose is usually a little skewed to provide a calmer side for preferred accommodation of visiting vessels. In this case, this would be on the North side of the facility.

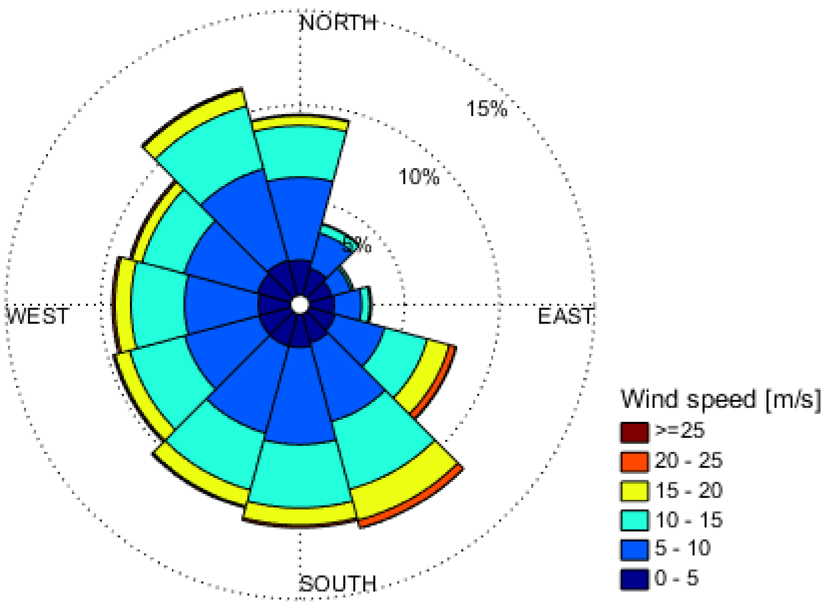


Figure 4-10 Representative wind rose chosen for RispEx probabilistic analysis

Table 4-12: Representative wind distribution chosen for RispEx, i.e. Annual directional sample distribution of non-exceedance [%] of 1-hour mean wind speed 10 m above sea level.

Wind [m/s]	Wind direction												Omni
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
< 2	0.26	0.23	0.24	0.24	0.24	0.23	0.25	0.21	0.27	0.25	0.25	0.27	**2.95**
< 4	1.14	0.98	0.88	0.88	0.89	0.99	0.99	1.05	1.12	1.07	1.13	1.18	**12.30**
< 6	2.65	1.99	1.58	1.68	1.92	2.30	2.60	2.59	2.50	2.36	2.55	2.83	**27.55**
< 8	4.47	2.89	2.05	2.30	3.02	3.98	4.77	4.52	4.16	3.92	4.22	4.81	**45.13**
< 10	6.27	3.48	2.27	2.70	4.06	5.80	6.83	6.47	5.81	5.56	5.82	6.88	**61.95**
< 12	7.78	3.80	2.37	2.94	5.02	7.46	8.50	8.02	7.25	6.96	7.06	8.65	**75.82**
< 14	8.76	3.97	2.42	3.07	5.89	8.91	9.74	9.17	8.40	8.04	7.88	9.86	**86.10**
< 16	9.27	4.02	2.43	3.12	6.63	10.01	10.52	9.87	9.11	8.73	8.32	10.54	**92.57**
< 18	9.51	4.05	2.43	3.16	7.09	10.75	10.90	10.26	9.47	9.06	8.54	10.91	**96.15**
< 20	9.63	4.06	2.44	3.18	7.44	11.23	11.11	10.49	9.64	9.27	8.69	11.13	**98.30**
< 22	9.68	4.06	2.44	3.19	7.64	11.50	11.21	10.58	9.73	9.36	8.76	11.21	**99.35**
< 24	9.70		2.44	3.19	7.74	11.63	11.23	10.60	9.75	9.40	8.80	11.23	**99.77**
< 26	9.70			3.19	7.80	11.68	11.24	10.60	9.76	9.41	8.82	11.25	**99.95**
< 28	9.70				7.82	11.68		10.60	9.76	9.42	8.82	11.25	**99.99**
< 30	9.70				7.82	11.68		10.60		9.42	8.82	11.26	**100.00**
< 32										9.42		11.26	**100.00**
Total	**9.70**	**4.06**	**2.44**	**3.19**	**7.82**	**11.68**	**11.24**	**10.60**	**9.76**	**9.42**	**8.82**	**11.26**	**100.00**
Mean	**8.6**	**6.4**	**5.3**	**6.4**	**10.2**	**10.4**	**9.2**	**9.1**	**9.1**	**9.2**	**8.6**	**9.1**	**9.0**
Maximum	**29.3**	**21.7**	**23.8**	**24.2**	**28.9**	**27.0**	**25.9**	**29.0**	**26.6**	**31.0**	**29.3**	**30.2**	**31.0**

4.4 CFD simulations for representative modules

The CFD calculation approach presented in this section should be considered together with the probabilistic calculation approach presented in section 4.3, as the CFD simulations are an integrated part of the probabilistic analysis.

4.4.1 Geometry model of the representative modules

There are 38 representative areas which are used for interpolation. This includes 26 conventional process areas, 5 FPSO type process areas and 7 wellhead areas.

The function, dimensions, and openness configuration of the 38 areas are tabulated in section 4.2.

For each of the representative areas probabilistic analysis have been performed to develop cloud exceedance curves and pressure vs cloud size curves as described in the previous section. FLACS ventilation, dispersion and explosion simulation results have been used as input to the probabilistic analysis. A representative FLACS geometry model has been developed for each area in order to perform the required simulations.

Representative geometry models for the representative areas have been selected based on

- Geometries most representatives in terms of reflecting future typical design solutions
- The dimensions and openness of the representative areas should correspond to what can be considered typical dimensions and openness configuration (addressed in section 4.2)
- There should be a variation in dimensions and openness levels of the representative modules that are aligned with the interpolation logic (addressed in section 4.2)

The as-built FLACS geometry was collected for the 8 facilities most recently (or soon to be) put in operation in Norway in order to fulfil the first bullet point. It is evaluated that recent design solutions are the best prediction of future design solutions, and that the quality and level of details of the geometry models are highest for the most recent facilities due to advances in digitalisation and CAD modelling.

Examples of some of the as-built FLACS geometry are shown in Figure 4-11 below.

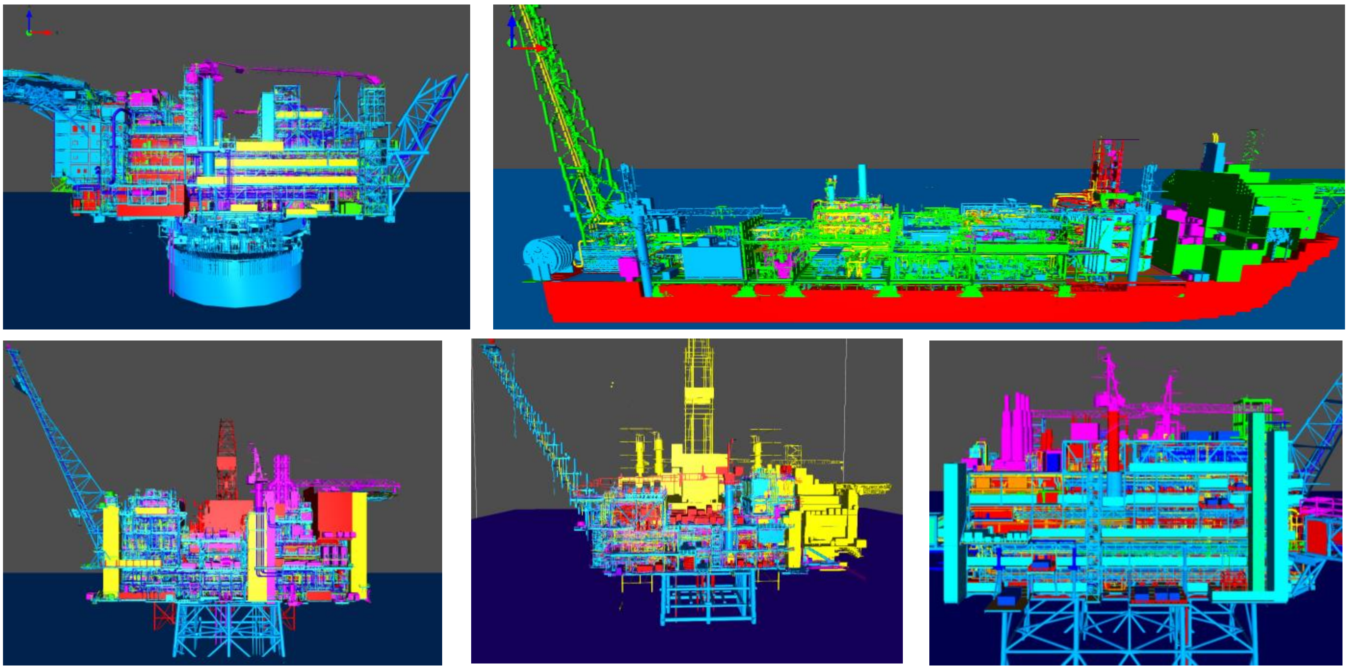


Figure 4-11 Examples of 5 of the as-built FLACS geometry models included in the RispEx geometry basis

The geometries have been visually inspected, and a more detailed evaluation of 38 of the process and wellhead areas or sub-areas at the 8 facilities are assessed more in details. Description of dimensions, coarse openness description and congestion level expressed as L/V and Ac/V are tabulated in Table 4-13. These are the congestion parameters as defined in the FLACS utility program cofile. The facilities have been anonymised by referring to each area by ID rather than name.

Congestion levels

One parameter that is based upon a representative level in the model rather than being part of the input to RispEx tool is the level of congestion in an area. The congestion level per area are tabulated in Table 4-13 for all the areas from the 8 as-built FLACS geometries that have recently (or will soon) been put in operation. A few of the areas has congestion level in terms of L/V around 3 m/m3. These are areas containing large compressor houses or other units that make the congestion lower than for the other areas. For the remaining process areas, the congestion level is in the range 6 - 8.5 m/m3.

The congestion level expressed as L/V for the 38 areas/sub-areas are also shown in Figure 4-12 which also show the contribution to the congestion from box shaped and cylinder shaped objects, respectively. Figure 4-13 show how the congestion contribution from box shaped objects are distributed in terms of side dimension of boxes, and Figure 4-14 show how the congestion contribution from cylinder shaped objects are distributed in terms of diameter of cylinders.

When assessing the congestion of the received FPSO geometry, the congestion level seems on the low side .

Table 4-13 Example of process or wellhead areas from the 8 geometries collected, including dimensions, coarse openness description and congestion level expressed as L/V and Ac/V

Asset ID	Area / module ID	Type of area	Length (m)	Width (m)	Height (m)	Openness	Congestion L/V (m/m3)	Congestion Ac/V (m2/m3)
1	1	Process area - int. facility	50	50	8	3 way	8.6	1.9
1	1	Process area - int. facility	50	50	10	3 way	7.2	1.8
2	1	Part of process area - FPSO	60	53	10	2 way	1.7	1.1
2	2	Part of process area - FPSO	60	53	10	2 way	1.3	0.8
2	3	Process area - FPSO	50	53	20	2 way	1.9	1.2
3	1	Process area - int. facility	35	28	7	3 way	5.8	2.0
3	2	Process area - int. facility	25	28	8	3 way	6.6	2.2
3	3	Process area - int. facility	25	28	8	3 way	7.1	2.3
3	4	Process area - int. facility	25	26	8	4 way	3.1	1.2
4	1	Process area - int. facility	27	30	7.25	2 way	8.8	2.9
4	2	Process area - int. facility	27	34	5	3 way	6.4	1.8
4	3	Process area - int. facility	27	30	5	3 way	6.7	1.9
4	4	Process area - int. facility	17	30	10	3 way	7.4	2.0
5	1	Process area - int. facility	25	28	7.5	3 way	8.4	2.0
5	2	Process area - int. facility	34	34	10.5	3 way	7.3	2.1
5	3	Process area - int. facility	25	28	11	4 way	6.4	2.0
6	1	Process area - int. facility	77	28	8	3 way	3.6	1.4
6	2	Process area - int. facility	67	28	8.8	3 way	4.4	2.0
6	3	Process area - int. facility	42	28	10	2 way	5.9	1.9
6	4	Process area - int. facility	29.5	28	10	3 way	5.8	1.9
6	5	Process area - int. facility	42	28	10	2 way	6.1	2.0
6	6	Process area - int. facility	28.5	28	10	3 way	6.0	2.0
6	7	Process area - int. facility	48.3	28	10	3 way	2.7	1.0
7	1	Process area - int. facility	28	28	8	2 way	3.2	1.6
7	2	Wellhead - int. facility	24	28	7.2	2way (wall west/north)	6.8	2.1
7	3	Wellhead - int. facility	24	28	7.8	2way (wall west/north)	5.5	1.6
3	5	Wellhead - int. facility	20	28	13	2 way	6.8	2.3
4	5	Wellhead - int. facility	23	28	7.25	2 way	7.2	2.4
4	6	Wellhead - int. facility	23	28	10	2 way	5.3	1.4
5	4	Wellhead - int. facility	21	26	7.5	2 way	10.5	2.7
5	5	Wellhead - int. facility	21	26	9.5	2 way	7.8	1.9
8	1	Wellhead - int. facility	24	43	13	3 way	7.4	3.6

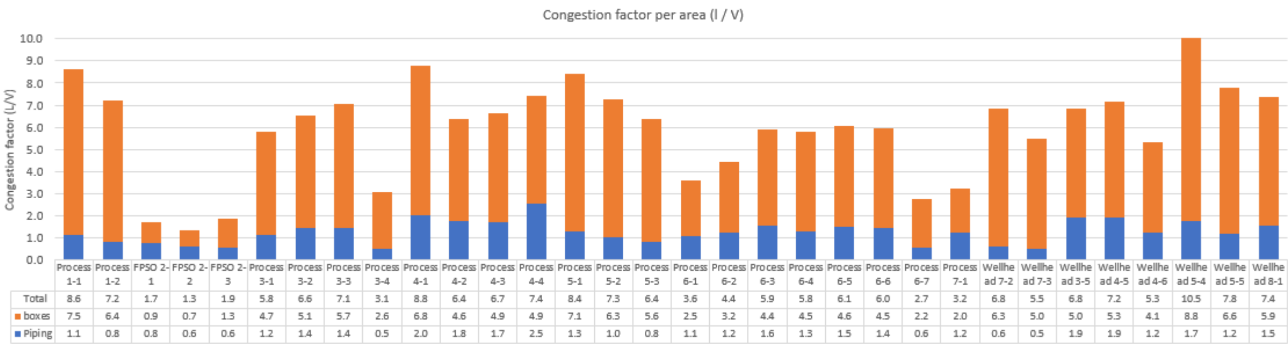


Figure 4-12 Congestion factor per area in terms of l/V for the as-built geometries of 8 recent facilities.

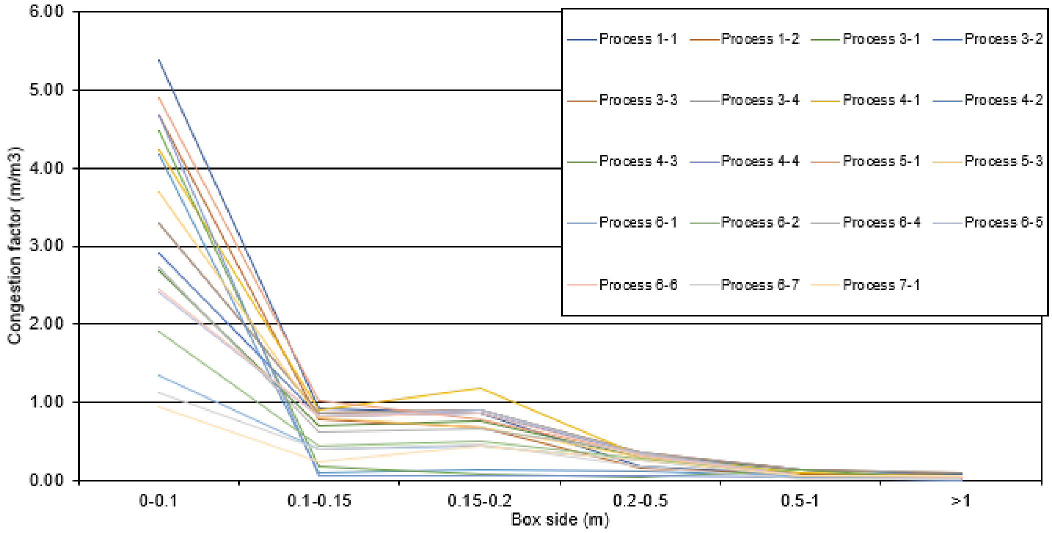


Figure 4-13 Congestion distribution for box shaped objects per area in terms of l/V for the as-built geometries of 8 recent facilities.

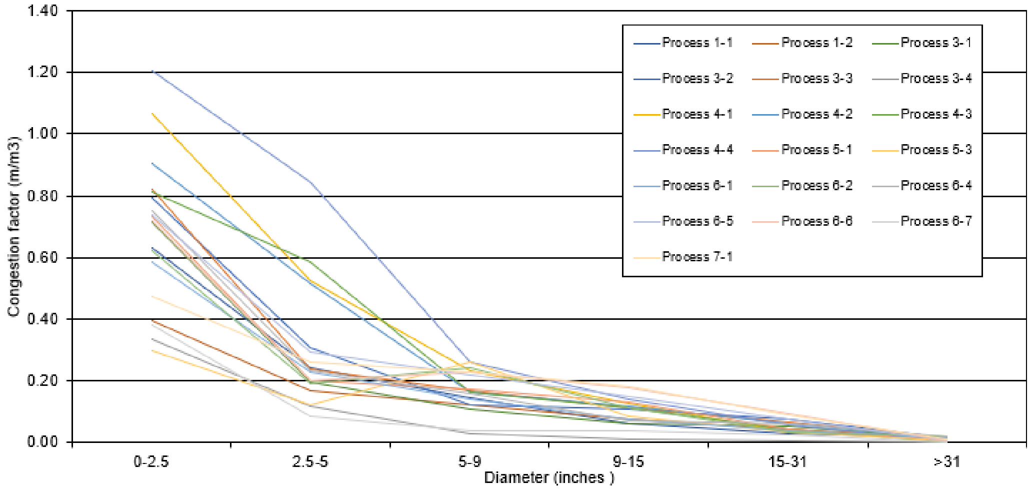


Figure 4-14 Congestion distribution for cylinder shaped objects per area in terms of l/V for the as-built geometries of 8 recent facilities

How areas are constructed

The geometry models of the representative RispEx areas as listed in section 4.2 are based on reuse of areas from the 8 as-built geometries collected. Areas are reused directly if layout, dimensions and openness correspond to what is defined as a representative area. For most areas, the areas from the 8 real as-built models are modified by chopping out regions or duplicating regions in the geometry model in order to obtain representative areas with realistic geometry and correct dimensions or openness.

The congestion levels of the representative areas after generating them from the existing representative as-built geometries are tabulated in Table 4-14, Table 4-15 and Table 4-16.

. these tables only show areas that have been modified. These levels are in the same range, but conservatively selected somewhat on the high end. This will affect the overpressures generated from explosion simulations. To prevent overly conservative RispEx relation between ignited cloud sizes vs overpressures, less weight has been put on the areas with highest congestion when fitting the parameters of the explosion response surface. More details on the representative geometries are provided in Appendix B.

The combinations of area volume and openness included in the set of representative areas are illustrated in Figure 4-15, Figure 4-16 and Figure 4-17. In between the dots, the model will interpolate to provide results. Outside the dots, results will be provided by extrapolation.

Table 4-14 Preliminary congestion levels for the representative process areas on integrated facilities

Area ID	Ventilated sides	Volume (m^3)	Openness (-)	L/V congestion	Ac/V congestion
03	2-ways	4508	0.16	9.0	2.1
04	2-ways	4200	0.11	7.3	1.8
01	2-ways	4200	0.07	7.3	1.9
05	3-ways	4200	0.16	7.3	1.8
02	3-ways	4200	0.14	7.3	1.9
08	2-ways	8192	0.13	8.5	2.0
09	3-ways	8192	0.20	8.5	2.0
10	4-ways	8192	0.47	7.8	1.8
11	2-ways	7980	0.17	5.8	1.9
06	2-ways	7980	0.10	5.8	1.9
12	4-ways	7980	0.48	5.8	1.9
07	4-ways	7980	0.37	5.8	1.9
13	3-ways	7840	0.19	4.4	1.6
14	4-ways	7840	0.47	4.4	1.6
16	3-ways	17112	0.15	8.7	1.9
17	4-ways	17112	0.45	8.0	1.8
18	2-ways	16810	0.13	6.1	2.0
15	2-ways	16810	0.08	6.1	2.0
19	3-ways	16810	0.20	6.1	1.9
21	3-ways	16810	0.16	4.9	1.6
20	4-ways	16810	0.47	6.1	1.9
22	3-ways	15960	0.23	5.8	1.9
23	3-ways	24600	0.16	4.9	1.6
24	3-ways	24600	0.19	6.1	1.9
25	2-ways	24600	0.13	6.1	2.0
26	4-ways	24600	0.46	6.1	1.9

Table 4-15 Preliminary congestion levels for the representative process areas on FPSO

ID	Ventilated sides	Volume (m^3)	Openness (-)	L/V congestion	Ac/V congestion
51	3-ways	34238	0.26	1.7	1.1
52	4-ways	34238	0.38	1.7	1.2
53	3-ways	33390	0.28	1.1	0.8
54	3-ways	60420	0.25	1.6	1.1
55	4-ways	60420	0.38	1.6	1.1

Table 4-16 Preliminary congestion levels for the representative wellhead areas on integrated facilities

ID	Ventilated sides	Volume (m^3)	Openness (-)	L/V congestion	Ac/V congestion
71	2-ways	4095	0.14	10.7	2.4
72	3-ways	4095	0.23	10.7	2.4
73	2-ways	7280	0.20	6.9	2.3
74	2-ways	10080	0.22	6.3	1.8
75	3-ways	10080	0.31	6.3	1.8

76	3-ways	13416	0.23	7.5	3.7
77	2-ways	13416	0.14	7.5	3.8

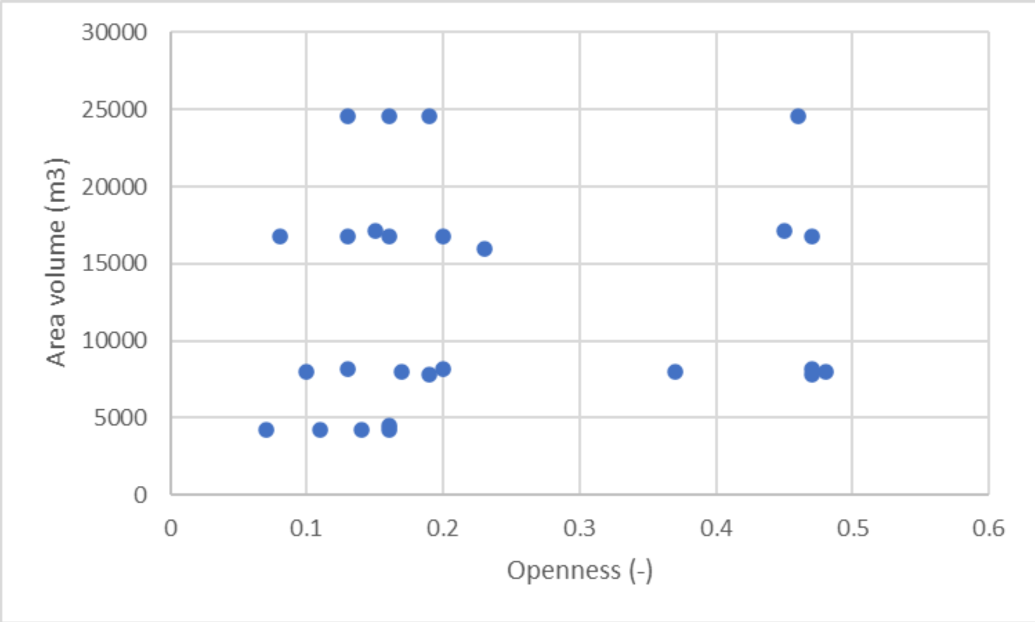


Figure 4-15 Openness and volume of representative conventional process modules part of RispEx interpolation basis.

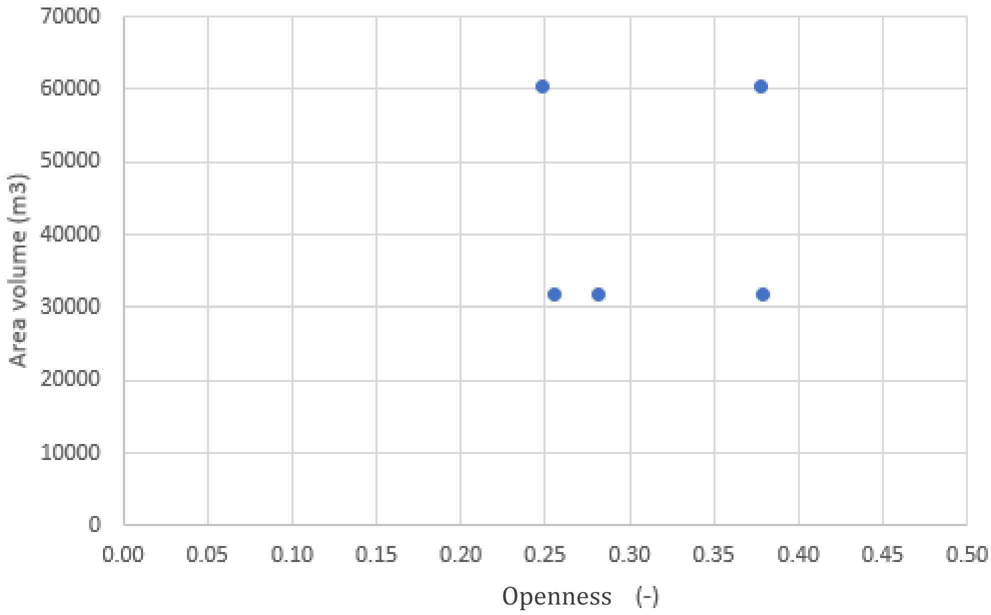


Figure 4-16 Openness and volume of representative process areas at FPSOs part of RispEx interpolation basis

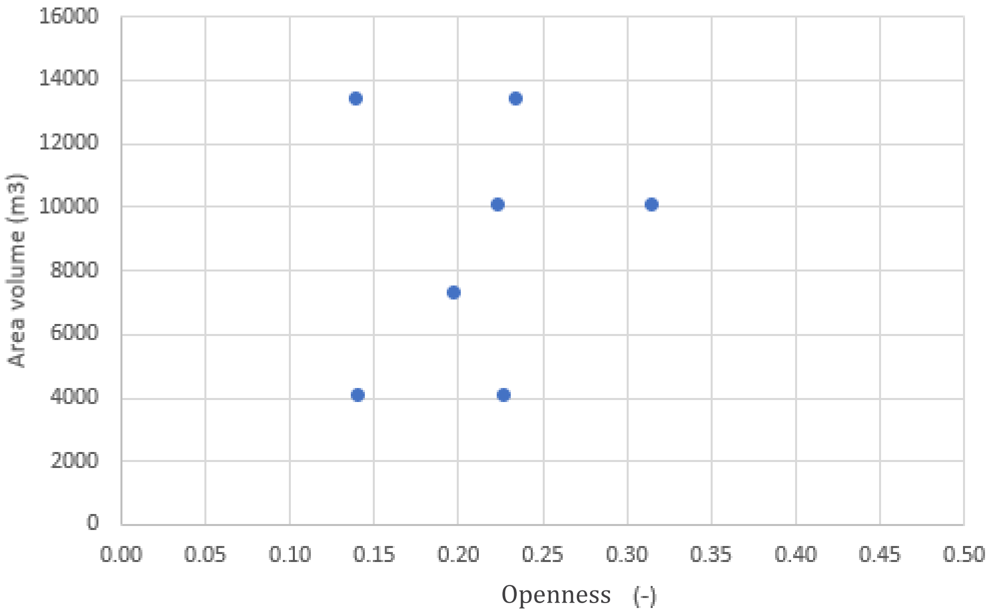


Figure 4-17 Openness and volume of representative wellhead areas part of RispEx interpolation basis

4.4.2 Ventilation simulations for the representative modules

Eight ventilation simulations were carried out corresponding to wind directions N, NE, E, SE, S, SW, W and NW (in platform north coordinate system). The simulations were performed for a representative unobstructed wind speed of 6 m/s (10 meters above sea level). For FPSOs, the fraction of time with wind from prevailing direction is much higher due to weather vaneing. For this rason, more vind directions from FWD are selected. With denoting FWD direction “E - East”, the wimulated wind directions for FPSO is E, SEE, SE, S, W, N, NE, NEE.

The ventilation rate (m3/s) and number of Air Changes per Hour (ACH) is recorded for the monitor region corresponding to the area volume defined in Table 4-1.

The purpose of the ventilation simulations is to use the results as input to selection of release rates in the dispersion simulations. In addition, ventilation rates are used in the probabilistic analysis when calculating the cloud sizes at different wind speeds that what is used in the simulations. It is applied that the ventilation rates are directly proportional to the outside wind speed. Summary of ventilation results for all representative areas, in terms of ventilation rates (m/m3) are provided in Appendix A.

4.4.3 Dispersion simulations for the representative modules

16 dispersion simulation cases has been carried out per representative RispEx area in order to generally describe the flammable cloud formation potential in case of hydrocarbon leak events in the area, and how dimensions and openness levels affects the cloud size and formation. Further, the purpose of the simulations is to be able to reflect how leak rates and durations, as well as wind conditions, affect potential cloud size accumulation. Cloud size in this context refers to equivalent stoichiometric cloud size, interpreted as the FLACS gas concentration monitor variable Q9. Results are used as input to the probabilistic analysis by the use of response surface technique.

There is a very large number of possible leak scenarios in a process module. Detailed simulations of every possible leak scenario, with every combination of leak location, leak direction, wind direction etc in the area is too extensive.

Hence, a limited number of simulations are performed to fit the parameters in a set of response surface equations rather than to simulate all combinations required for a NORSOK Z-013 approach with high resolution. The objective of the dispersion simulations is therefore to use the results extracted from the dispersion simulations to develop dispersion response surfaces for dispersion. Response surfaces are mathematical functions that are used to represent the size and transient development of a gas cloud with respect to various parameters including leak rate, wind speed, wind direction and leak direction.

The selection of the simulated cases is based on judgment, experience, as well as general industry experience and academic sources ref. /7/, /8/ and /11/. 16 simulations provide relatively few points for curve fitting of the dispersion response surface, however based on experience it provides sufficient data to ensure acceptable parameter accuracy of the response surfaces.

4.4.3.1 Dispersion response surfaces

Dispersion response surfaces are split between the two effects, first the speed effect, and then the direction effect. The speed effect (may also be thought of as mixing effect) considers the combination of wind speed and leak rate (keeping all other effects constant) and the direction effect consider wind direction and leak direction. The latter effect aims at describing the maximum cloud size that would occur when an ideal combination of leak rate and wind speed was present.

The response surfaces per area are subsequently used in the probabilistic explosion analysis.

Speed effect

The response surface function for the filling fraction for different leak rates and wind speeds reads:

$$\frac{V_f}{V} = \frac{1-e^{-P_3 \bar{u} t}}{1+\frac{1}{C_1 R^{P_1}}+C_2 R^{P_2}}.$$

Here, t is the time from the leak starts, $\bar{u}$ is the average wind speed inside area (m/s) and P3 is constant that is fitted towards ventilation simulations to be able to reflect how quickly the cloud tend to reach steady state size within the relevant area.

In the denominator C2 = 4.7 and P1= 3/2 are constants (ref. /12/). Curve fitting towards the dispersion simulation results are performed for the parameters C1 and P2 in order to capture the typical dependency between the flammable cloud size, release rate and ventilation rate for a specified module based on a limited number of dispersion simulations. C1 and P2 are tabulated for all representative areas in Appendix B.

The non-dimensional leak rate R is intuitively understood as the rate of mixing between leaked gas and air flow through the module, and is defined as follow:

$$R = \frac{Q_g}{Q_a} = \frac{\dfrac{\dot{m}}{\rho_g}}{\dfrac{Q_{aref}}{u_{ref}} u}$$

Here, u is the outside wind speed (m/s), Qaref/uref is the reference ventilation rate, normalised by the reference wind speed. Qa is the air volume flowrate (m^3 /s) through the module before the leak starts, and Qg is the gas volume flowrate (m^3 /s).

Generally, for typical offshore platforms, the R values expected to create maximum equivalent cloud sizes due to worst case HC-air mixing is around 0.1, which result in a mix close to stoichiometric concentration. For R values significantly lower, the HC gas is diluted below flammable limits by natural ventilation. For R values significantly higher, ventilation rates are not sufficient to dilute the HC concentration below UFL, resulting in a cloud that are too “rich” to ignite.

The shape of the curve given by the equation above, $\frac{V_f}{V}$ as a function of R, is shown in Figure 4-18. The figure also shows example on how this curve can be fitted to a limited set of dispersion simulation results as marked by green, blue and red dots. A conceptual illustration of the mixing of the cloud inside the module for three different parts of the curves are included in the figure. In these illustrations, the module/area is marked by a black frame, gas concentration between LFL and UFL is marked with yellow colour and gas concentration above UFL is marked with orange colour.

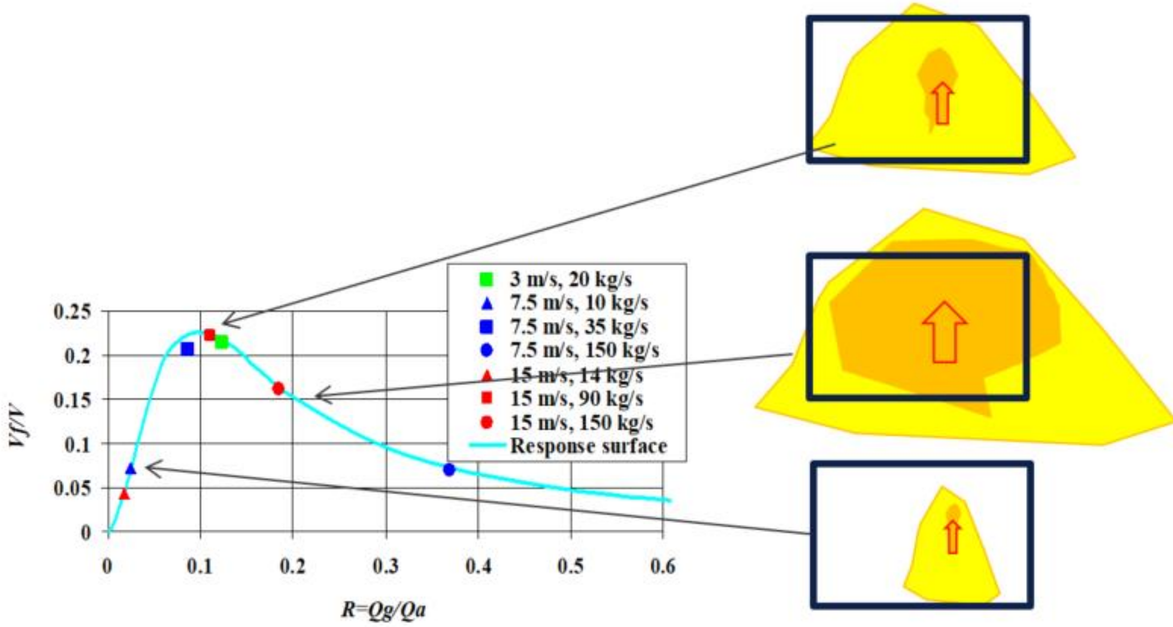


Figure 4-18 Dependency between maximum flammable cloud size and R and how this curve can be fitted towards simulation results. In the illustration on the right on how clouds look like in a module for the different parts of the curve, yellow denotes flammable region and orange denotes concentration above upper flammable limit.

Based on ventilation rates obtained through ventilation simulations, many of the simulated dispersion cases are selected with wind conditions and dispersion release rate resulting in a R value close to 0.1. For moderate sized modules and/or modules that are not very open, this result in release rate typically around 5-15 kg/s with common wind speeds (5-12 m/s). For modules with higher ventilation rates (due to larger size and/or lower openness level) higher release rates are typically required to obtain R close to 0.1. Leak rates considerably higher than 10 kg/s will often have a calculated frequency of ignition that is lower than 1.0E-4. Based on experience, dimensioning cloud sizes typically is obtained from leak sizes 5-15 kg/s, resulting in cloud sizes 500 – 1500 m3. It is aimed at determining realistic dispersion response surfaces in particular in this region. Therefore, for all modules, some dispersion simulation cases are performed for leak rates 5 – 15 kg/s, regardless if this correspond to a R value much lower than 0.1.

To summarize; dependency between maximum flammable cloud size and R as shown in Figure 4-18 can be determined by fitting P3, C1 and P2 of the equation in the start of this subsection towards dispersion simulation results. P3 is set as a distribution between 0.05 (25%), 0.1(50%) and 0.15 (25%). Summary of parameter value for C1 and P2 for all representative areas are provided in Appendix B. This equation, as illustrated in Figure 4-18, only show the how leak rate and ventilation rate is expected to affect the flammable cloud size. The cloud size will also depend on leak direction, as well as leak direction relative to wind direction, which is not reflected in the equation given above.

Direction effect

This will introduce a second equation of the dispersion response surface, which is applied to account for how wind direction and leak direction affect the flammable cloud size. The equation for the maximum filling fraction as a function of wind direction for a given leak direction reads:

$$\frac{V_{f\,\max}}{V} = \begin{cases} A + B\cos(\alpha - \alpha_{\max}), & \alpha \neq \alpha_W \\ \dfrac{V_{f\,\max W}}{V}, & \alpha = \alpha_W \end{cases}$$

where, A and B are constants determined from CFD simulations. α the wind direction relative to platform North. The variable α_{max} is defined as the wind direction where the cloud has its largest size, except for "wake wind". Wind direction of wake wind is denoted α_W. Wake wind in a RispEx area will typically be wind from west, since there is firewall towards West and presumed to be LQ and utility area on the west side of the facility. Wake wind can also occur with wind from East in the 2-ways ventilated areas. An illustration of how the wind direction affects the shape of the curve describing the cloud size is given in Figure 4-18. As illustrated in the figure, the "cos" function is applied to make the maximum cloud size occur when wind α s from α_{max}. The wind direction that is towards the leak direction, is usually equal or close to α_{max}. One such equation is applied per leak direction for 6 different leak directions. When the leak is directed towards a large structure, a wall or a deck, a diffusive jet occurs, and the effect of the wind direction (the value of B) is smaller. α_W is the wake wind direction in this figure illustrated from East. Wake wind causes a larger cloud size due to large re-circulating zones.

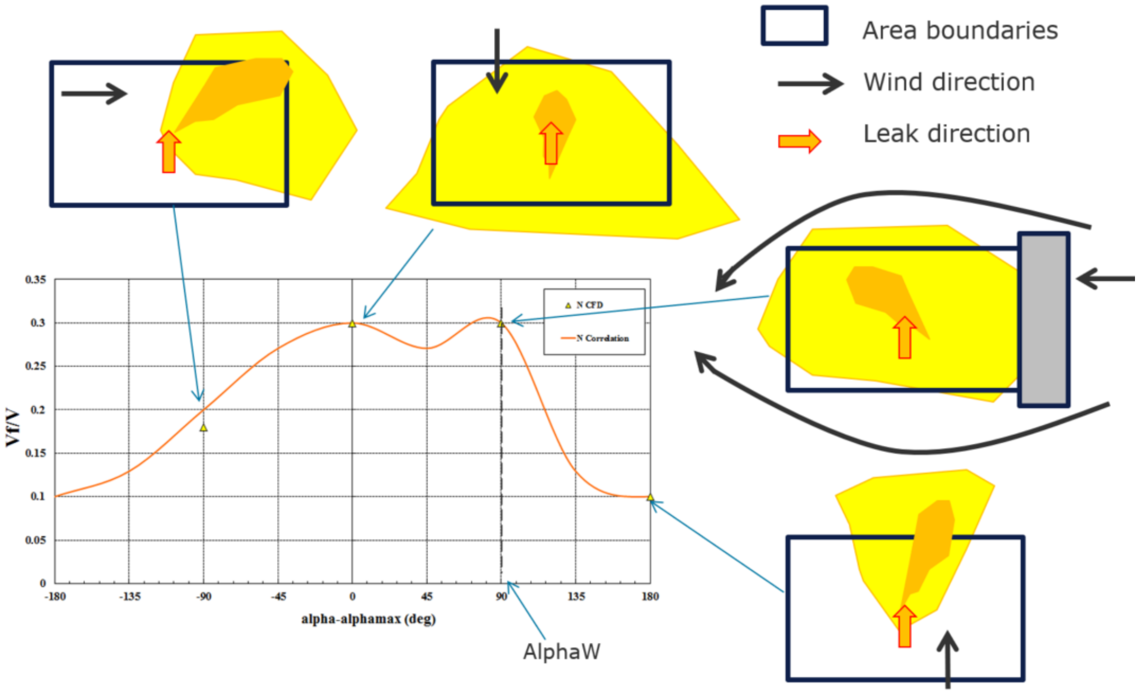


Figure 4-19 Dependency between maximum flammable cloud size and (alfa-alfamax), and how this curve can be fitted towards simulation results. (alfa-alfamax) is the angle between the wind direction and the worst case wind direction. Three illustration is also included to show typically the wind speed relative to the leak direction affects the mixing and flammable cloud size inside the module. Yellow denotes concentration within the flammable region.

A set of A, B and α_{max} is found for each of 6 leak directions (leak towards N, E, S, W, up, down). One value of α_W will be selected and will be applicable for all leak directions. Summary of parameter value for A and B for all representative areas are provided in Appendix B.

Selection of which dispersion simulation cases should be chosen to best fit the response surface parameters will vary slightly depending on module size, openness and shape. An example of a suggested simulation list for module ID 11 can be listed as shown in Table 4-17. A summary of all dispersion simulation cases for all representative areas, as well as the resulting simulation results are provided in Appendix B.

Table 4-17: Main input and results from the Dispersion simulations performed

Case No.	Leak rate [kg/s]	Leak dir.	Wind dir.	Wind speed [m/s]	R value
020101	8	N	W	7	0.13
020102	8	S	W	7	0.13
020103	8	E	W	7	0.13
020104	8	E	S	5	0.04
020105	8	W	W	7	0.13
020106	8	Down	W	7	0.13
020107	8	Down	S	5	0.04
020108	8	Up	S	7	0.03
020109	15	N	N	5	0.06
020110	15	N	S	5	0.07
020111	15	N	NW	7	0.07
020112	15	Down	W	12	0.14
020113	20	N	NW	12	0.05
020114	20	Down	W	12	0.19
020115	20	Down	S	5	0.09
020116	20	Down	E	12	0.23

Transient CFD simulation strategy

It should be noted that the dispersion runs are performed with a constant leak rate based on the following approach:

- Run ventilation simulations and establish steady-state flow on the module/platform. This, typically, takes around 160-300 seconds of numerical simulation time.
- The gas leak is initiated after this and the leak rate is ramped up from 0 to the leak rate specified and then kept constant until the time where the flammable cloud approaches steady state. The realistic cloud build-up time is captured giving one of the input parameters to Express.
- The leak is then shut down and the cloud is allowed to disperse for another 60 seconds. This is completed to allow the rich areas of the cloud to mix, which can sometimes lead to a larger maximum cloud size than during the release phase. It is the maximum cloud size during the simulation which is used as representative in the probabilistic analysis. This maximum cloud size can occur either during the build-up phase or during shutdown.

The reason for not running with transient leak rates with a leak profile corresponding to a realistic depressurisation of a gas segment is partly due to simulation time, as well as to limit the complexity. Since dispersion simulations are performed for more than 30 areas as part of RispEx development, some adequate simplifications need to be carried out. Given that the simulations are performed as steady-state, the transient behaviour of the leak based on activation of ESD and blowdown, followed by a decreasing leak rate as pressure drops inside the segment, is not directly considered in the CFD simulations. In essence, it is used infinite inventory. However, the transient nature of the leak (based on activation of ESD and blowdown) is accounted for in the probabilistic analysis simulation tool based on the inventory of the segment and process condition parameters.

4.4.4 Explosion simulations for the representative modules

An explosion may take place if a flammable gas cloud ignites; resulting in pressure and drag loads both inside and in the vicinity of the ventilation openings. Explosion pressures are established as a function of cloud size primarily. The cloud location and ignition locations are also varied and included as parameters that introduces a probability distribution of the explosion pressures.

The results from the gas dispersion analysis are used to estimate frequency of ignited gas cloud sizes and combined with the results from explosion simulations it is used to obtain pressure exceedance curves which are used to develop recommended dimensioning loads.

In each of the reference modules, 36 explosion simulations are carried out with ignition of stoichiometric cloud sizes typically ranging from 600 to 1600 m3.

The following combinations of cloud sizes, ignition points and cloud locations/shapes is typically carried out for each area:

- Ignited cloud sizes, i.e. 600, 900, 1100, 1400, 1700 m3 (example from area ID 11)
- 3 ignition locations, i.e. South East corner of cloud, Middle of cloud, North side in upper part of cloud
- Two different cloud shapes and locations per combination above, i.e. cloud close to firewall and cloud located centrally in area

Explosion simulations are performed with a grid resolution of 0.5 meter inside the congested and confined region of the area. The distances between grid lines are stretched from outside this refined region.

The overpressures reported are evaluated as the maximum of panel pressure recorded 4x4 m2 panels on each of the main targets of interest (local loads), and as the maximum average pressure over the full targets (global loads), with the following targets of interest

- Deck
- West Firewall
- Ceiling, if applicable

In addition to overpressures, the overpressure impulses are recorded as input to correlation assessment of overpressure duration calculations.

Drag and drag impulse are calculated based on volume averaging the radial drag using cuboids with dimension 9m x 1m x 1m. The dimension of the volume is selected based on piping span tables. Benchmarking has also been performed with 3m, 6m, and 12m long volumes. Volume averaging of the drag is equivalent to the surface averaging performed when using pressure panels to record the pressure. The following approach is used to calculate the drag for each simulation:

- The drag in each principal direction in each control volume is recorded at 50 different fuel levels throughout the explosion simulation
- The radial drag for each potential 9 meter long cuboid is calculated for each principal direction and for each timestep.
- The drag impulse is calculated by numerically integrating the drag time series for the cuboid with the highest maximum drag in each principal direction
- The representative drag value and drag impulse is taken as highest computed drag value and highest computed impulse value across the three principal directions

Explosion equation used in RispEX

The subsequent sections show the maximum local load for each simulation on a target. This data is later coupled with gas dispersion simulations and the ignition model to generate pressure-frequency curves.

For explosion overpressure estimation, response surfaces are applied in the probabilistic analysis.

The governing equation applied is the Thor equation, as presented in ref /13/, but simplified in order to be fit for purpose of RispEx, as well as updated parameter values found by fitting the parameters to explosion simulations performed for the representative RispEx areas.

A mathematical explicit function giving the explosion pressure as a function of the ignited cloud size is used in order to calculate the pressure exceedance curve when the cloud exceedance curve has been established. The original equation, given in ref. /8/, are defined with five parameters; three parameters for openness, one for congestion and one for the equivalent stoichiometric gas cloud size and can be expressed as follow:

$$\frac{P}{P_0} = K_{tot} V_f^{P_V} \left(\frac{l}{V}\right)^{p_l} \left(\frac{A_V}{A}\right)^{p_A} h^{p_h} C$$

Where P is the local (4x4 m^2) panel pressure and P_0 is the atmospheric pressure. V_f is the gas cloud size at the time of ignition. The congestion parameter l/V is not used, since the representative module are assigned representative levels of congestion. The other variables and parameters in the equation are the area opening fraction for explosions, denoted Av/A, minimum distance between plates, denoted h, and the corner coefficient, C.

When fitting the explosion response surface parameters to the explosion simulation results, the equation is simplified by expressing the overpressure as a function of cloud size, and fitting the parameters K and P_v, as well as the variance in the term Φ:

$$\frac{P}{P_0} = \Phi \cdot K \cdot V_f^{P_{eV}}$$

The equation $K \cdot V_f^{P_{eV}}$ will then provide the median observed explosion overpressure (2). It is noted that this exponential equation fits well for cloud volumes up to a certain fraction of the area volume. For larger cloud volumes, the observed (simulated) explosion pressures does not increase exponentially and start to increase more linearly. This effect is not included in the above equation, and it is assessed that it is not required to include this effect since it occurs mainly for larger cloud volumes and at very high overpressures compared to what is relevant in the context of design explosion loads.

However, the overpressure will vary depending on several factors including the shape of the cloud, location of the cloud and ignition location. To capture this effect, a term Φ is introduced. It is represented with a log normal distribution with mean 1 and variance assessed by simulation results. The simulation results are evaluated for the areas to assess if either K, P_{eV} or variance of Φ could be applied as constants. Similar values for all areas are assessed. Note that in the RispEx web tool, this distribution is plotted for different percentiles.

In order to prevent a too complex interpolation logic, it was observed that the parameter P_{eV} as well as the standard deviation of Φ could be assigned constant values independent of the volume and openness of the area without losing too much information from the explosion simulation results. Reasonable predictions of the explosion simulation results were obtained when P_{eV} was assigned a value of 1.5 for all conventional process areas and 1.3 for all process areas on FPSO, standard deviation of Φ was set to 0.8 for all conventional process areas and 0.6 for all process areas on FPSO.

With the standard deviation of Φ and P_{eV} fixed, K is fit to the explosion simulation results for each of the RispEx areas, and the most likely K estimated per area. The K estimated for the RispEx areas based on explosion simulations are listed in Appendix B.

The resulting relation between the ignited cloud size and the overpressure to targets, i.e. local 4 x 4 m2 overpressure to the firewall of the area, will be similar to what is plotted in Figure 4-20 to Figure 4-23. These plots show FLACS simulations and response surface values for four selected RispEX areas.

(2) Note that the notation is change slightly compared to the original Thor equation, by naming the power parameter P_{eV} rather than P_V. This is to clearify that this parameter is used to reflect the effect of the explosive cloud volume, as there is another parameter introduced below which is used to reflect the effect of the area volume. This parameter is denoted P_{aV} where the letter a show that it is related to area volume and not explosive cloud volume.

The larger blue dots in the figures show explosion simulation results, the dark line show the median pressure of the response surface, and the lighter blue stars show randomly generated overpressures around the median pressure using the lognormal distribution with a standard deviation of 0.6. Visual inspection shows that with P_{eV} fixed to 1.5 to process areas, the K gives a reasonable prediction of the relation between ignited cloud volume and explosion overpressure distribution. K's predicted for the RispEx areas are tabulated in Appendix B.

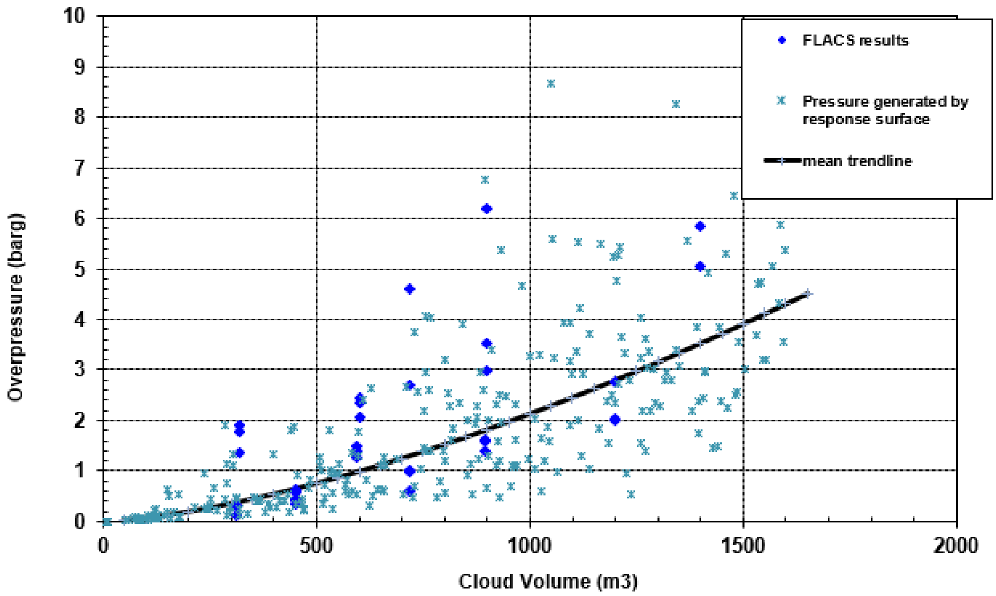


Figure 4-20 Example of overpressure on the firewall as a function of ignited flammable cloud size for RispEx area ID 4. Parameter fitting gives K = 7.5E-5.

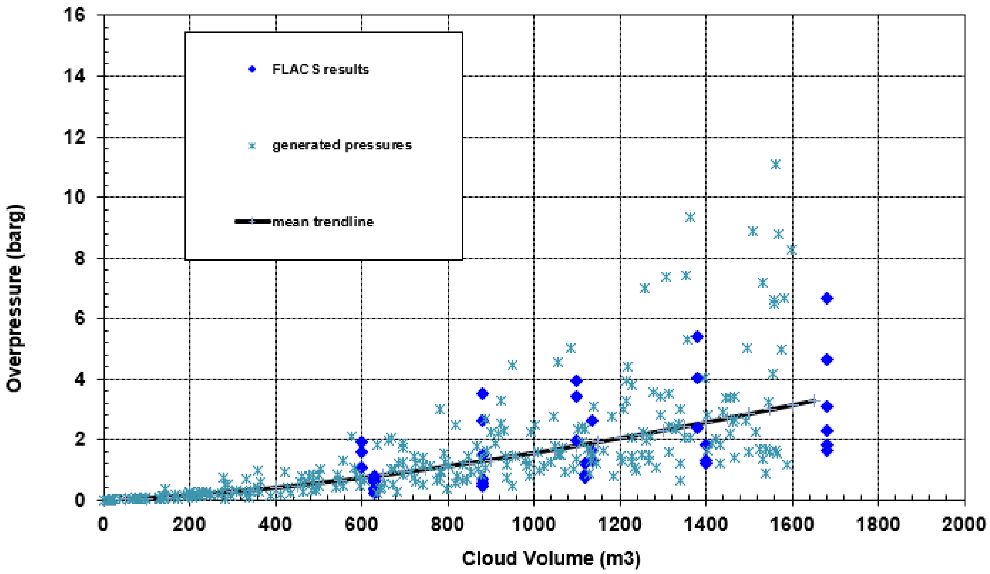


Figure 4-21 Example of overpressure on the firewall as a function of ignited flammable cloud size for RispEx area ID 7. Parameter fitting gives K = 4.9E-5.

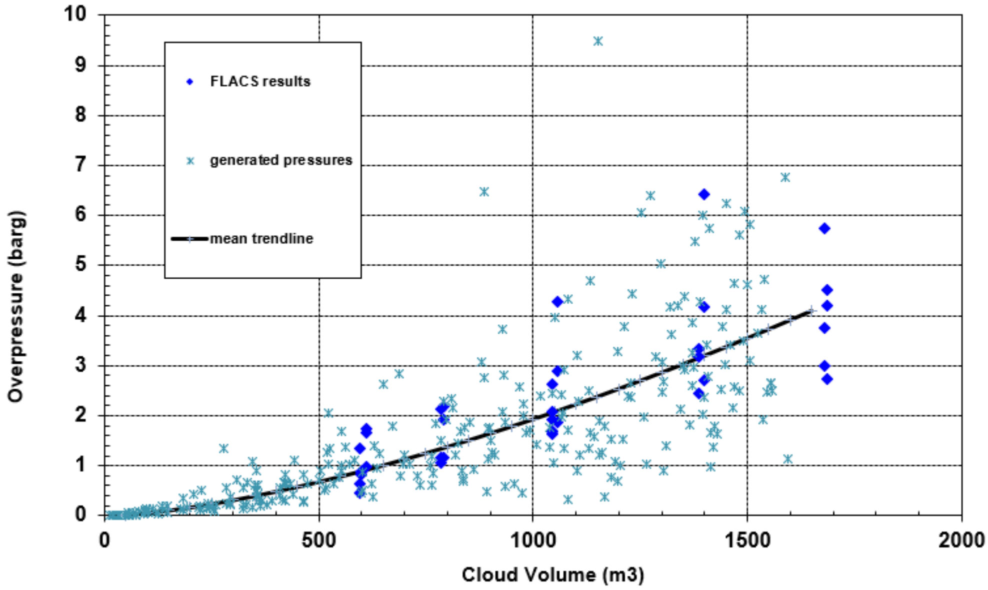


Figure 4-22 Example of overpressure on the firewall as a function of ignited flammable cloud size for RispEx area ID 16. Parameter fitting gives K = 6.0E-5.

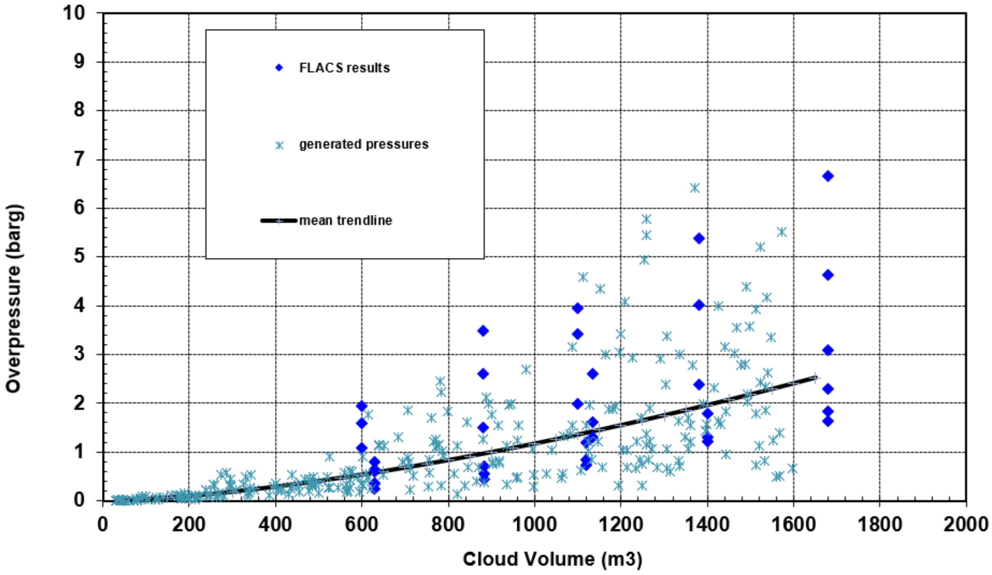


Figure 4-23 Example of overpressure on the firewall as a function of ignited flammable cloud size for RispEx area ID 7

Drag loads

The drag model in RispEx is equivalent to the explosion overpressure model described above:

$$\frac{D}{P_0} = \Phi \cdot K \cdot V_f^{P_{eV}}$$

Like for explosion overpressure the equation $K \cdot V_f^{P_{eV}}$ will then provide the median observed drag. Based on the simulation results, and to ensure consistency with the local explosion pressure model, the parameter P_{eV} is kept consistent with the value used in the local overpressure equations. The standard deviation, Φ, is observed to deviate slightly for the drag values and the explosion overpressure and this parameter is therefore refitted to the simulation results. The standard deviation is fitted to the value 0.4 for fixed process areas and 0.6 for FPSOs.

Correlations between local overpressure and global overpressures and durations

RispEx estimates the local overpressure on 4x4 m2 panels on blastwalls and decks that should be used as DeAL and area drag loads to be applied to piping and various structures and objects with small dimensions. To define explosion loads that can be implemented in design, it is as a minimum also necessary to define global explosion loads to decks and walls in the area. In the design process, it is also necessary to detail out the explosion loads to various units, but the detailed/specified loads to particular units may be derived from the general local and global overpressure values as well as the general area drag if these are available. In addition, to ensure a format of the defined explosion load in line with what is needed for implementation of the load, it is also necessary to provide pressure impulse and duration associated with the overpressure and drag.

Global overpressures are calculated based upon a simplified correlation approach in RispEx. The local overpressure is here the "main" load that is used in setting the overall explosion pressure level in the area and the other loads are calculated typically as proportional to the local overpressure.

Pressure pulse durations of the loads are also calculated based on a simplified correlation approach.

Global loads

RispEx esimates the magnitude of global loads based upon the function

$$P_g = A_g \cdot P_l$$

Where P_g is the global overpressure, P_l is the local overpressure to walls/decks, A_g is the correlation factor for global overpressure relative to local overpressure.

Pulse duration

RispEx then estimates the pressure pulse duration based upon the function

$$Duration = B_i \cdot P_i^{C_i}$$

P_i is the overpressure (or drag), B_i and C_i is parameters fit towards the simulation results, i=l (local overpressure duration), i=g (global overpressure duration) and i=d (drag duration). Based on assessing the best parameter fit of correlations from the explosion simulations, these parameters are defined as constant per type of area. (one set of constant A_i , B_i and C_i for conventional process areas, FPSO process areas and wellhead areas, respectively). If taking account of factors such as openness and volume, it is possible to provide better fit and more accurate area specific values for global loads and drag loads with durations. However, considering the coarse nature of the RispEx approach, it is evaluated that a constant correlation parameter per type of area (not taking account to volume, openness or other factors of the area) will provide adequate loads.

By fitting the parameters towards explosion simulations performed for the 38 representative RispEx areas, the parameter set in Table 4-18 is selected.

Table 4-18 RispEx parameter set to determine global explosion load, drag load and durations based upon local overpressure for different types of areas.

Case No.	Conventional process area	FPSO process area	Wellhead area	Description
B_l	80	80	80	Correlation constant for local overpressure duration
C_l	-0.3	-0.3	-0.3	Correlation power term for local overpressure duration
A_g	0.7	0.6	0.7	Correlation parameter for global overpressure
B_g	100	80	100	Correlation constant for global overpressure duration

C_g	-0.2	-0.2	-0.2	Correlation power term for global overpressure duration
B_d	30	40	40	Correlation constant for drag duration
C_d	-0.35	-0.30	-0.35	Correlation power term for drag duration

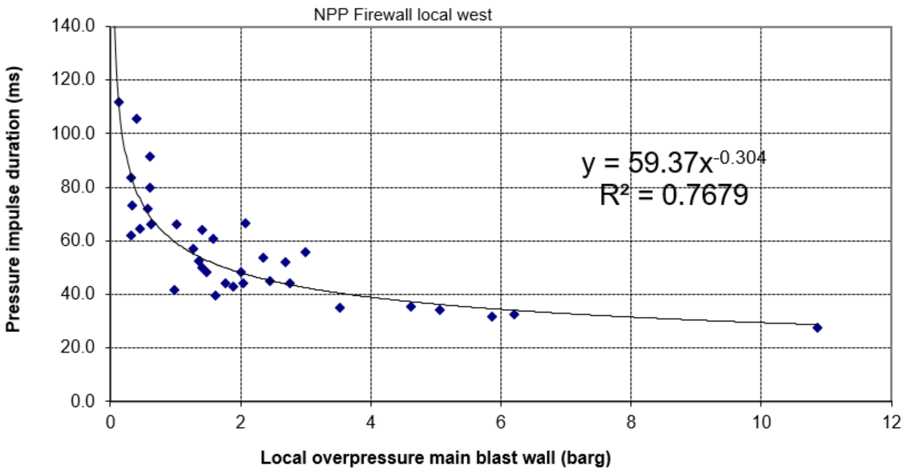


Figure 4-24 Example of evaluation of correlation between local overpressure and duration for area ID 4. For this particular case, the correlation is ~30% below the general RispEx correlation of $80{*}P^{-0.3}$. The general correlation can be considered a conservative average for the local overpressure vs duration correlation factor for the 26 process areas.

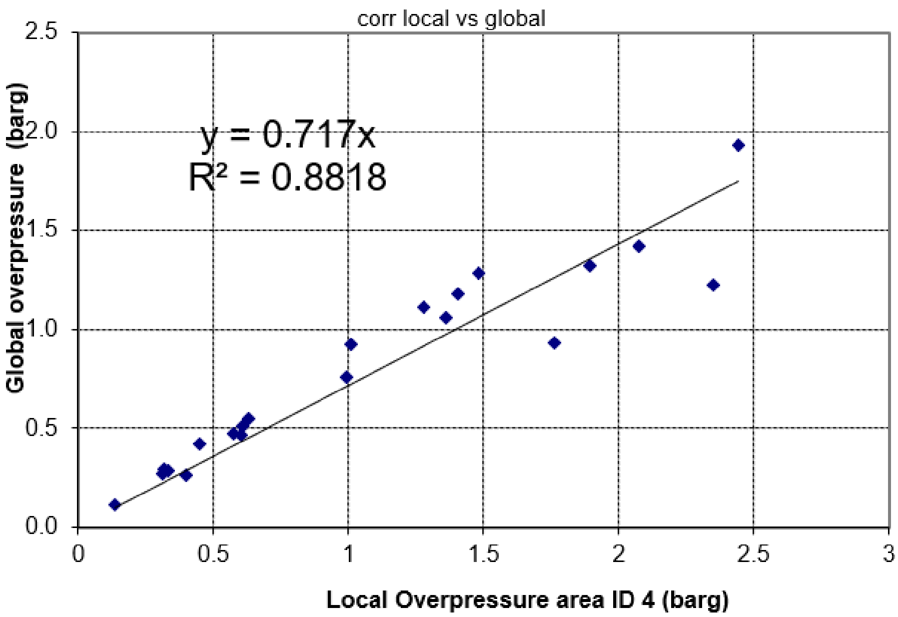


Figure 4-25 Example of evaluation of correlation between local and global overpressure for area ID 4. For this particular case, the correlation correspond well with the general RispEx correlation of 0.7. 0.7 can be considered a conservative average for the global vs local overpressure correlation factor for the 26 process areas.

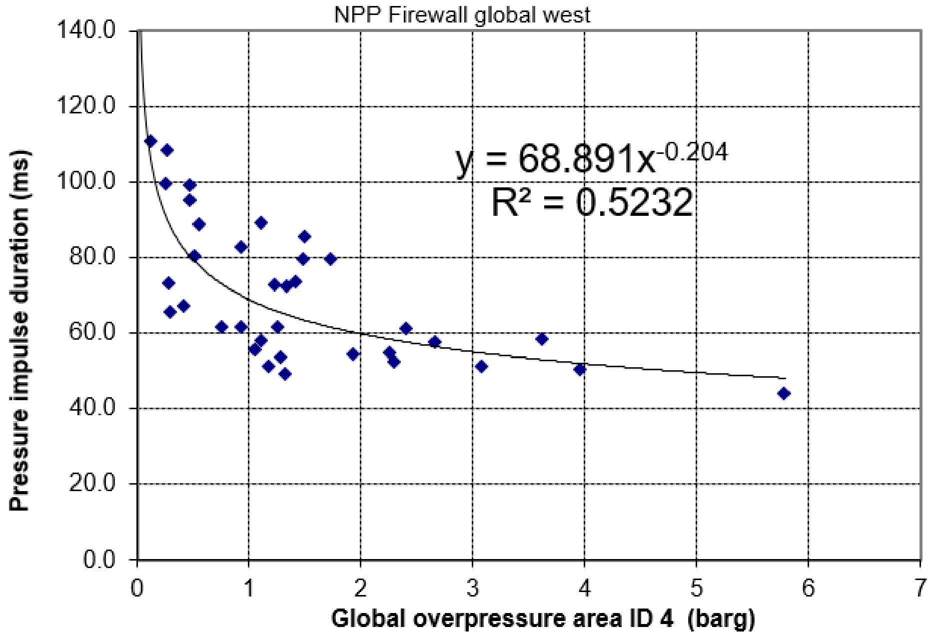


Figure 4-26 Example of evaluation of correlation between global overpressure and duration for area ID 4. For this particular case, the correlation is ~30% below the general RispEx correlation of 100*$P^{-0.2}$. The general correlation can be considered a conservative average for the local overpressure vs duration correlation factor for the 26 process areas.

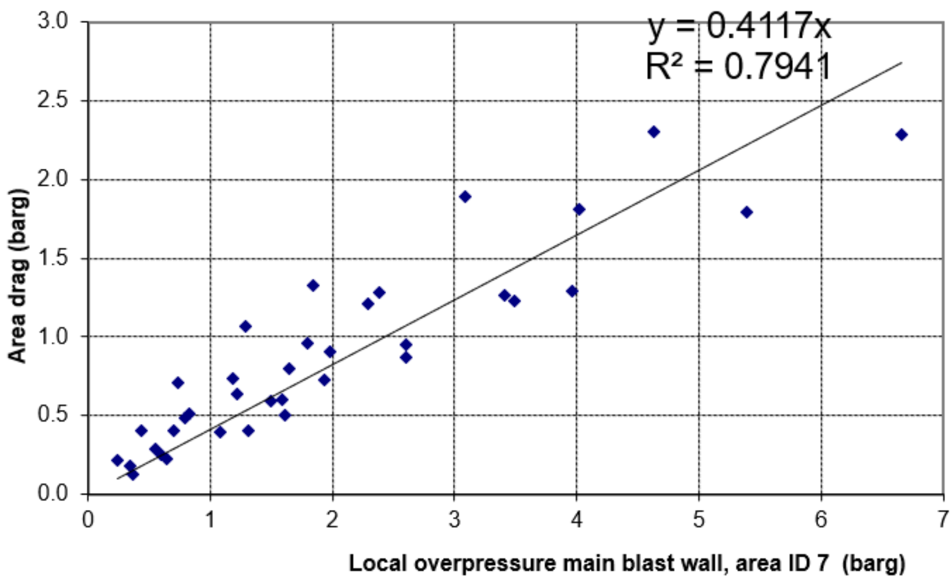


Figure 4-27 Example of evaluation of correlation between local overpressure and drag for area ID 7. For this particular case, the correlation corresponds well with the general RispEx correlation of 0.4.

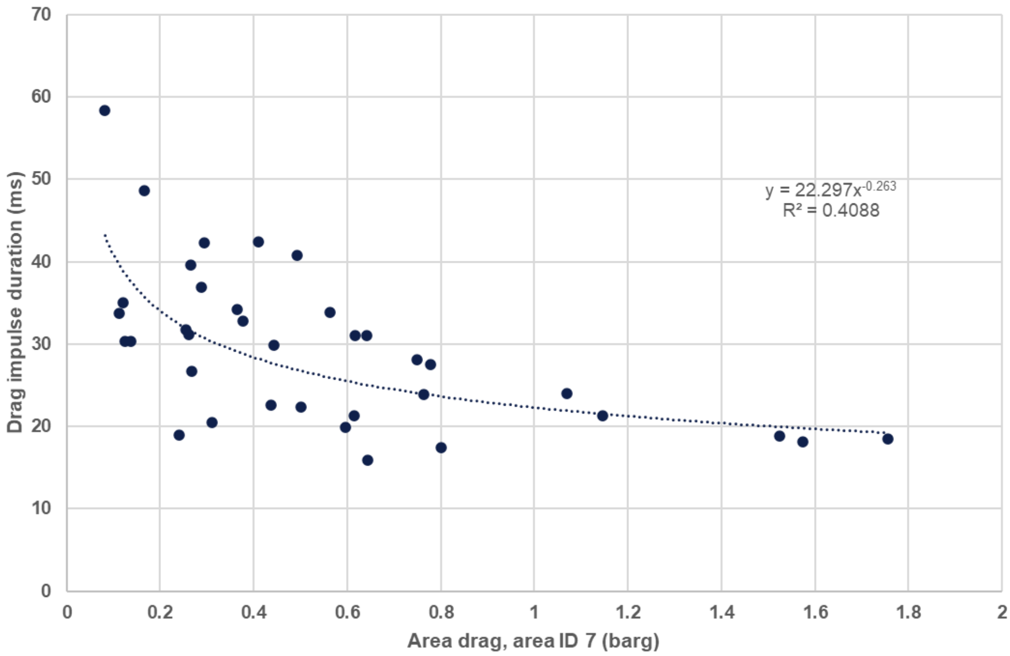


Figure 4-28 Example of evaluation of correlation between drag and drag duration for area ID 7. For this particular case, the correlation is well below the general RispEx correlation, in particular for low drag values. The general correlation can be considered a conservative average for the drag vs duration correlation factor for the process areas.

4.5 Interpolation logic

The basis of the tool consist of predefined cloud size exceedance curves for a fixed number of representative areas. In addition, the basis contains parameters describing the overpressure vs ignited cloud size relation curves. The parameters as a function of area volume and openness is defined based on explosion simulations of representative areas.

The cloud exceedance curves and overpressure exceedance curves for an area are calculated from dimensions and openness input in the tool based on interpolation between the predefined curves.

The principles and description of the interpolation logic are presented in this section.

The steps in the interpolation procedure can be summarized as follows:

1. **Interpolation logic to calculate cloud exceedance curves**. This is done by interpolation between the predefined cloud exceedance curves $f^k(V)$ for representative modules to find the area specific cloud exceedance curve. This interpolation is done for the probability curves, i.e. the aggregated probability of ignited cloud size given leak $f(V)$. An illustration of this is given in Figure 4-29. The interpolation is performed independently per leak size category, for leak size categories:
   - Small process leaks, 0.1-1 kg/s
   - Medium process leaks, 1 – 10 kg/s
   - Large process leak, >10 kg/s
   - 2 kg/s blowout and well events (If relevant)
   - 10 kg/s blowout and well events (If relevant)
   - 50 kg/s blowout and well events (If relevant)
2. **Scale the cloud exceedance curve** to account for the user defined probability of external ignition.

3. Convert from cloud probability exceedance curve to frequency-based cloud exceedance curve. This is done by multiplying by the leak frequency and combining the cloud exceedance curves for all the 3-6 leak type categories into one overall cloud exceedance curve for the area as a whole.
4. Establish the overpressure vs ignited cloud size relationship for the new RispEx area and use this relationship to convert the cloud exceedance curve to a pressure exceedance curve. An illustration of this is given in Figure 4-58. This is performed only for the local overpressure on the blast wall in the area
5. Use RispEx correlation factors to establish the other overpressure and pulse duration loads for local overpressure to blast wall, global overpressure to blast wall and general area drag load, based on the local overpressure value established in step 4.
6. Extract the design explosion loads for the RispEx area from the curves based on the predefined target frequency. An illustration of this is given in Figure 4-59. Then, use the exceedance curves in combination with response surface models to extract a relevant scenario that cause consequences in line with the design explosion loads in the RispEx area.

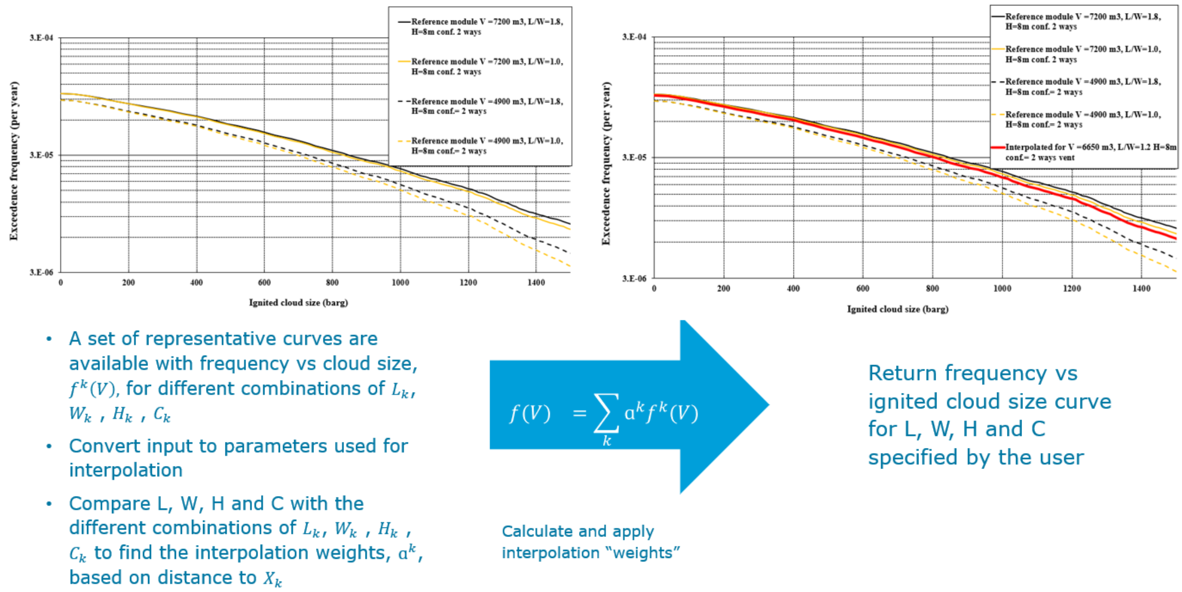


Figure 4-29 Illustration on how cloud exceedance curve can be established based upon interpolation between the curves already established for the predefined RispEx area.

4.5.1 Relation between cloud exceedance probability curves for RispEx areas

The openness and volume for the new RispEx area is found based on the input defined by the user. Based on these two parameters of the new RispEx area relative to the parameters of the predefined areas, the cloud exceedance probability curves for all the representative areas are interpolated between to estimate the cloud exceedance probability curve for the new RispEx area.

It is a linear interpolation that is performed for each parameter applying only the nearest precalculated curve on each side.

- This means that if openness and volume specified by the user correspond well with the openness and volume of one of the representative areas, the two associated cloud exceedance probability curves will also be very similar.
- If openness and volume specified by the user will be midway between the openness and volume of two of the predefined areas, the cloud exceedance probability curve for the RispEx area should be close to midway between the two associated cloud exceedance probability curves of the two relevant representative areas.

- If openness and volume specified by the user differ significantly from the openness and volume of one of the predefined areas, the two associated cloud exceedance probability curves will be independent, and hence not likely to share characteristics.

A prerequisite for the interpolation logic to be meaningful is that there is a clear trend between the ignited cloud size probabilities and the two key governing parameters, openness and volume, throughout all the representative areas.

These trends can be investigated by looking at the probability to exceed a specific ignited cloud size calculated for all the representative areas. This is done to investigate what effect the volume and openness has on the calculated cloud size probability for each area type.

Plotting trends for all areas

Figure 4-30 and Figure 4-31 show that there is a clear trend in the calculated results of conventional process areas; the probability of flammable cloud sizes tend to be larger in more confined areas.

Figure 4-32 that there is a clear trend in the calculated results of conventional process areas that flammable cloud sizes tend to be larger in larger areas. For very large areas the effect abates.

Figure 4-33 and Figure 4-34 show that there is a clear trend in the calculated results of conventional process areas that frequency of flammable cloud sizes tend to be larger in more confined areas as well as in larger areas.

Similar plots are given for process areas on FPSOs in Figure 4-35 to Figure 4-38.

Figure 4-39 to Figure 4-43 show similar plots for wellhead areas.

For all types of areas, it is seen that both the probabilities and frequencies for ignited cloud sizes has a clear trend based on openness and area volume.

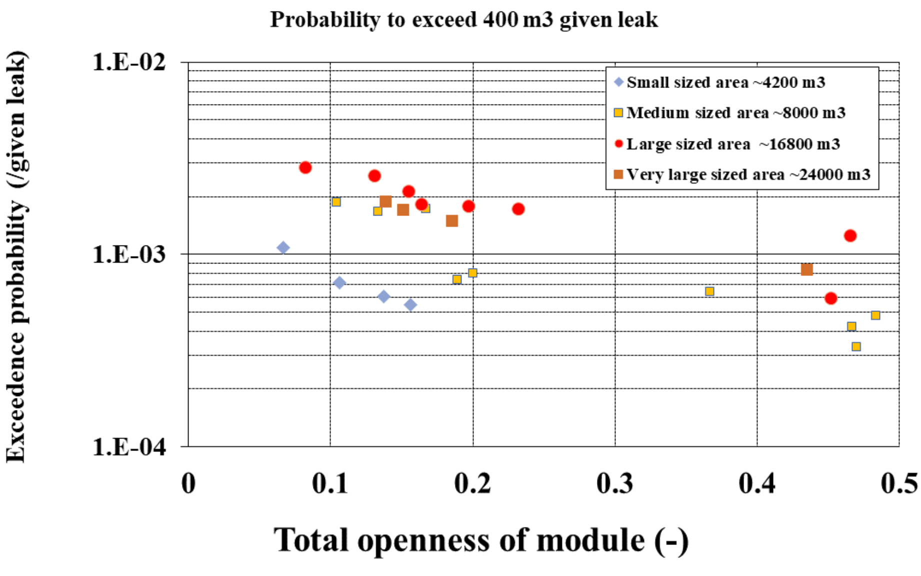


Figure 4-30 For conventional process areas: The plot shows the relation between the openness in the area vs the probability of exceeding an ignited cloud size of 400 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

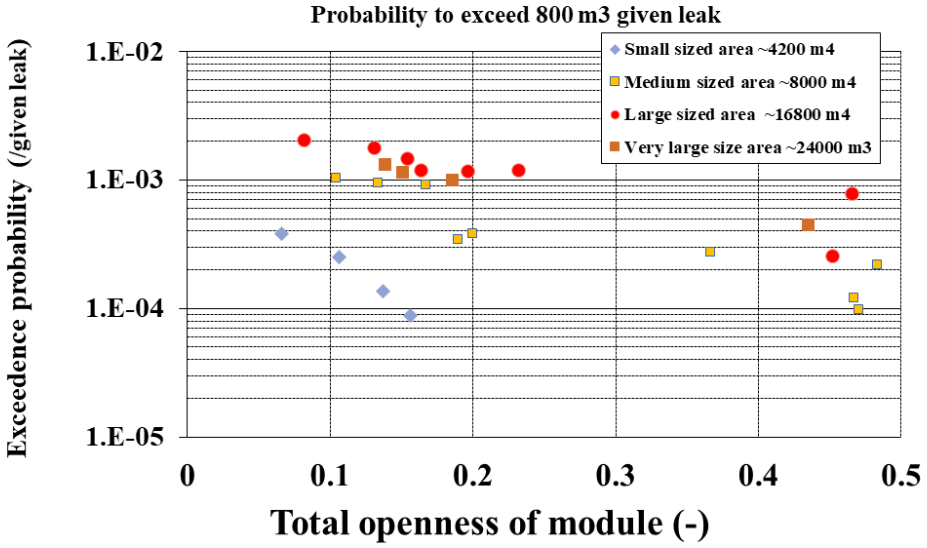


Figure 4-31 For conventional process areas: The plot shows the relation between the openness level in the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

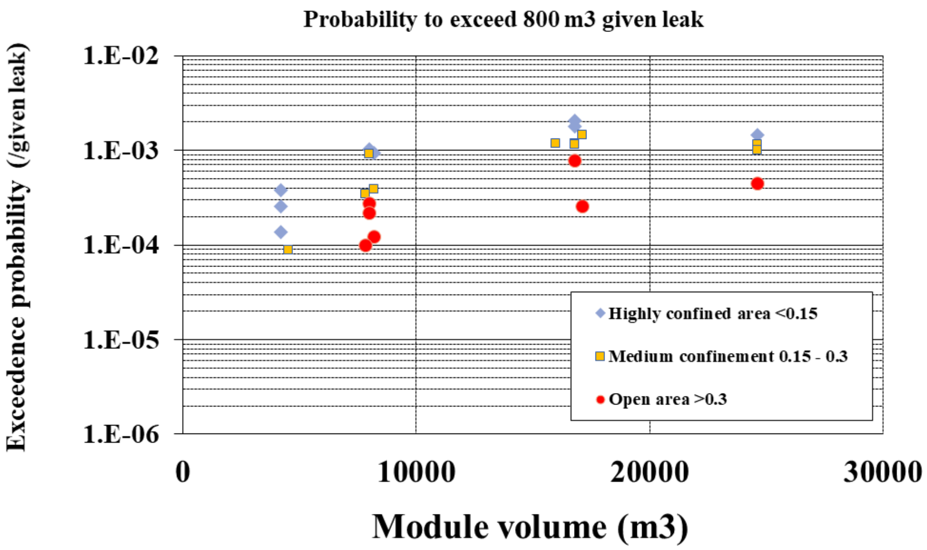


Figure 4-32 For conventional process areas: The plot shows the relation between the volume of the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in larger areas

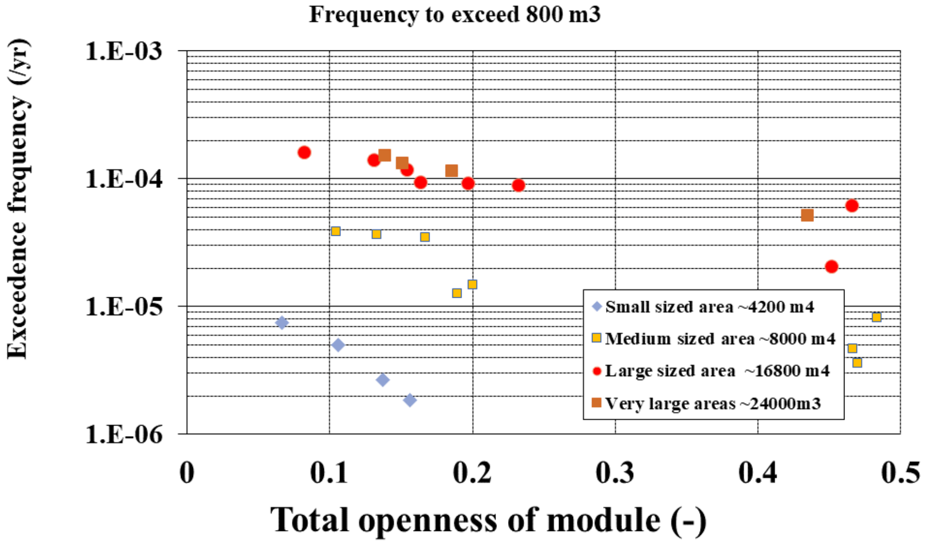


Figure 4-33 For conventional process areas: The plot shows the relation between the openness level in the area vs the frequency of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

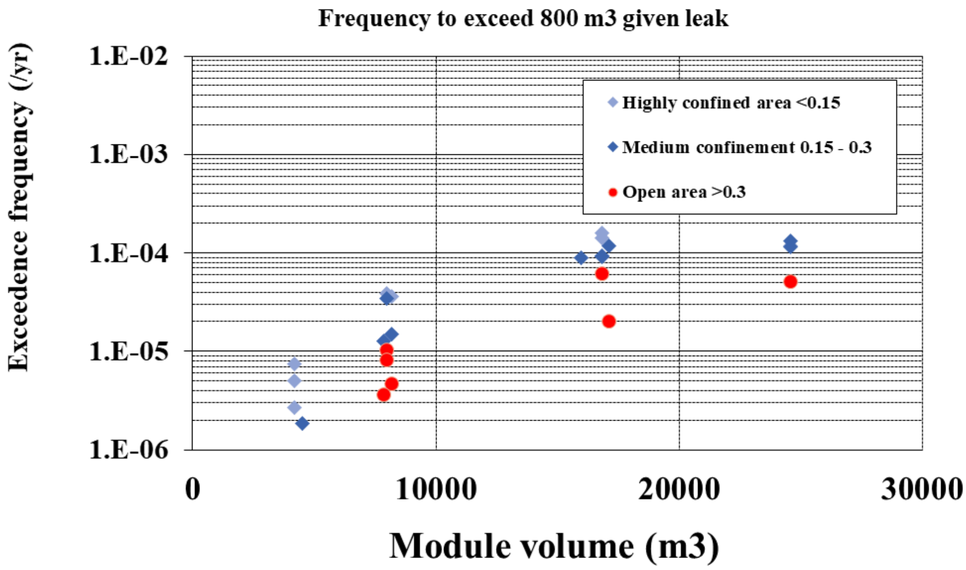


Figure 4-34 For conventional process areas: The plot shows the relation between the openness level in the area vs the frequency of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

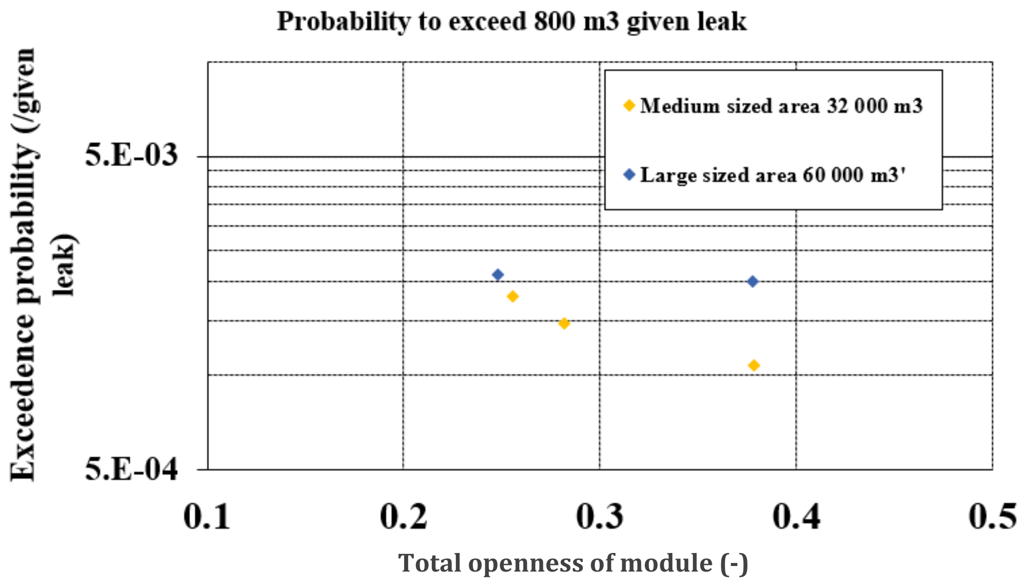


Figure 4-35 For FPSO process areas: The plot shows the relation between the openness level in the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules. Despite only two data points are available for the largest module size, it seems that the trend is not as apparent for the larger sized FPSO area.

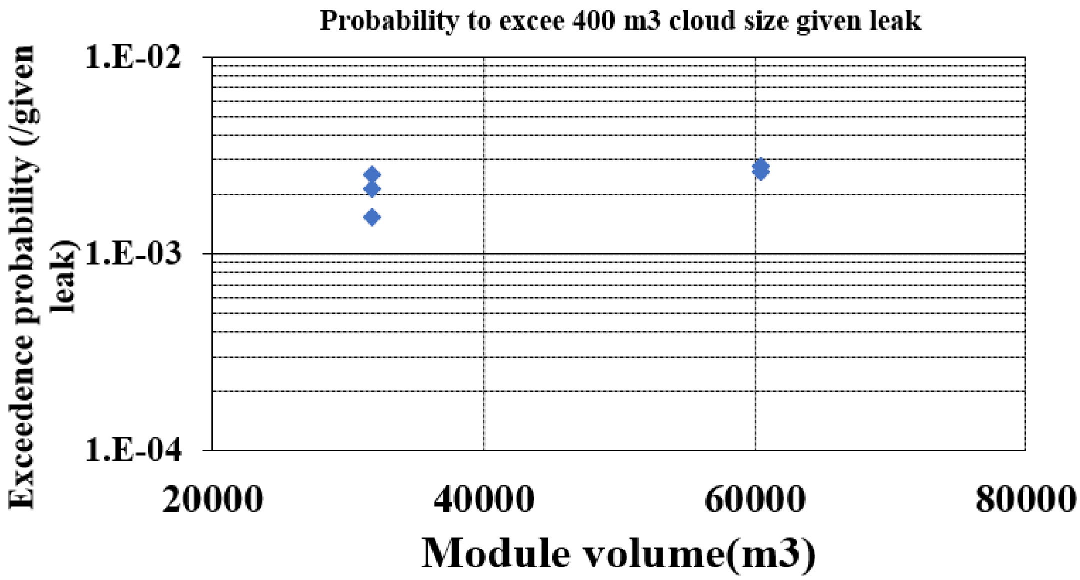


Figure 4-36 For FPSO process areas: The plot shows the relation between the volume of the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a trend in the calculated results of larger flammable cloud sizes in larger areas

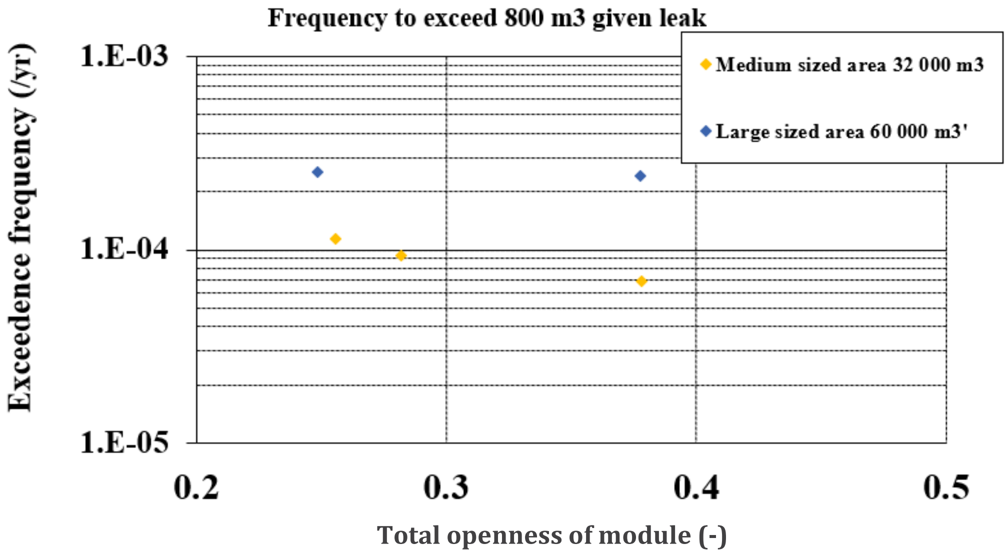


Figure 4-37 For FPSO process areas: The plot shows the relation between the openness level in the area vs the frequency of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

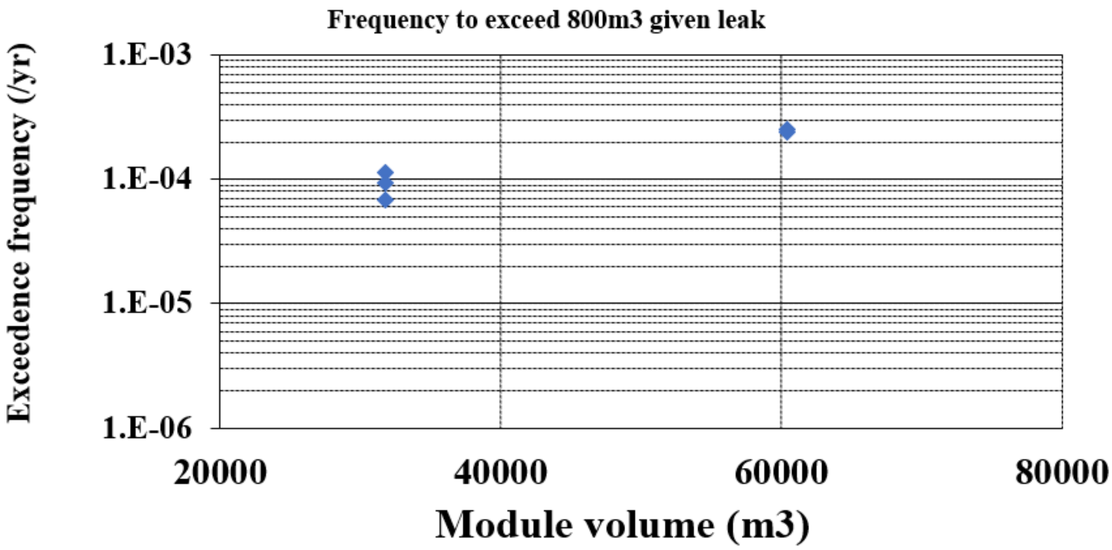


Figure 4-38 For FPSO process areas: The plot shows the relation between the openness level in the area vs the frequency of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

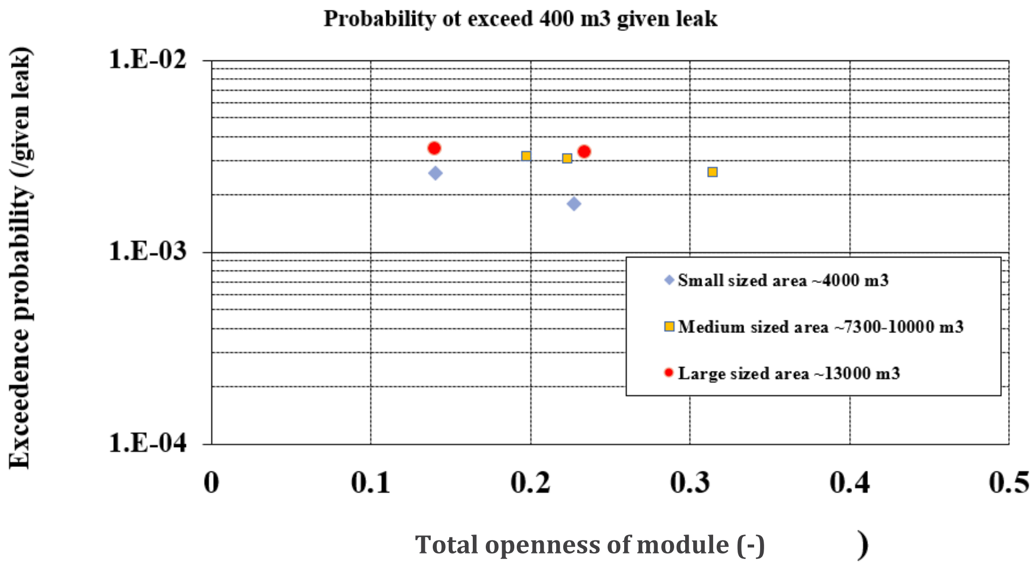


Figure 4-39 For conventional wellhead areas: The plot shows the relation between the openness of the area vs the probability of exceeding an ignited cloud size of 400 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in larger areas

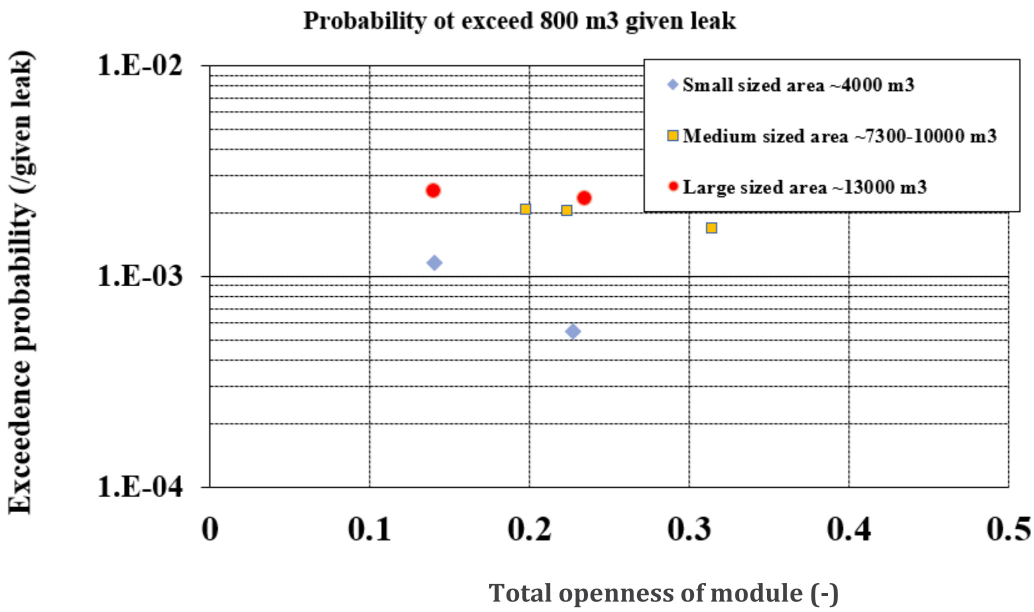


Figure 4-40 For conventional wellhead areas: The plot shows the relation between the openness of the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in larger areas

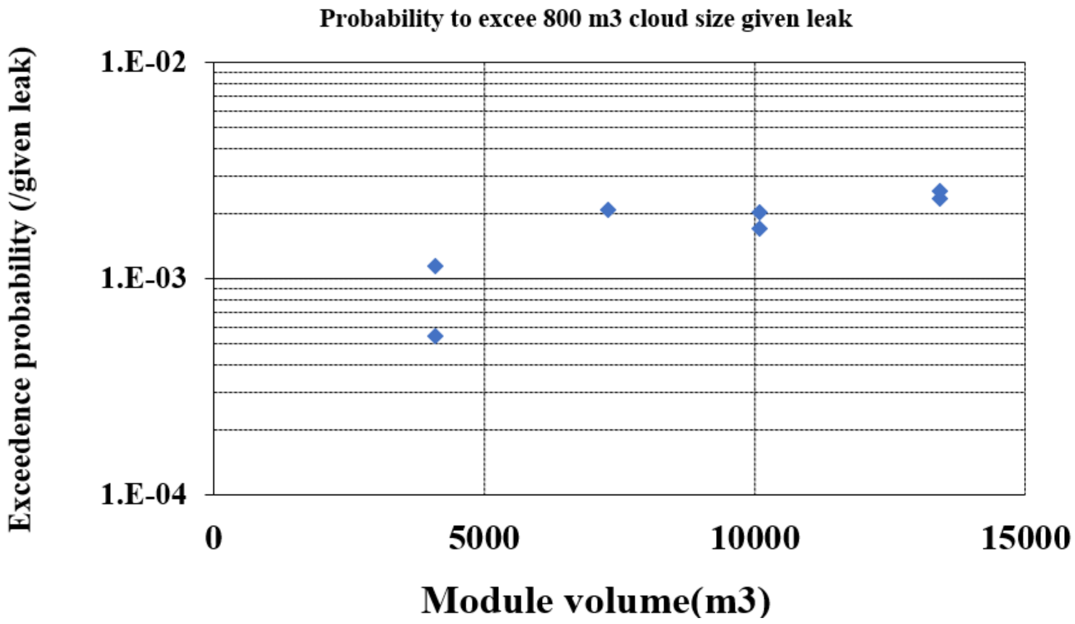


Figure 4-41 For conventional wellhead areas: The plot shows the relation between the volume of the area vs the probability of exceeding an ignited cloud size of 800 m3 given a leak in the area. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in larger areas

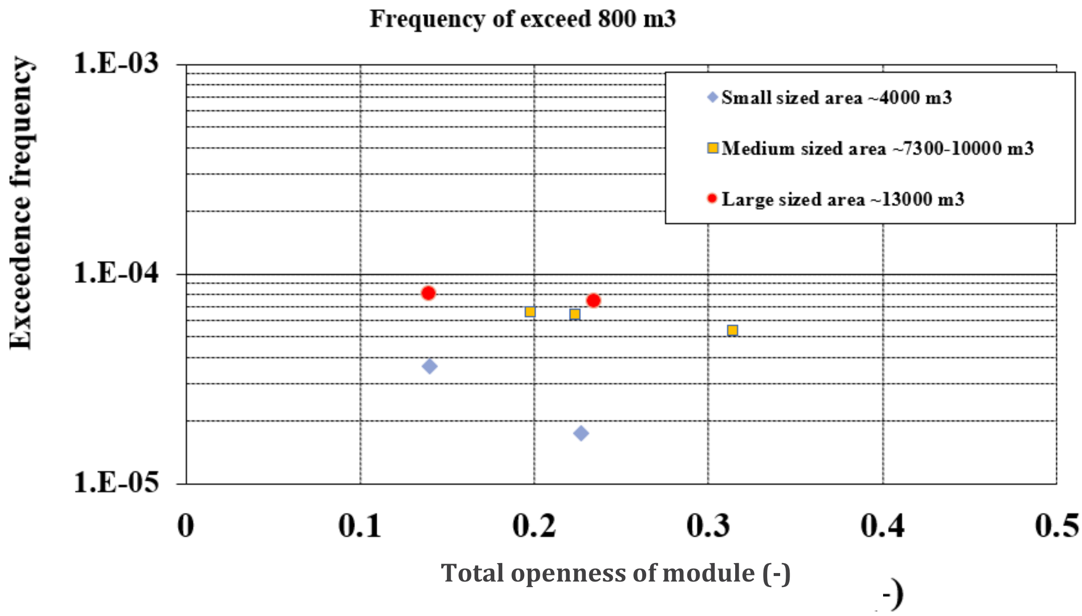


Figure 4-42 For conventional wellhead areas: The plot shows the relation between the openness level in the area vs the frequency of exceeding an ignited cloud size of 800 m3. It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in more confined modules

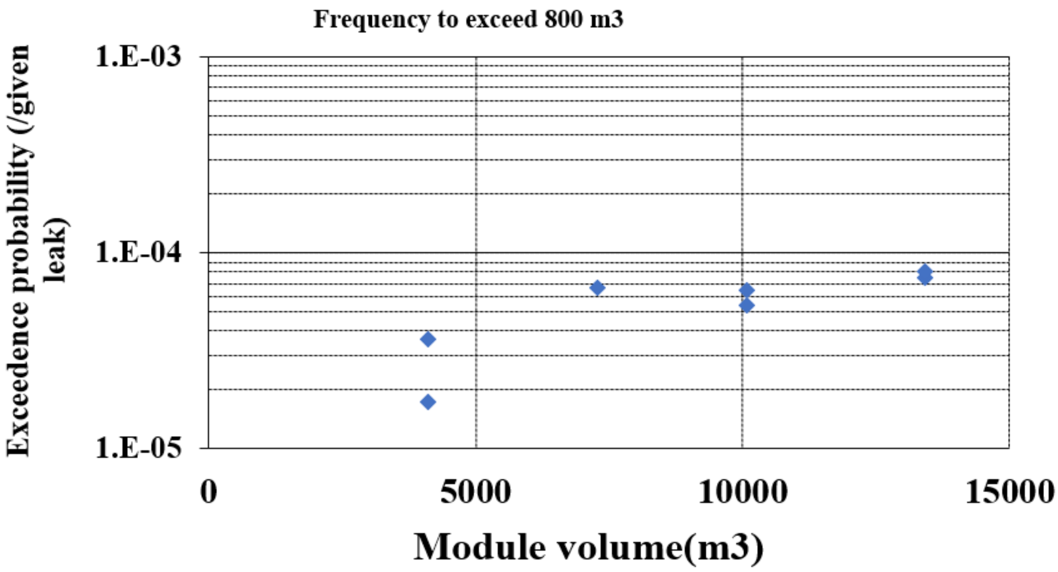


Figure 4-43 For conventional wellhead areas: The plot shows the relation between the volume in the area vs the frequency of exceeding an ignited cloud size of 800 m3 . It is seen that there is a clear trend in the calculated results of larger flammable cloud sizes in larger modules

4.5.2 Interpolation of volume and «openness» to find cloud exceedance probabilities

Two different interpolation schemes for openness and volume, respectively, are selected based on

- The effect the two input parameters, volume and openness, have on the cloud size probabilities in the explosion analysis performed for the representative RispEx areas, and
- The distribution of the two parameters within the representative areas (volumes mainly clustered together with 3 volume size categories, with approximate volume size categories V_s, $2V_s$ and $4V_s$ used for simulations (V_s is here the volume size of the smallest volume category. For process areas the volume size categories are ~4000 m3, ~8000 m3 and ~17 000 m3). For openness a more uniform spread of openness levels is applied in the range ~0.07 - ~0.5.

The two interpolation schemes applied are

- Interpolation on volume: Piecewise linear interpolation
- Interpolation on openness: Locally weighted average

4.5.3 Interpolation on volume

The interpolation scheme applied when interpolating on volume is piecewise linear interpolation.

This means that if the volume of the new RispEx area correspond to one of the volume categories for the representative areas, then the resulting RispEx cloud exceedance probability curve will correspond to a combination of cloud exceedance probability curves for the representative areas within the corresponding volume category (with relative weighting depending on the openness of these areas). No weight is in this case taken from the cloud exceedance probability curves for the representative areas for the two different volume categories.

When the volume of the new RispEx area is between two representative volume categories, then resulting RispEx cloud exceedance probability curve will be weighted in between the cloud exceedance probability curves for the curves of the two different volume categories.

For example, when assessing the probability of the ignited cloud exceeding a specific value, such as 800 m3 for a confined module (i.e. openness between 0.07-0.13) the black line in Figure 4-44 shows which probability of exceeding 800 m3 will be estimated by RispEx depending on the volume of the RispEx area.

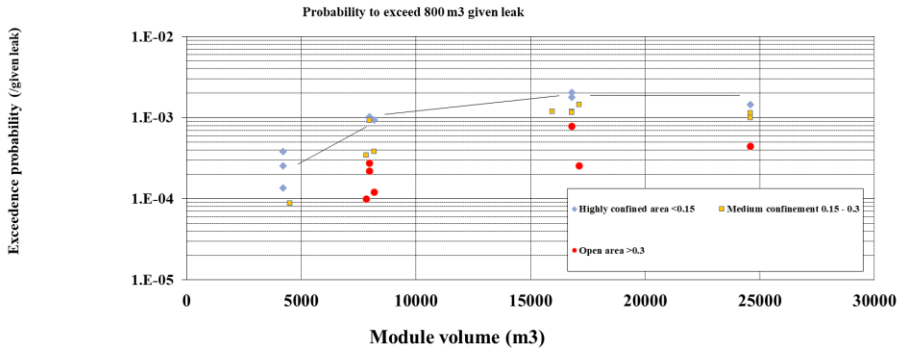


Figure 4-44 Example of piecewise linear interpolation of probability of exceeding an ignited cloud size of 800 m3 for a RispEx module with low openness (the blue markers).

4.5.4 Interpolation on openness

The interpolation scheme applied when interpolating on openness is locally weighted interpolation.

This means that the cloud exceedance probability curve for a new RispEx area (when volume is fixed) will correspond to a weighted average of the cloud exceedance probability curves for the representative areas with similar area volumes, with highest weights assigned to the representative areas with the closest match in openness level.

To exemplify this, look at the predicted probability of exceeding 800 m3 cloud size with openness 0.15, when points are available for openness 0.1, 0.13, 0.17, 0.19, 0.2, 0.37, 0.45 etc as shown in Figure 4-45. Weights are assigned according to a bell-shaped kernel function. The bandwidth of the local weighting per area type is tabulated in Table 4-19. The yellow dots show the probability of exceeding 800 m3 that are known for the representative areas. The locally weighted average value that estimates the probability of exceeding 800 m3 when the openness level is 0.15 is shown as a blue cross.

The mathematical function estimating the probability of exceeding a certain cloud size (denoted *Y*hat(X_0)) based on a set of known points, Y(Xi), i corresponding to different openness levels, are given by:

$$\hat{Y}(X_0) = \frac{\sum_{i=1}^{N} K_{h_\lambda}(X_0, X_i) Y(X_i)}{\sum_{i=1}^{N} K_{h_\lambda}(X_0, X_i)}$$

Here, Khg, is a kernel function, which is a bellshaped function with a bandwidth b:

$$K(x^*, x_i) = \exp\left(-\frac{(x^* - x_i)^2}{2b^2} \right)$$

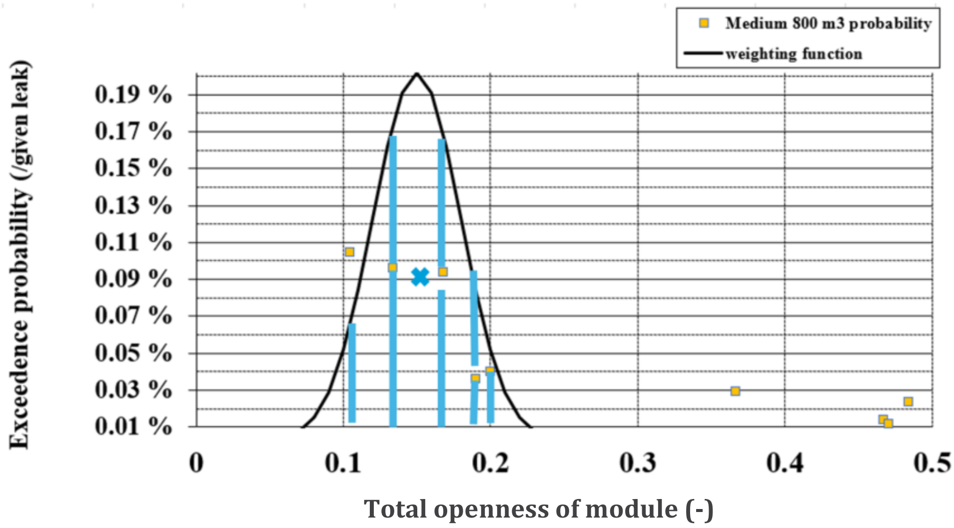


Figure 4-45 Example of locally weighted average for openness 0.15 showing the magnitude of the weights assigned to the openness for which the probability of exceeding 800 m3 are known.

The yellow curve shown in Figure 4-46 show an example of what cloud exceedance probability will be predicted for the full range of RispEx openness levels when the module volume is fixed to volume corresponding to the medium sized volume category.

For confined areas, close to or less than the lowest openness included in the set of representative areas, this type of estimation will give underpredictions, since it will always predict lower than the highest value for which data is available for. The dotted line in the figure show how locally weighted average behave when the openness level is low. To avoid optimistic prediction for confined modules, a hybrid interpolation scheme is applied for low openness. The interpolation scheme is coded so that it smoothly transforms from a locally weighted interpolation to a piecewise linear interpolation / regression between the data points available for the two lowest openness levels. The resulting interpolated value for probability of exceeding 800 m3 is shown as a solid yellow line above the dotted line in Figure 4-46. Ideally the yellow curve should appear smoother, and the reasons for the slight non-smooth curve is the inconsistency between the points from different geometries, congestion levels, etc.

The openness region where the interpolation smoothly changes from locally weighted to piecewise linear interpolation on openness is tabulated in Figure 4-12.

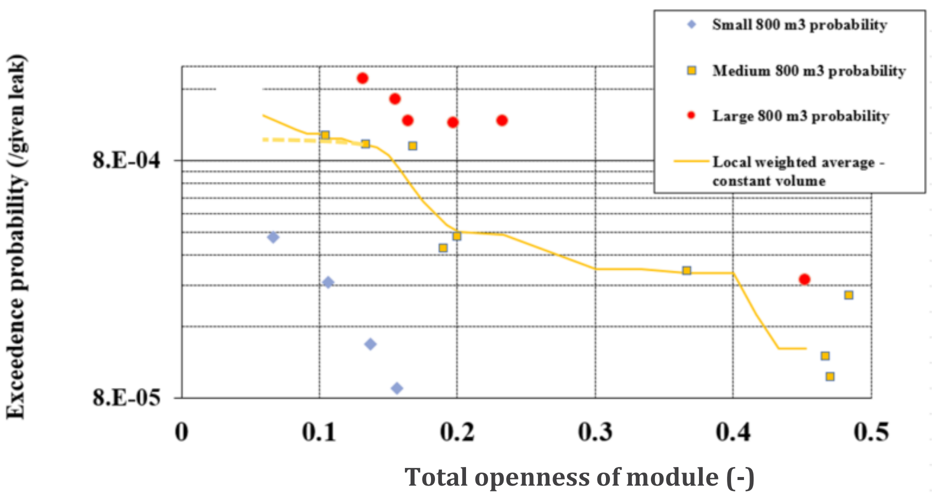


Figure 4-46 Interpolation results showing cloud size exceedance probability predicted for the full range of RispEx openness when the module volume is fixed to volume corresponding to the medium sized area category.

Table 4-19 Interpolation parameters used for interpolation on openness

parameter\area type	Conventional process area	FPSO process area	Wellhead area
Band width for local weighting on openness	0.05	0.05	0.02
Linear interpolation applied below this level	0.09	0.1	0.13
Local weighting applied above this level	0.11	0.25	0.15

4.5.5 Two-dimensional interpolation

The interpolation scheme when interpolating on volume is presented in section 4.5.3 and the interpolation scheme on openness is presented in section 4.5.4. In order to achieve two-dimensional interpolation, the interpolation weights obtained for one-dimensional interpolation are multiplied together and normalized.

When the interpolation weights then are applied to all points on the cloud exceedance probability curve, then the interpolated RispEx cloud exceedance probability curve is obtained.

For process areas, the interpolation is performed for three curves; one for small leaks, one for medium leaks and one for large leaks.

For wellhead areas, the interpolation is performed for three additional curves; one for blowouts and well events corresponding to 2 kg/s well releases, one for blowouts and well events corresponding to 10 kg/s well releases and one for blowouts and well events corresponding to 50 kg/s well releases.

4.5.6 Adjusting curves for external ignition

In case of presence of strong external ignition sources (outside the explosion area) this is not reflected in the RispEx explosion analysis for the representative areas. Significant contribution to the ignition probability caused by external ignition will affect the explosion risk in the area. Such strong ignition sources may be

- Diesel engine combustion air intake
- Gas turbine combustion air intake

If location and / or strength of ignition source will affect the major accident risk picture, then this is raised though HAZID/HAZAN.

In this case, the user of RispEx should evaluate exposure probability of ignition source and potential mitigating measures, and calculate the external ignition probability outside the RispEX tool. Based on this evaluation the user may assign external ignition probability for different leak categories directly in the tool, and the estimated effect on the explosion loads will be reflected in the output results.

The user should evaluate the exposure probability for different combination of leak sizes and wind conditions, and may based on this estimate exposure probability per leak size category. Based on gas exposure probability and ignition intensity found in MISOF2, the user can define external ignition probability contribution for medium and large leaks, which may be specified directly into the RispEx tool (Medium leaks 1-10 kg/s, Large leaks >10 kg/s)

External ignition for blowouts and well releases must if relevant also be specified in the case the area is a wellhead area. The default ignition probability due to external ignition for each leak size category and leak type is 0, and in this case the curves found based on interpolation are not affected. It is not possible to include external ignition probability for small leaks.

Effect from external ignition contribution that is specified by the user will be reflected in all RispEx results/output including Design Accidental explosion Load. This is achieved by scaling the curves giving ignited cloud sizes vs probability given leak. The scaling factor per leak category that will be used to scale all probabilities in the probability vs cloud size curve is:

$$P_{ex} / P_{in} + 1$$

Where P_{ex} is external ignition contribution and P_{in} is ignition probability excluding external ignition.

Ignition probability excluding external sources (may also be referred to as internal ignition), is simply the probability of an ignited cloud size of 0 m^3 or more given leak for the relevant leak category.

An example of how this is expected to contribute is given as follows:

3 examples for a 42 x 28 x 9 m 2-ways ventilated module:

- Base case – no external ignition: 1E-4 pr yr pressure = 0.1 barg
- Sensitivity 1% external ignition probability on large leaks: 1E-4 pr yr pressure = 0.2 barg
- Sensitivity 3% external ignition probability on large leaks, 0.5% on medium: 1E-4 pr yr pressure = 0.45 barg

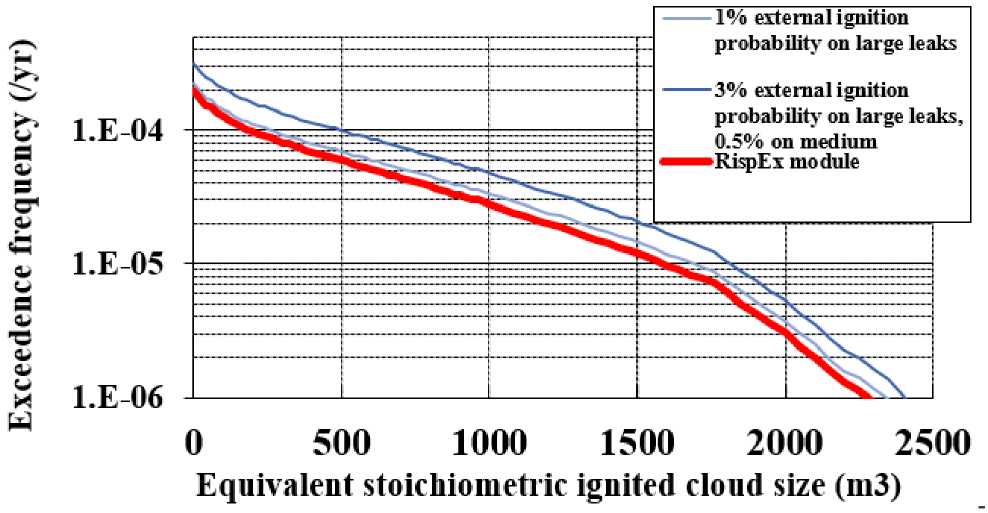


Figure 4-47 Example of curves showing the frequency vs cloud size curves after scaling the cloud size probabilities to reflect external ignition for two different external ignition probability cases

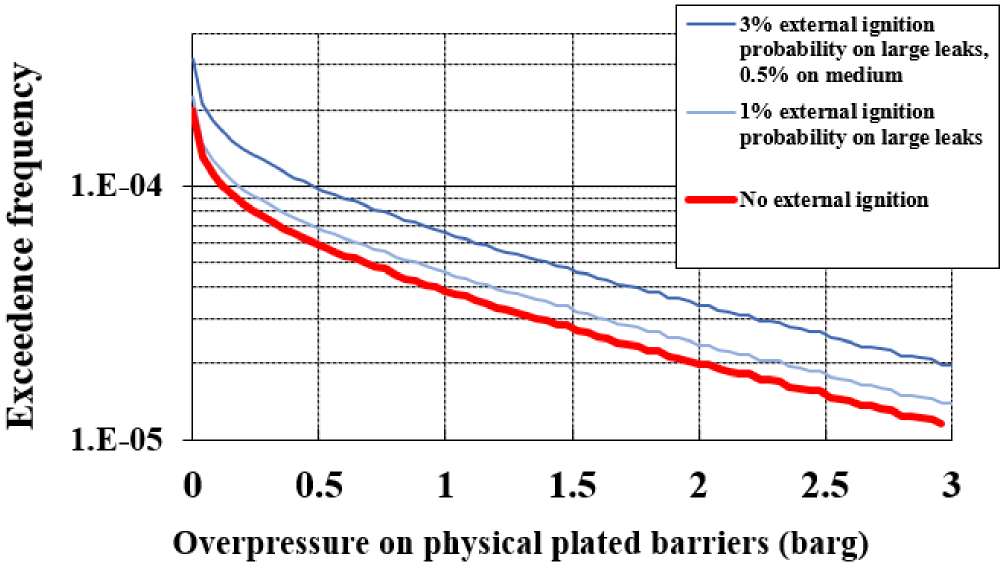


Figure 4-48 Example of curves showing pressure exceedance curves after scaling the cloud exceedance curves to reflect external ignition for two different external ignition probability cases.

4.5.7 Transforming cloud exceedance probability curves to one frequency curve

When the cloud exceedance probability curves are obtained for small, medium and large leaks respectively, they can be added together[3] and multiplied with the overall leak frequency for process leaks in the area to establish the cloud exceedance (frequency) curve. The overall leak frequency for process leaks are found based on the approach described in section 4.3.2.

For wellhead areas, the cloud exceedance curve from blowouts and well events needs to be added as well. Probability vs cloud size given leak curves are available for three blowout and well leak size categories; 2 kg/s, 10 kg/s and 50 kg/s. For these curves, the probabilities are given based on given leak for that particular leak size category. Two different representative blowout and well release representative rate categories are available for selection from input; Rate category <15 kg/s and rate category > 15 kg/s. For RispEx, a blowout rate of 10 kg/s is representative for the lowest blowout rate category (<15 kg/s) and 50 kg/s is representative for the highest blowout rate category (>15 kg/s). Since a choked release is assumed to have a release rate 20% of the full release rate, 2 kg/s will be a representative rate for choked flow for the >15 kg/s category, and 10 kg/s will be a representative rate for choked flow for the >15 kg/s category. Frequency for choked flow and full flow blowout and well release events, respectively, are available from the approach described in section 4.3.2. Then the two cloud exceedance probability given blowout or well release in the relevant rate category curves can be multiplied by the release rate frequency and added to the process events to find the overall calculated explosion risk cloud size curve for the particular area with contriution also added for blowouts and well releases as well.

4.5.8 Relation between overpressure vs cloud size for RispEx areas

4.5.8.1 Relation for blast walls

When fitting the explosion response surface parameters to the simulation results as described in 4.4.4, the parameters Pv and variance in the term of Φ is fixed, with values as listed in the bottom

3 Note that since the curves gives the probability of exceeding a certain cloud size for a given leak category given leak, the curves can be multiplied with the overall leak frequency and added together. If the curves had expressed the probability of exceeding a certain cloud size for a given leak category given leak in the same leak category, the curves would have needed to be multiplied with the leak frequency of the associated leak category before added together.

two rows of Table 4-20. K_w is calculated to obtain a best fit towards the explosion simulation results for the equation.

$$\frac{P_W}{P_0} = \Phi \cdot K_W \cdot V_f^{p_{eV}}$$

K_W is fitted for each area, resulting in a set of 21 K_w-values for conventional process areas, 5 K_w -values for FPSO process areas, and 7 K_w-values for wellhead areas. Where the subscript W indicates that the value relates to the blast wall.

It is then developed a general expression for K based on RispEx input parameters.

The dependency/correlation between K_w and openness are evaluated based on the scatter plot shown in Figure 4-49. It is shown that the K_w value decrease as the module becomes more open. The trend line plotted show that this can be captured by an exponential function.

The dependency/correlation between K_w and volume are evaluated based on the scatter plot shown in Figure 4-50. It is shown that the K_w value tend to increase for smaller modules, while for larger modules it seems that K_w is no longer sensitive to the volume. The trend line plotted show that this can be captured by a power function. It is seen that it is a large spread relative to the trend line, and this is because each of the dots represent K_w estimated for areas with a large spread in openness.

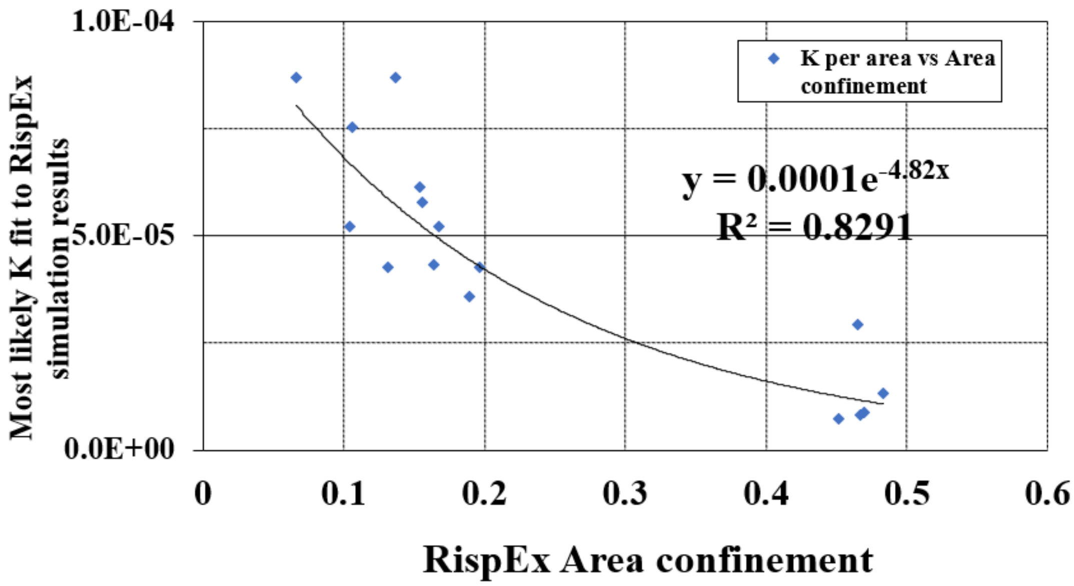


Figure 4-49 Dependency between openness level and K. The fit is good, and the slight spread to some extent due to the effect of volume which is not shown in this plot.

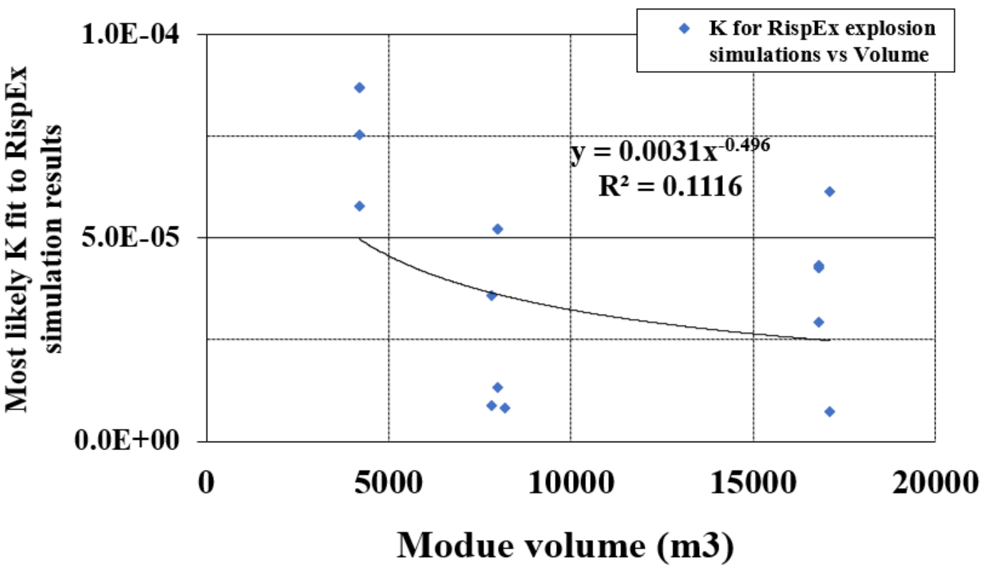


Figure 4-50 Dependency between module volume and K. Note that the relatively large spread is that for each module volume there is a range of different openness levels.

When looking at the combined trend of volume and openness for the set of the best fit K values for the range of modules with different volume and openness, the following expression is found to predict the K_w with an adequate accuracy:

$$K_W = C_W V^{p_{aV,W}} \cdot e^{\text{conf} \cdot p_{c,W}}$$

Here, V is the volume and conf is the openness factor of the area. C, p_v and p_c are parameters for which values are selected to achieve a good prediction. One set of C, p_v and p_c are found for conventional process areas. Since the congestion of several of the representative areas are considered above average, less weight is put on the K-values obtained from explosion simulations for these areas.

Based on the parameters listed in Table 4-20 the equation $\frac{P_W}{P_0} = \Phi \cdot K_W \cdot V_f^{p_V}$, with K given by $K_W = C \cdot V^{p_{V,W}} \cdot e^{\text{conf} \cdot p_{c,W}}$, the explosion overpressure as a function of ignited cloud size is uniquely defined in RispEx based on area parameters “area volume” and “area openness level”.

One set of parameters is identified for FPSOs. For wellhead areas, C_W, $p_{v,W}$ and $p_{c,W}$ are used from the parameters determined for conventional process areas.

The parameter set given in Table 4-20 are found to completely determine the explosion response surfaces for blast walls in RispEx. When plotting the K_W fitted to the explosion simulations for the representative areas towards the K_W obtained from the general equation expressing K_W as a function of area volume and area openness, it is seen from Figure 4-51 that the general expression provides a reasonable estimate for use in RispEx.

Table 4-20 RispEx parameter set to determine explosion response surface for blast walls based on volume and openness of area

Case No.	Conventional process area	FPSO process area	Wellhead area
C_W	0.0095	0.035	0.0095
$p_{ev,W}$	-0.51	-0.5	-0.51
$p_{c,W}$	-4.7	-2	-4.7
$p_{av,W}$	1.5	1.3	1.5

Φ_W	0.6	0.8	0.6

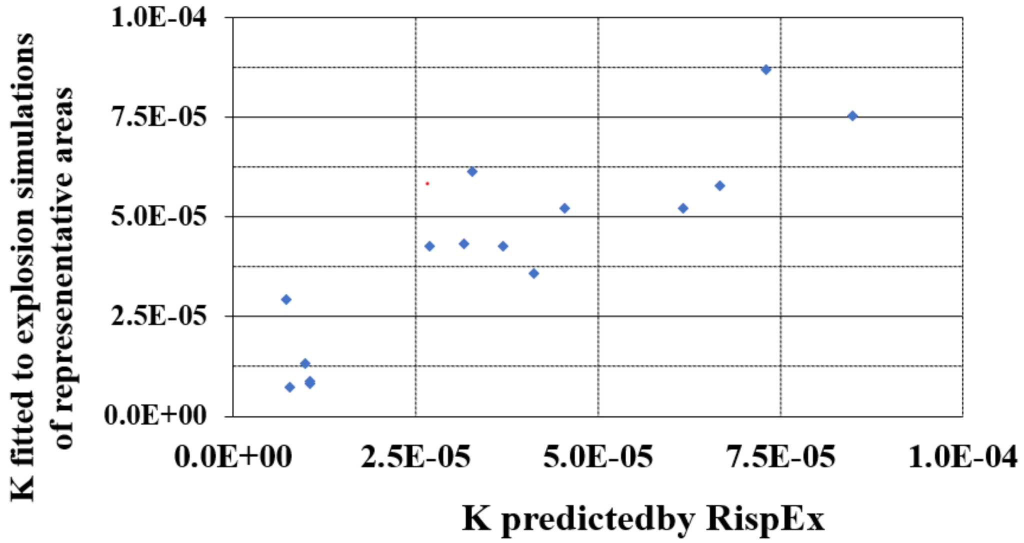


Figure 4-51 The plot show the K's obtained by fitting the K to explosion simulation results when standard deviation of Φ and p_v are assigned fixed values of 1.5 and 0.6 respectively vs K's calculated based on the equation used in RispEx. Some areas with very high openness are been given less weight when parameters are fitted to predict K by volume and openness to prevent being overly conservative, hence some more points are located above the line K_pred vs K simulated.

Very large areas

The parameter fitting described above does not include very large process areas included in Version 1.3 of RispEx. Explosion simulations were performed for very large areas, and compared with the RispEx predicted K value. The comparisons are presented in Figure 4-52 and Figure 4-53. The plots show that the calculated values for the new very large areas are somewhat lower than the RispEx predicted values. Based on the comparison it is concluded that the original RispEx parameter set presented in Table 4-20 remains valid (or potentially somewhat conservative) for the very large areas and no change is made to the parameters.

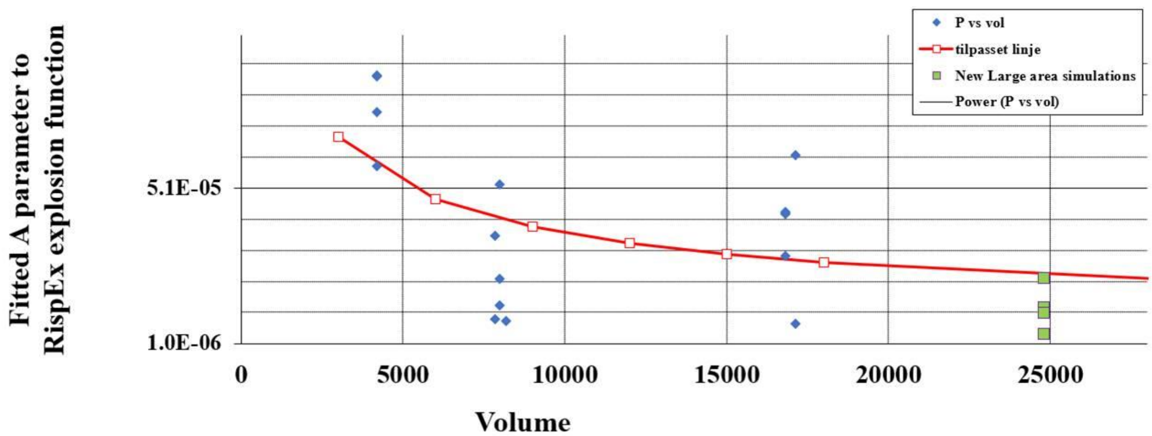


Figure 4-52 The plot show the K's obtained by fitting during RispEx development, and for the new Very Large areas.

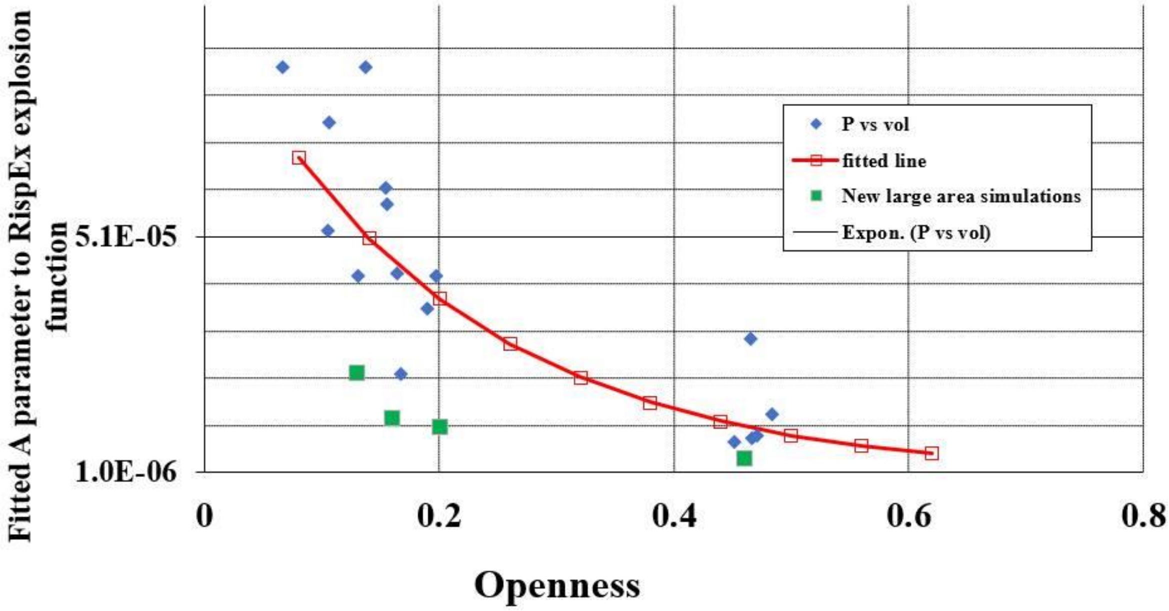


Figure 4-53 The plot show the K's obtained by fitting during RispEx development, and for the new Very Large areas.

4.5.8.2 Relation for decks

RispEX was originally developed with blast walls as the primary explosion target. RispEx was extended to include a separate calculation for horizontal divisions in version 1.6. The relation was updated in version 2.0.

The relation for decks is the same as for blast walls, but with different parameters for calculating *K*. The overpressure is calculated with the relation

$$\frac{P_D}{P_0} = \Phi \cdot K_D \cdot V_f^{p_{eV}}$$

Where the subscript *D* indicates the deck. As for the blast walls, the parameter K_D is determined through the relation:

$$K_D = C_D V^{p_{aV,D}} \cdot e^{\mathrm{conf} \cdot p_{c,D}}$$

With the two stage multi parameter curve fitting approach applied for blast walls, there can be multiple equally good fitting curves through each dimension. An example of two equally good fits towards confinement is presented in Figure 4-54. As the overpressure on the blast wall and deck is normally correlated it was investigated whether the fitting could be simplified by fixing one of the parameters. To do this the overpressure on the decks was normalized with the pressure on the blast wall through:

$$P_{Normalized} = \frac{P_D}{P_W}$$

The normalized pressure was then plotted vs volume and openness. The results are presented in Figure 4-55.

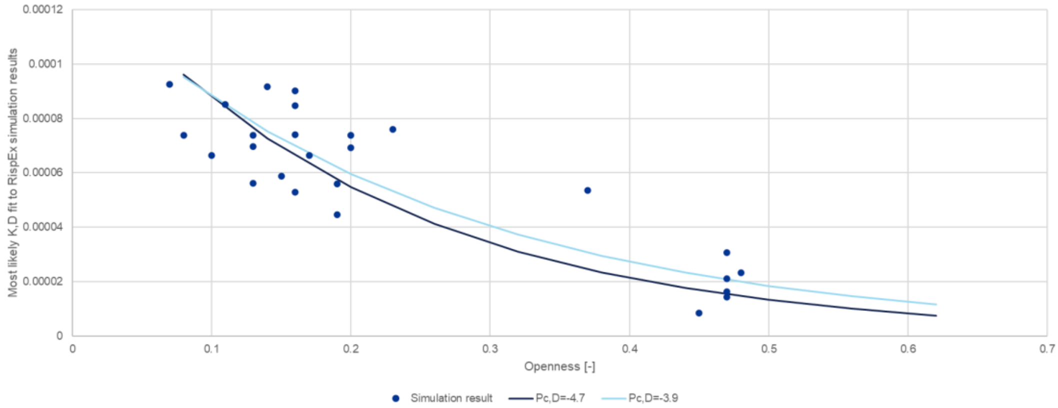


Figure 4-54 Illustration of how multiple parameters can fit equally well in one dimensions of a multi parameter fit

Based on the results it was determined that the normalized overpressure is correlated with the volume of the area, but nearly uncorrelated with the openness of the area. As the volume of the area increases, the normalized pressure on the deck increases. This is because for small modules an explosion will generally be equally distanced from the blast wall and the deck. As the volume increases the distance from an average explosion to the blast wall tends to increase, but the distance from the deck will remain constant since large modules are normally much longer and wider than they are tall.

Based on the above considerations the confinement parameter was kept constant and the volume parameter was fitted. The resulting parameters for decks is presented in Table 4-21

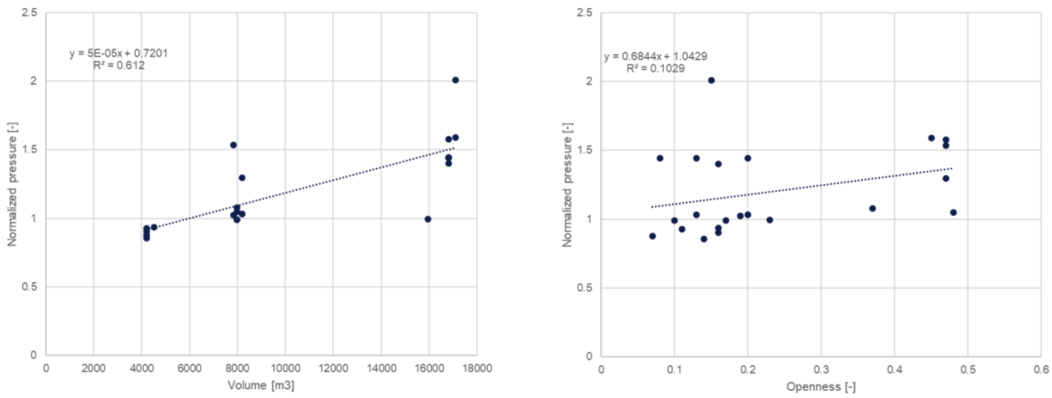


Figure 4-55 Relation between the normalized overpressure and the volume (left) and openness (right)

Table 4-21 RispEx parameter set to determine explosion response surface for decks based on volume and openness of area

Case No.	Conventional process area	FPSO process area	Wellhead area
C_D	0.0013	0.006	0.0013
$p_{ev,D}$	-0.28	-0.3	-0.28
$p_{c,D}$	-4.7	-2	-4.7
$p_{av,D}$	1.5	1.3	1.5
Φ_D	0.6	0.8	0.6

4.5.8.3 Relations for drag loads

As described above RispEX was originally developed with blast walls as the primary explosion target. RispEx was extended to include a separate calculation for drag in version 2.0.

The relation for drag is the same as for blast walls, but with different parameters for calculating K. The overpressure is calculated with the relation

$$\frac{D}{P_0} = \Phi \cdot K_{Drag} \cdot V_f^{p_{eV}}$$

Where the subscript D indicates the deck. As for the blast walls, the parameter K_D is determined through the relation:

$$K_{Drag} = C_D V^{p_{aV,Drag}} \cdot e^{\mathrm{conf} \cdot p_{c,Drag}}$$

As described for overpressure on decks, there are multiple potential fits for the multivariate equation above. The drag was therefore was normalized with the pressure on the blast wall and with the pressure on the decks through:

$$D_{Normalized,Wall} = \frac{D}{P_W}$$

$$D_{Normalized,Deck} = \frac{D}{P_D}$$

The normalized drag was then plotted vs volume and openness. The results are presented in Figure 4-55 and Figure 4-56.

The figures show that the drag normalized with wall pressure tends to increase with module area and is nearly uncorrelated with area openness. The drag normalized with deck pressure increases slightly with module area and decreases with module openness.

Based on the above considerations both the volume and openness parameters were fitted. The resulting parameters for decks is presented in Table 4-21

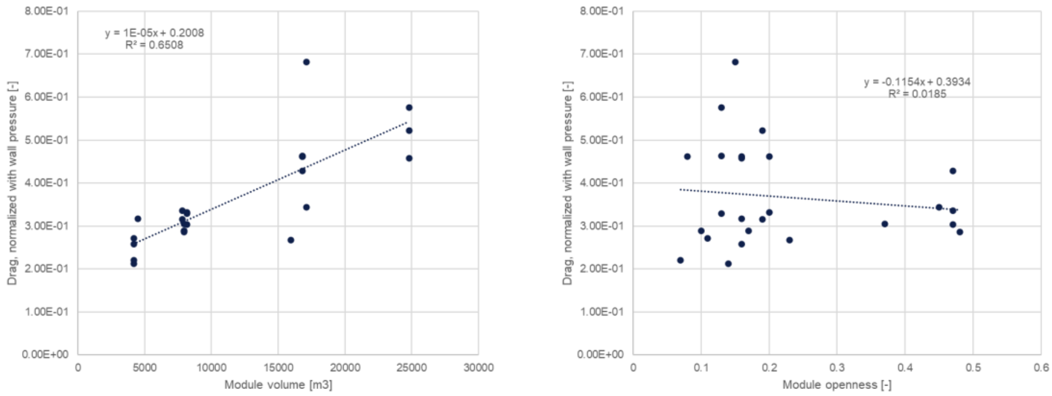


Figure 4-56 Relation between the drag normalized with local wall pressure and the volume (left) and openness (right)

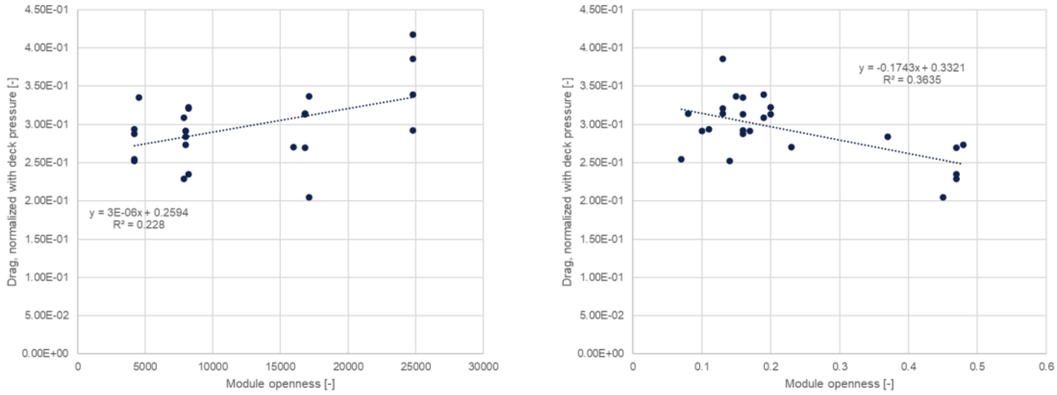


Figure 4-57 Relation between the drag normalized with local deck pressure and the volume (left) and openness (right)

Table 4-22 RispEx parameter set to determine explosion response surface drag based on volume and openness of area

Case No.	Conventional process area	FPSO process area	Wellhead area
C_{Drag}	0.00035	0.0014	0.00035
$p_{ev,Drag}$	-0.26	-0.29	-0.26
$p_{c,Drag}$	-5.2	-2.2	-5.2
$p_{av,Drag}$	1.5	1.3	1.5
Φ_{Drag}	0.4	0.6	0.4

4.5.9 Establishing the pressure exceedance curve

The cloud exceedance found for the RispEx area are transformed to pressure exceedance curve by applying the explosion response surface for the RispEx area.

The transformation uses the equation $\frac{P}{P_0} = \Phi \cdot K \cdot V_f^{p_{eV}}$ where K depend on the area volume and openness as described in the section above. An illustration of this step is given in Figure 4-58. The left plot shows the cloud exceedance curve. The middle plot shows different percentiles of the overpressure vs cloud size curves. By combining these two curves, the pressure exceedance curve to the right can be estimated.

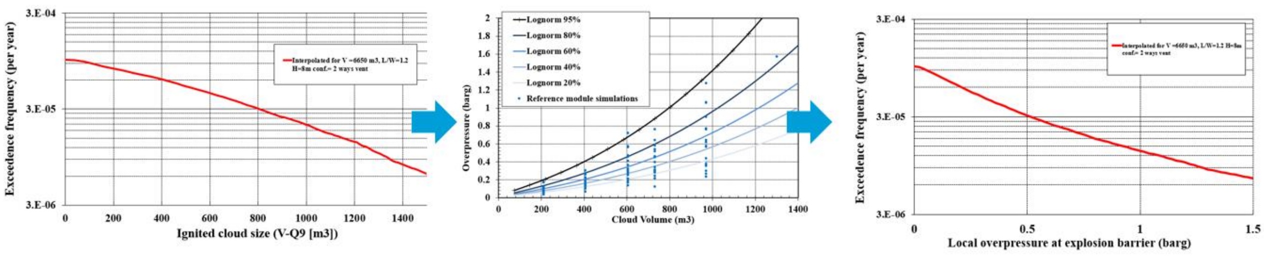


Figure 4-58 Illustration on how cloud exceedance curve can be transformed to pressure exceedance curve by using cloud volume vs overpressure relation found from explosion simulations.

4.5.10 Determining the design explosion loads

After cloud exceedance and pressure exceedance curves are established, the design ignited cloud size and leak event suggested based on the target frequency (or the scaled target frequency) can be read off the curves.

Design cloud size and design local overpressure are read off the curves established based on interpolation. The local overpressure duration, as well as the global overpressure and duration, and drag and drag duration, are determined based on the correlation factors presented in section 0.

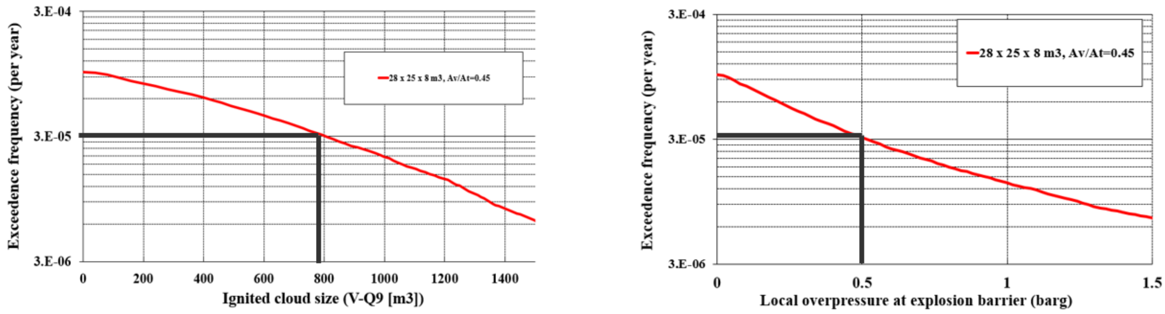


Figure 4-59 Illustration on how , the design ignited cloud size can be read off the curves at a target frequency

5 Digitalization of model

RispEx is developed as an online calculation tool with a dynamic webpage user interface. The online calculation tool is developed and delivered as a functioning standalone source code, in addition to the version hosted by DNV. The overall architecture of the RispEx calculation tool is shown in Figure 5-1.

Examples/screenshot of user interface is shown in section 3.4 and further illustrations of user interface as well as guidance for using the model is provided in Appendix A User manual. The source code is included in separate files attached to this report, and a detailed summary of the source code are given in Appendix C.

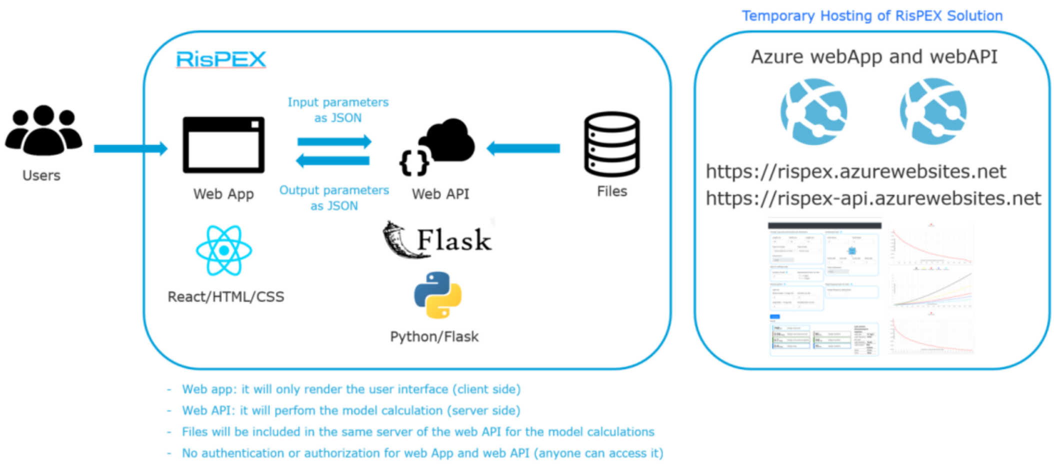


Figure 5-1 Archtecture of RispEx

6 References

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

RispEx Appendix A – RispEx User manual

Report for:
RISP Participants, att: Equinor Energy AS

JIP: Risk informed decision support in development projects (RISP)		
RispEx-decision support for explosion design loads – Appendix A: RispEx user manual		
Security classification of this report:	Distribute only after client's acceptance	
Report no: DNV report no 2020-0628	**Revision:** Rev 03	**Report date:** 22 September 2023
Prepared by: Sjur Helland, DNV	**Reviewed by:** Jens Johansson Garstad, DNV	**Approved by:** Unni Nord Samdal, Equinor

Document history

Revision	Date	Description/changes	Changes made by
Rev A	19.06.2020	Draft A, issued for comments	Jens Garstad, DNV Asmund Huser, DNV
Rev 0	17.08.2020	Updated based on comments.	Jens Garstad, DNV Asmund Huser, DNV
Rev 01A	15.10.2021	Draft. Update with process area types and large areas	Sjur Helland, DNV Jens Garstad, DNV
Rev 01	15.11.2021	Updated based on comments.	Sjur Helland, DNV Petter Vollestad, DNV
Rev 02A	19.12.2022	Draft. Inclusion of guidance on design scenario and design cloud	Sjur Helland, DNV Jens Garstad, DNV
Rev 03A	04.07.2023	Draft. Updated to reflect new drag model	Sjur Helland, DNV Jens Garstad, DNV
Rev 03	22.09.2023	Updated based on comments.	Sjur Helland, DNV Jens Garstad, DNV

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1 Application of RispEx

A key step in the process of designing a safe facility is to define Design Accidental Loads (DeAL) for explosions. Design explosion loads should preferably be defined by FEED, in order to provide input to package specifications of long lead items and provide a proper basis for cost and weight estimates.

RispEx is a tool that should be used to provide Design explosion loads for hazardous areas at offshore facilities (process and wellhead areas) based upon key drivers of explosion risks which at the same time defined knowledge already within FEED. Application of RispEx is further described in section 3.9 of the main report.

RispEx is a tool located on a dynamic web site. Note that a Veracity user is required to access RispEx, and access must be granted to each user.

In summary, the primary purpose of RispEx is to provide design explosion loads that can be defined within FEED phase and followed up throughout the design and operation life of the facility, including:

- **Design Accidental Load in terms of local explosion loads to main physical barriers** separating the area from neighboring areas. Local explosion load to walls and decks are given in the format of 4x4 m^2 panel overpressure and associated impulse durations. In application/implementation of the load the most vulnerable 4 by 4 m^2 section of the wall or deck need to remain in function throughout the explosion event.
- **Design Accidental Load in terms of global explosion loads to main physical barriers** separating the area from neighboring areas. Global explosion load to walls and decks are given in the format of panel overpressure covering the entire wall or deck, and associated impulse durations[1]. In application/implementation of the load the most vulnerable 4 by 4 m^2 section of the wall or deck need to maintain in function throughout the explosion event.
- **General Design Accidental drag loads for the area.** The drag loads are relevant for piping and structural elements with dimensions less than 0.5 m in cross section/ diameter. Drag loads are given in the format peak dynamic pressure within the area and associated impulse duration. A curve providing reduced loads for larger affected areas is provided, however this model is currently on HOLD . In application/implementation of the load all pipes and structural elements/units located within the area and in proximity to the ventilated sides can be considered potentially exposed to the drag load. A reduction factor within sub-areas/zones of the area and/or related to a distance from the ventilated opening is not included in this version of the tool.

Detailing of the design explosion loads are not defined for the current version of RispEx. In addition to Design Explosion loads, the tool provides example of accidental explosion event that are expected to cause loads of similar magnitude as the Design Explosion loads defined for the area. The accidental events provided by RispEx can be used by development project for e.g. ALARP assessment, design optimizing and management of change purposes. The actual process for application of the accidental events are not defined for the current version of RispEx. For certain assessments/required decision support it might not be sufficient with the accidental scenarios provided, and other analysis or methods may be required.

When describing the input and output in this user manual, input parameters are marked in **blue**, while output parameters are marked in **red**.

1 Global DeAL impact area: As global failure mechanisms may occur upon exposure to smaller sections than the entire wall, and the simulated overpressure to a smaller section of the wall is typically higher than the simulated overpressure to the entire wall, the simulated global loads are based upon monitor panels that in vertical direction typically range from deck level up to the ceiling, and in horizontal direction typically extend 14 meters in length.

2 Validity envelope and input

2.1 Validity envelope for overall concept design

This section describes which types of concepts and areas RispEx is valid for. The required design and layout restrictions that needs to be in place in order to provide valid Design Explosion loads for the area with RispEx is described. How to interact with the tool to get the required output results is also described.

Validity envelope for when RispEx are valid is described in section 3.6 in the main report. The validity envelope contains requirements to the area / facility in general, such as related to function of facility and area, layout constrains, performance requirements of safety systems etc. In addition, the validity envelope contains constrains on input, i.e. predefined intervals for the input for which the output can be considered valid.

A summary of the overall concept design validity envelope is provided in Table 2-1.

Table 2-1: Validity envelope, overall concept design

Validity envelope dimension	Requirements
Overall concept and design	Design according to PSA requirements and NORSOK S-001 Design according to ISO 13702 Naturally ventilated areas Areas that does not contain HPHT equipment. Concepts with natural gas only. RispEx is not valid for concepts with more reactive or heavy gases such as hydrogen or LPG/LNG. Minimum 2-ways ventilated areas (Minimum two naturally ventilated sides of the area. In areas with only two ventilated sides, they should be located on opposite sides, i.e. not a area with L-shaped configuration of blast walls) Wind speed distribution similar to Norwegian Continental Shelf (typical)

2.2 User interface and general functionality

When accessing the dynamic web site containing the tool the user are provided the user interface as shown in Figure 2-1. The user needs to enter all required input fields and press calculate. Upon clicking calculate, all the output from the tool is provided below the input fields. By pointing the mouse cursor above the icon at the top of each input field region, a help text comes up as shown in Figure 2-2 providing short guidance on how the input should be defined.

When entering a combination of input not supported by RispEx, for which the tool is not able to produce and return validated results, an error message is return in the dialog box. An example is provided in Figure 2-3.

When entering input with values not within the validity envelope, the tool will still produce and return results. However, a warning message is return in the dialog box. An example is provided in Figure 2-4. Use of RispEx outside the validity envelope is not recommended and will be on the user’s own responsibility.

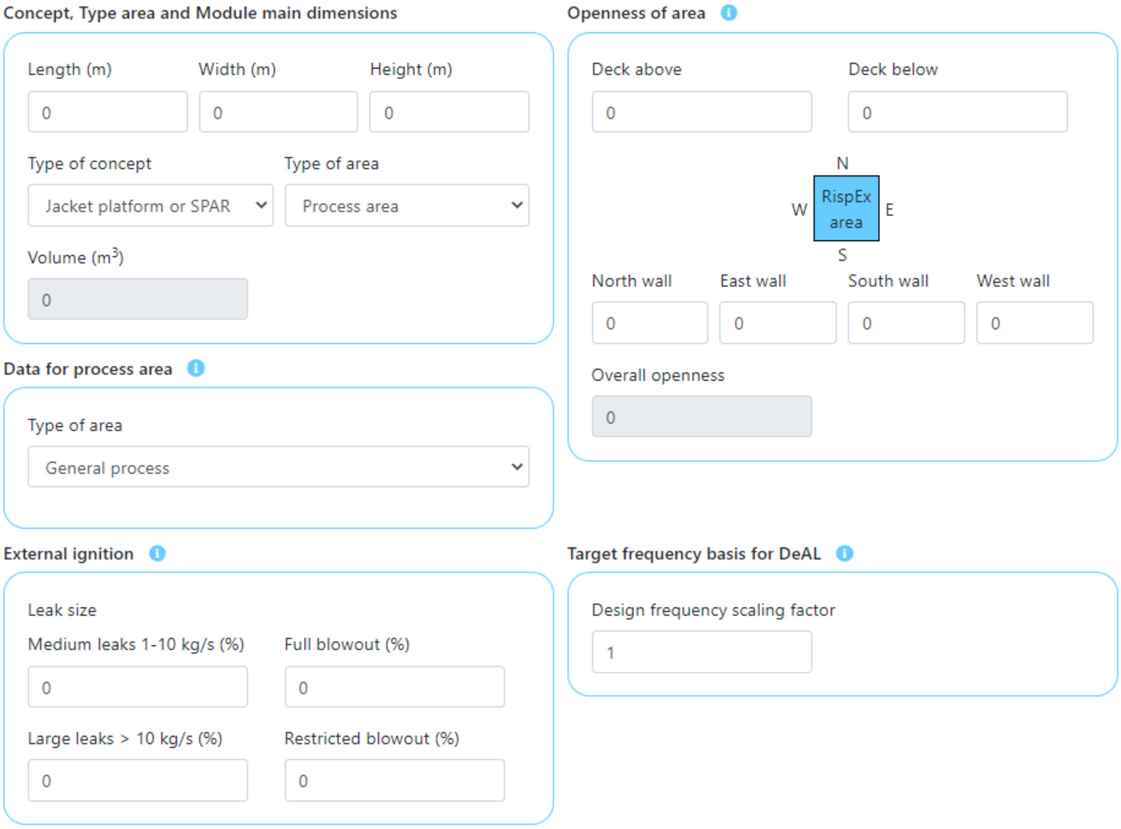


Figure 2-1 User interface of RispEx

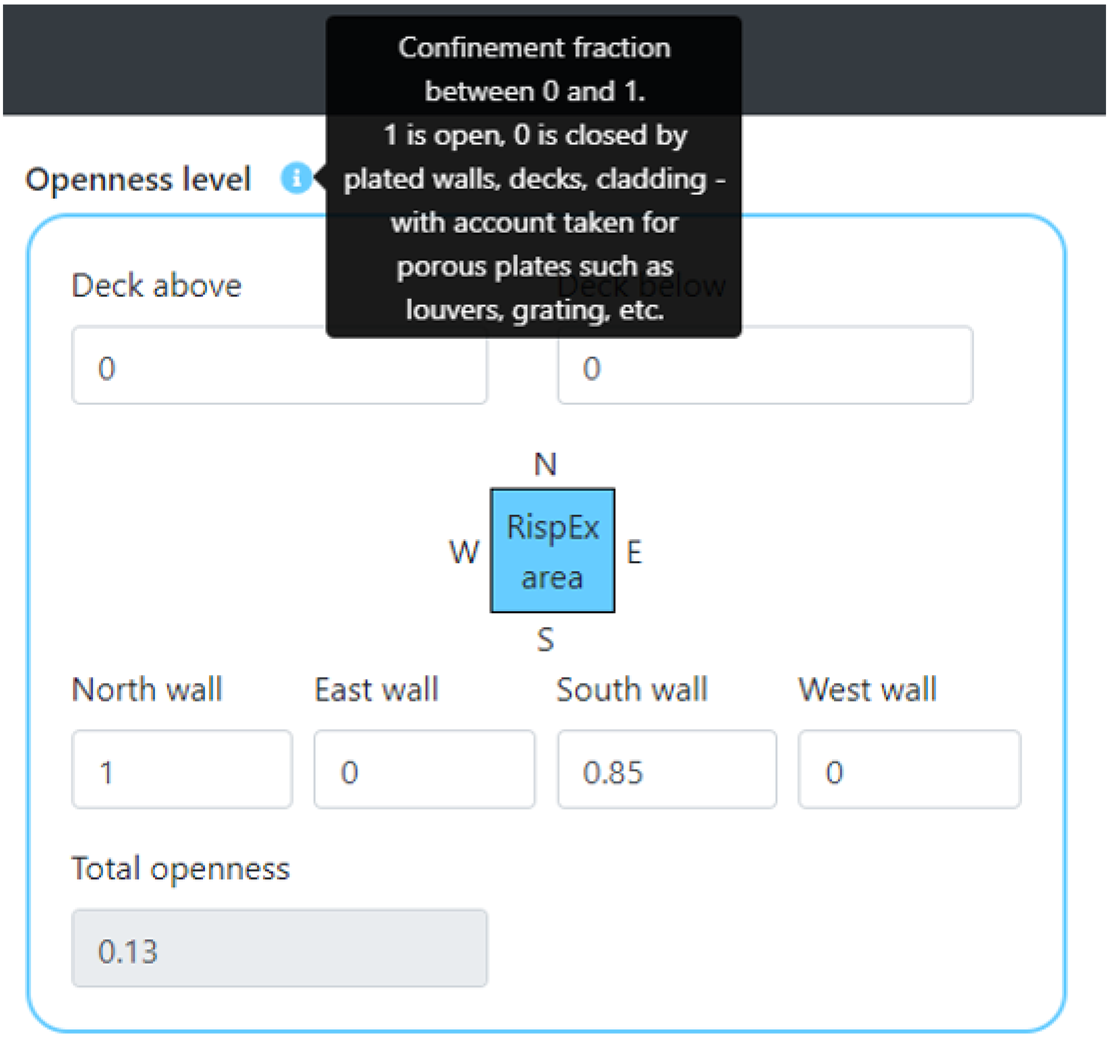


Figure 2-2 Example of help text in RispEx tool

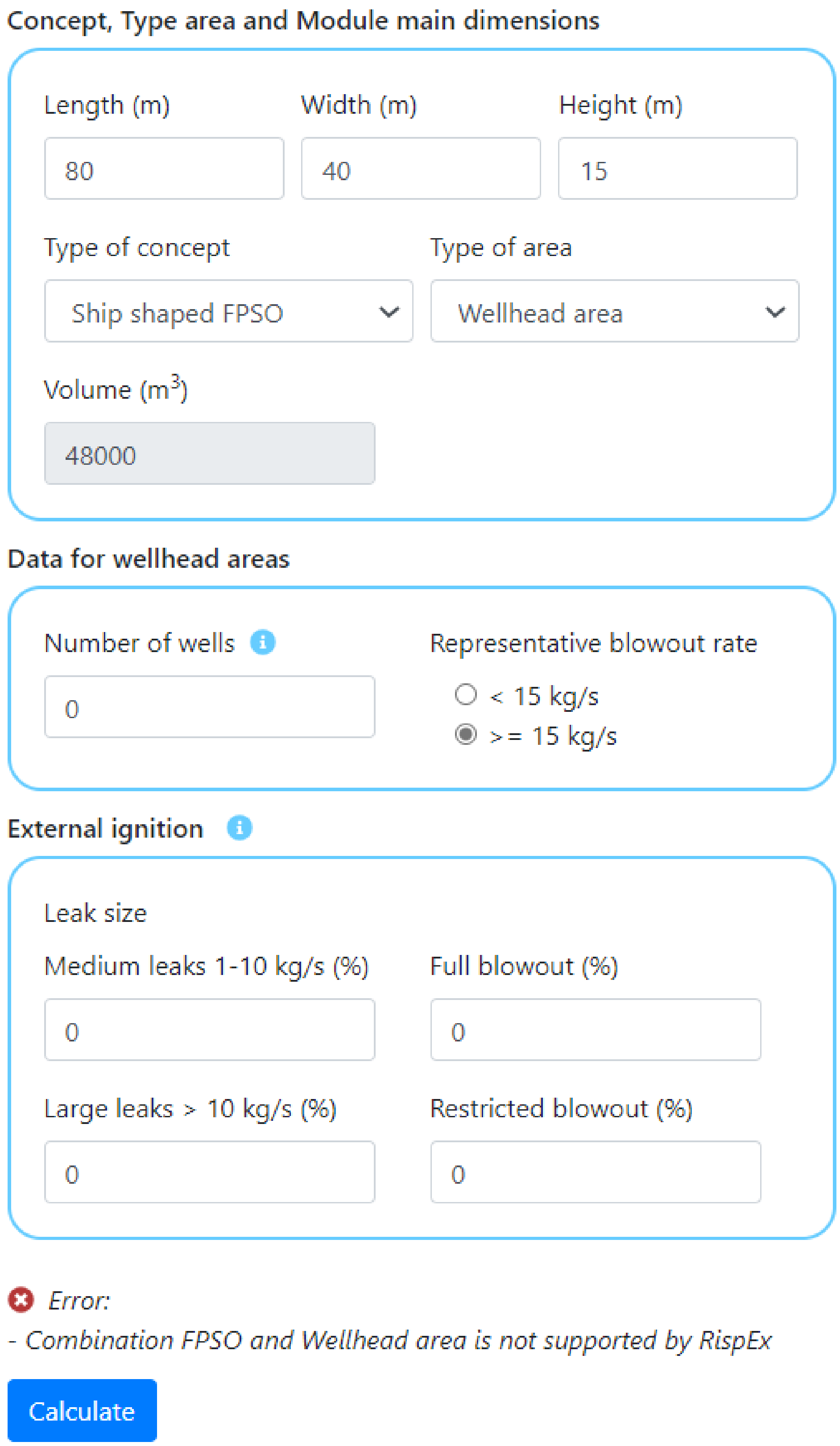


Figure 2-3 Example of error message returned when input is not supported by RispEx tool

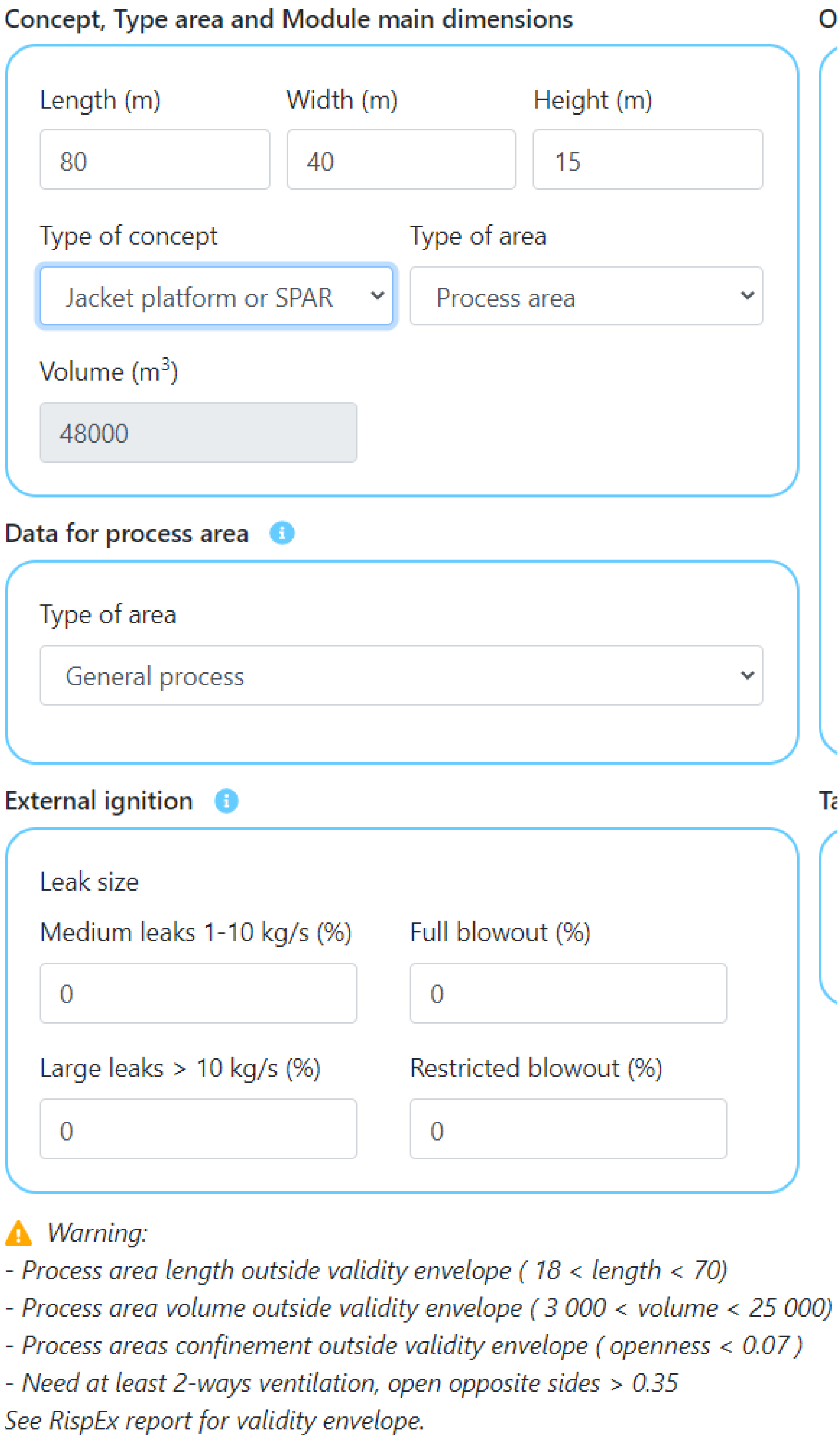


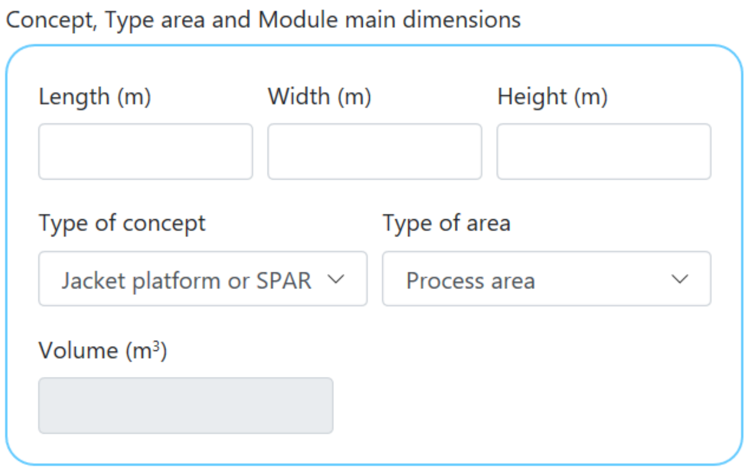
Figure 2-4 Example of warning message returned when input values are not within validity envelope (results will still be produced and visible)

2.3 Definition of input parameters

Input to the RispEx tool is described in section 3.4.1 in the main report. A summary of the overall validity envelope for individual input parameters (e.g. Length) or for combination of input parameters (e.g. volume) is provided in Table 2-2.

The following guidance are given in order to correctly define the input parameters in line with requirements and basis of the tool:

The first input field region of the RispEx tool contains type of concept and area, as well as dimensions of area:



Type of concept:

Two different concept definitions are available for selection in the current version of the tool

- Ship-shaped FPSO: Includes weather-vaned ship shaped FPSOs.
- Jacket platform / SPAR: Includes module based topside modules on offshore facilities with fixed orientation. The wind rose used as basis is typical North sea wind rose, but there is no fixed requirement related to actual orientation. The basis of the tool is that there is a firewall towards the direction for which prevailing wind comes from.

The wind rose applicable for the basis of RispEx is shown in Figure 2-5. However, for both types of concepts, deviation of the orientation of the facility relative to the prevailing wind direction is acceptable, since the basis of the tool is that there is a firewall towards the direction for which prevailing wind comes from, hence results can be considered conservative for any deviation from this. However, for all types of concept, caution must be taken when wind speed distribution significantly differs from typical north sea wind speed distribution. Higher fraction of low wind speeds will reduce ventilation rate compared to what is defined as basis of the tool and may result in optimistic results.

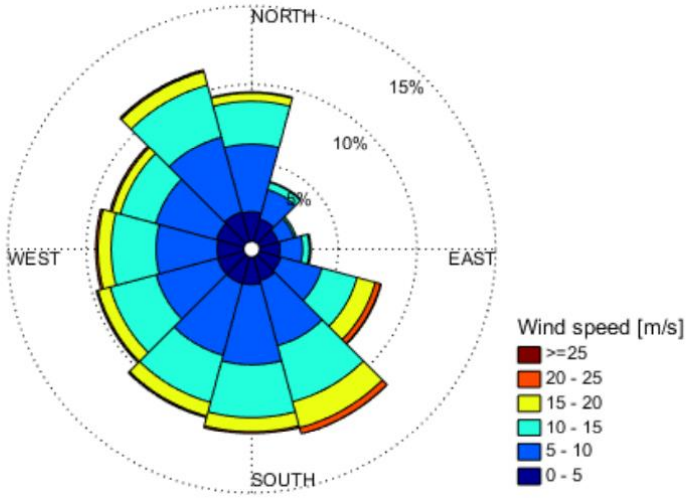


Figure 2-5 Wind rose used as basis for RispEx

Type of area:

Two types of areas are supported for Jacket platform / SPAR design, and one type of area is supported for FPSO design:

- Hydrocarbon process area is supported for all types of concepts. The process area may include all types of hydrocarbon process functions. RispEx supports different types of hydrocarbon process areas through predefined area types. If parts of the area contain process utilities or other utility equipment, the calculated design loads may be considered conservative.
- Wellhead area is only supported for Jacket platform / SPAR concepts. Wellhead area in this context contains wellheads, X-mas trees, flowlines, manifolds such as production manifold, test manifold, gas-lift manifolds, injection manifolds. Production wells, also including wells with artificial lift, is valid. Other types of wells such as gas injection, water injection and/or WAG wells are also valid. Only limited amount of other type of process functions can be included such as one test separator and one metering skid.

Dimension parameters:

The dimensions defined for the area is the congested region included within the outer load-bearing structural members of the module frame. The area is limited by firewalls, either in terms blast wall functioning as physical area barrier, walls of escape tunnels or other type of, or structural frame members, normally not including the exterior walkway. The exception is if there is more than 3 meters of congested region with equipment and or piping on access balconies or cantilevers outside the outer walkways. In that case, the dimensions of the area should be extended to include the congested region outside the walkways. Apart from this, the dimensions are defined as follows

- **Length** – measured along the FPSO or "along" topside facilities as illustrated in Figure 2-6 and Figure 2-7. For the RispEx explosion loads to be valid, there needs to be a fire wall either at West boundary and/or East boundary of the area. Length parallel to the firewall(s) in the area.
- **Width** – measured "across" the FPSO (starboard to portside) or "across" topside facilities (North to South) as illustrated in Figure 2-6 and Figure 2-7. For the RispEx explosion loads to be valid, the process area needs to extend across the entire vessel/facility with both the Starboard/Portside (or North/West) side of the area naturally ventilated without walls that obstruct the ventilation entirely. Width orthogonal to the firewall(s) in the area.

- **Height** – measured from plated deck level up to the ceiling above the area, or where the congested region ends for weather deck type designs.

Non-rectangular areas can be reflected based on representative dimensions Length, Width, Height which give the volume corresponding to the L shaped area , as long as the length and width do not deviate from the projected length and height of the L shape area with more than 10%.

An intermediate result calculated based on the dimensions and used for interpolation in the RispEx engine is the area **Volume.** This is simply the Length*Width*Height.

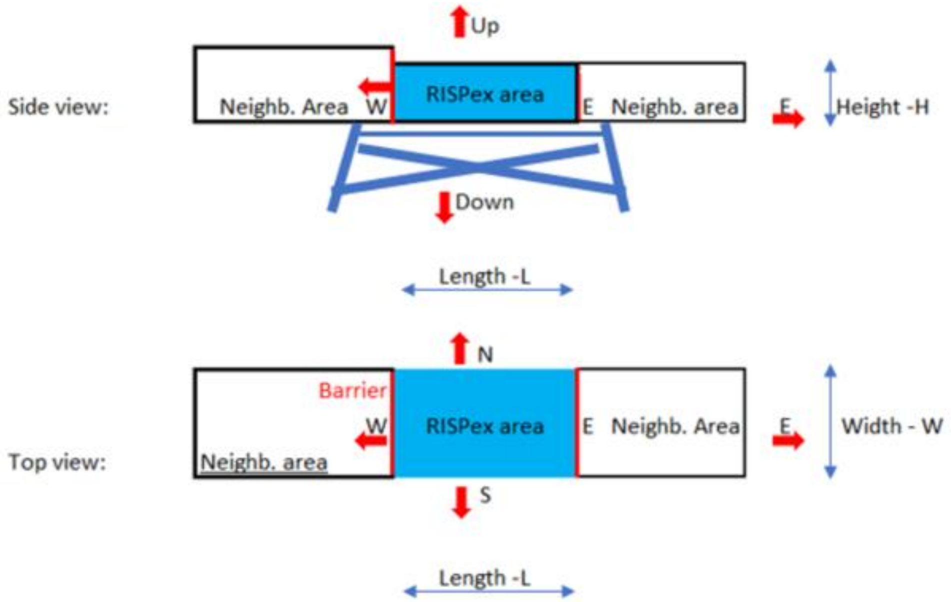


Figure 2-6 Representative configuration of a 2-ways ventilated area for conventional process area and wellhead area (open towards Platform North and Platform South). Despite not shown in the illustration, there may be deck levels above and/or below the RispEx area. For 3-ways ventilated areas, the side of the RispEx area towards the area denoted "Neighb. Area" toward East is removed, and the East side naturally ventilated as well. For 4-ways ventilated areas, the RispEx area will in addition not have a plated deck plate or ceiling upwards. There may be laydown areas and/or plated or grated access balconies above the process area for 4-ways ventilated areas. This will be reflected by the confinement level parameters in upwards direction.

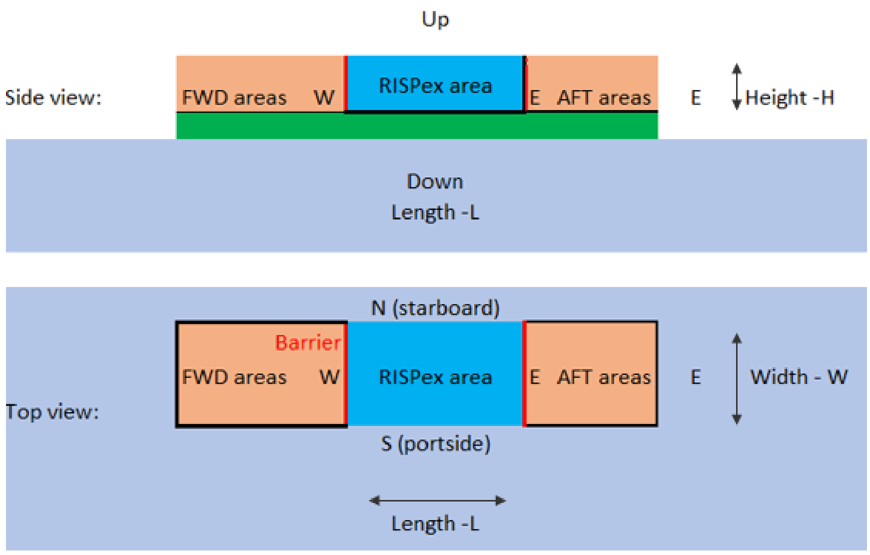
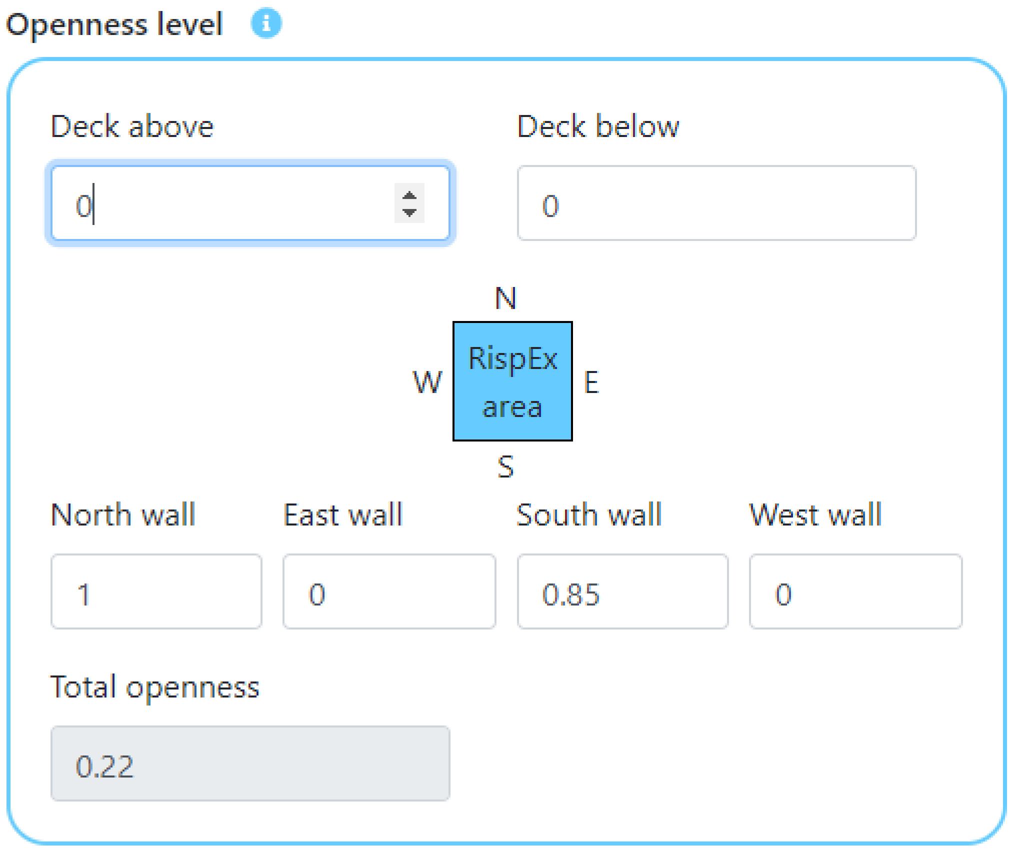


Figure 2-7 Representative configuration of a 3-ways ventilated area on an FPSO (open towards Starboard, portside and up). On this drawing, the turret is to the left (not shown).

Confinement/Openness parameters:

The next input field region of the RispEx tool contains openness levels per side of area, as well as displays the intermediate output result "Total Openness" of the area:



The openness of the area is defined per side of the area, for the sides Deck above, Deck below, North wall (for FPSO this correspond to starboard side of process area), East wall (for FPSO this correspond to side of process area towards AFT), South wall and West wall.

Openness per side of the area is entered as a value from (and including) 0 to (and including)1. 0 is fully plated. 1 is fully open. A value between 0 and 1 denotes the fraction of the given side which is covered by plating/cladding etc. Louvers and grating should also be reflected when the user input a confinement level value. Then the user must take account for the openness of the louver or grating. A confinement level value of 0.5 may be used for regions fully covered by louvers, and a value of 0.7 may be used for regions fully covered by grating.

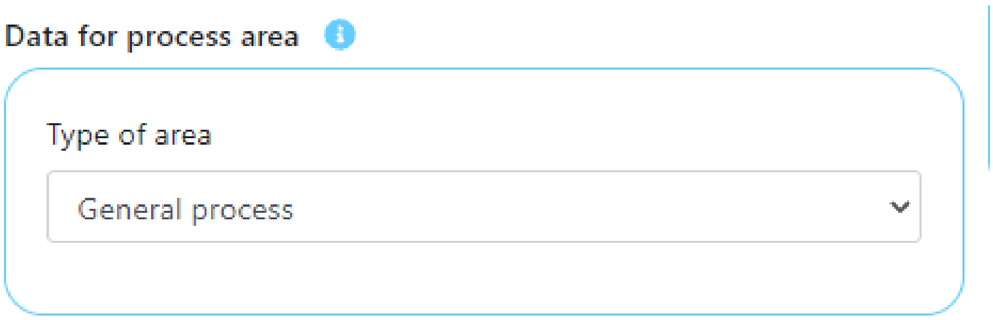
An important aspect of the defined openness is that only decks, cladding, walls or other solid or porous plates intended for shielding should be taken account for when defining the openness value. Various obstruction from piping, equipment, structural elements or other objects should not be accounted for. Based on this, the openness due to the defined confinement level value should be higher than the effective openness of the ventilated side. The reason for this is to prevent the need for an estimation of what the openness will be due to various piping and equipment in an early part of the development project. Hence, only objects intended for shielding such as weather cladding and solid walls needs to be predicted when assigning confinement level as input. Apart from this, the confinement levels per side are defined as follows

- **Deck above** – Confinement level between 0 and 1. For area with a fully plated ceiling the confinement level for deck above is 0. For weather deck type areas with openings in vertical direction, the confinement level will correspond to the fraction of the top of the congested region that is open upwards. When the ceiling is not fully plated, a confinement level below 1 will typically be caused by access balconies, smaller deck for specific equipment or units located on it (such as cooler deck above compressors, run-down tanks, tote-tanks etc) or other intermediately sized decks such as laydown areas. Since these types of decks will not be likely to be located at the exact same elevation, the confinement level may be calculated based on the projected area of any plated or grated decks partly covering the area within the top $1/3^{rd}$ vertical part of the area. As an example, a 5 x 10 m^2 deck 6 meters above the deck level on a weather deck type area with footprint 500 m^2 will reduce the confinement level value by 50/500 = 0.1. If the deck is grated with an openness of 50%, the confinement level would be reduced by 0.5*50/500 = 0.05.

- **Deck below -** Deck plate below area needs to be plated in the current version of RispEx tool, hence this parameter will always be set to 0 or close to 0. Small openings or grated fractions acceptable when the area is located at cellar deck level. An openness beyond 10% (corresponding to 0.1 in the tool) is outside the validity envelope.
- **North wall** – walls or cladding at the area boundaries, i.e. supported to module frame inside the exterior walkway should be reflected. Some concepts have the cladding, or additional cladding outside the walkways or at the outer boundary of the cantilever balconies. This cladding should also be counted. The projected area of the "inner" and "outer" cladding should be taken into account. This will be the cladding or walls seen when looking into the area from outside the facility.
- **East wall** – similar as for North wall. Exception is if firewall, confinement level = 0. East and/or west wall need to be fire wall.
- **South wall** – similar as for North wall
- **West wall** – similar as for East wall

Type of process area

The next input field region of the RispEx tool contains data for process areas (and by definition is applicable only for process areas).

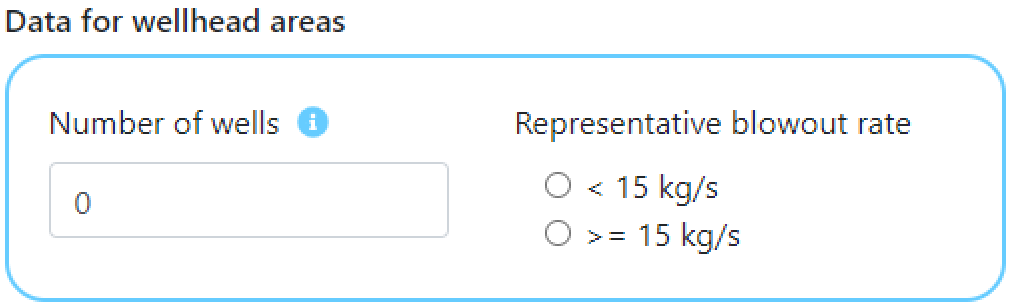


The data for process areas contains a dropdown menu with the following options:

- **Gas processing:** An area containing predominantly hydrocarbon gas processing equipment such as compression or gas treatment areas.
- **General process:** An area containing a mix of oil and gas processing equipment.
- **Oil separation:** An area containing two-phase lines and separators, but limited or no gas processing equipment.
- **Oil processing:** An area containing oil processing equipment such as oil stabilization and export pumps, but limited or no two-phase or gas processing equipment.

Number of wells, Representative blowout rate

The next input field region of the RispEx tool contains data for wellhead areas (and by definition is applicable only for wellhead areas). It can be left empty or be populated when producing explosion loads for process areas, without being reflected in neither case:



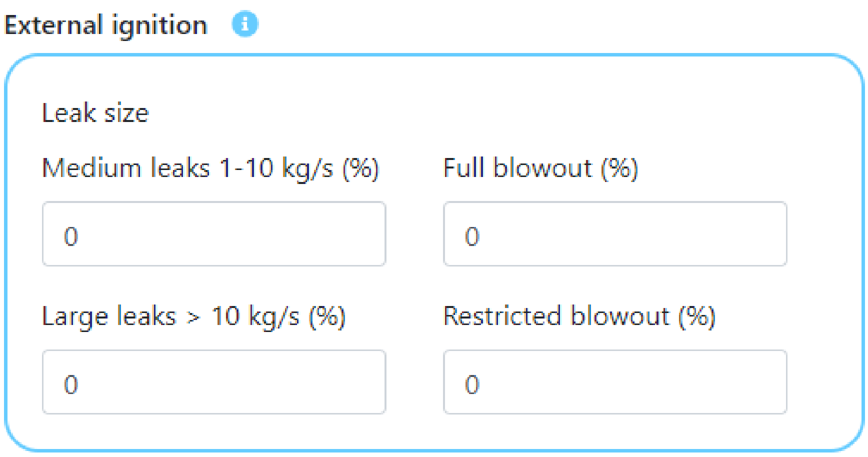
The data for wellhead areas contains following fields

- **Number of wells:** This is the number of wells both including producing wells as well as gas injection or WAG wells. Water injection wells do not need to be included. The number of available slots that potentially may be used for hydrocarbon production and/or gas injection should each be counted once, in order for the explosion loads to be defined for the full lifetime of the facility. The number of wells are used for frequency estimates within the RispEx tool, which result in scaling of the cloud size vs frequency curve and the overpressure vs frequency curve.
- **Representative blowout rate:** The consequences of a blowout with release within the wellhead area is very dependent on the hydrocarbon release rate caused by the blowout. Furthermore, the blowout rate is very reservoir specific. To be able to reflect this effect in the defined explosion loads, two different blowout rate categories are available for selection; is the typical blowout rate below 15 kg/s for a full blowout when counting release rate of gas and volatile liquid, or is the typical blowout rate above 15 kg/s.

External ignition:

The potential for external ignition is dependent on the presence of any strong external ignition sources, as well as the location of the external ignition sources relative to the RispEx area and the associated exposure probability upon a hydrocarbon leak in the RispEx process or wellhead area. Leaks ignited externally would increase the explosion risk, and should be reflected in the design explosion loads, but these scenarios are not included in the RispEx basis curves.

For this reason, RispEx provides an option of including explicitly the probability of ignition due to external ignition sources given leak of a certain size:



The leak size categories or leak types that external ignition can be defined for is external ignition probability given:

- **Medium leaks 1-10 kg/s**
- **Large leaks >10 kg/s**

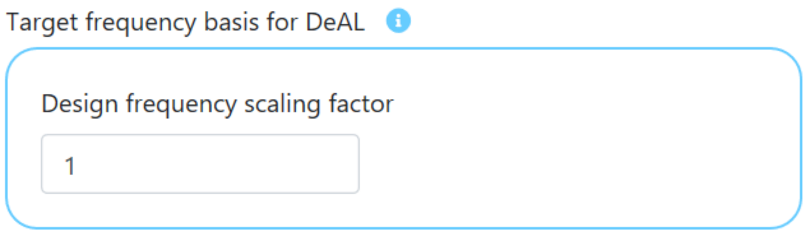
- **Full blowout**
- **Choked blowout** (choked blowout is in RispEx assumed to have a release rate 20% of the release rate from a full blowout)

Note that the external ignition probability for the blowout scenarios are only applied for wellhead areas.

There is no required way to calculate the external ignition probability for the 4 categories, but the following approach is possible:

1. Assign 1-3 sub-scenarios within the given leak category and assign a probability for each of the sub-scenarios as well as a representative release rate per sub-category. The sum of the probabilities of the sub scenarios must be 1. There is also possible to define a representative release duration or release profile per sub-scenario depending on the preferred level of detail of the assessment and/or how precise knowledge is available for the potential leak scenarios within the RispEx area.
2. Assign 1-8 representative wind directions and a probability per wind direction based on the wind rose/metocean data, for which the sum should 1.
3. Assign 1-4 representative wind velocities per wind direction, and a probability per wind velocity per direction. The sum of all velocities associated with each direction should be 1
4. Assign an ignition probability per combination of sub-scenario (release rate), wind direction and wind speed, and sum up the contribution from all the combinations to find an estimate for the overall external ignition probability given a leak in the defined category. Assigned ignition probability per combination may be estimated in a simplified way or based on exposure probability found from CFD dispersion simulations in combination with ignition probability upon exposure as suggested in the MISOF2 report. For combustion air intake without flame arrester to diesel engine or gas turbine, it is considered ok to apply an ignition probability of 0.5 given exposure.

Scaling of target frequency:



In RispEx the design explosion load is based upon a predefined target frequency. When this scaling factor is set to 1, the design explosion load is returned directly in the output fields. In order to be able to evaluate how sensitive the design explosion loads are with respect to the defined target frequency, it is possible to adjust the target frequency with a scaling factor to see the effect on the Design Explosion loads. As example: If the target frequency is 7E-5, then a scaling factor of 2 will return the explosion loads with an associated return frequency of 1.4E-4, and a scaling factor of 0.5 will return the explosion loads with an associated return frequency of 3.5E-5.

Two alternative applications of the scaling factor may be

- If design explosion load is defined as total frequency of all areas sharing a common main area boundary should add up to the target frequency, then a Design frequency scaling factor 1/N may be used per area when N areas within the same main area are sharing a common main area barrier.
- If the project wishes to include a frequency based contingency on the Design explosion load, this can be achieved by applying a design frequency scaling factor below 1. A scaling factor of 1 provides the minimum DeAL value (dimensioning load + a margin defined by the RISP steering committee), and a scaling factor below 1 will add additional margin.

The valid region for all input parameters in order to produce valid design explosion loads as output is summarized in Table 2-2.

Table 2-2: Validity envelope: constrains on input, i.e. predefined intervals for the input for which the output can be considered valid as well as fixed input

Validity envelope dimension	Requirements
RispEx user input parameters	<u>Dimensions, FPSO concepts:</u> Area volume: *30 000 - 70 000 m³* Area length: *30 - 120 m* Area width: *range to be included 30 – 60 m* Area height: *range to be included 8 – 25 m*
	<u>Dimensions, Process areas - other concepts:</u> Area volume: *3 000 - 28 000 m³* Area length: *18 - 70 m* Area width: *range to be included 18 – 50 m* Area height: *range to be included 5 – 20 m*
	<u>Dimensions, Wellhead areas - other concepts:</u> Module volume: *3 500 - 13 000 m³* Module length: *20 - 25 m* Module width: *25– 44 m* Module height: *7– 15 m*
	<u>Openness:</u> Firewalls: Openness 0 Lower deck: Openness 0- 0.1 Open/partly open sides: Openness 0-1 Top deck/roof: Openness 0-1 Note that some restrictions to the confinement levels per side in RispEx is that the floor deck needs to be 0-10% open, and two adjacent vertical sides (e.g. both the North and South sides) both needs to have openness > 0.35. Confinement level overall for FPSO concept: >0.18 Confinement level overall for other concepts: >0.07
RispEx fixed input parameters	Minimum blowdown time; 15 min to 6.9 barg Gas detector design/density according to NORSOK S-001 Design of ESD system according to NORSOK S-001 Reliability of safety systems according to NORSOK S-001
	Max closing time ESD valves: 30 sec Maximum number of hot work hours: 100 hours hot work class A in habitat

	Congestion within “Normal” levels *

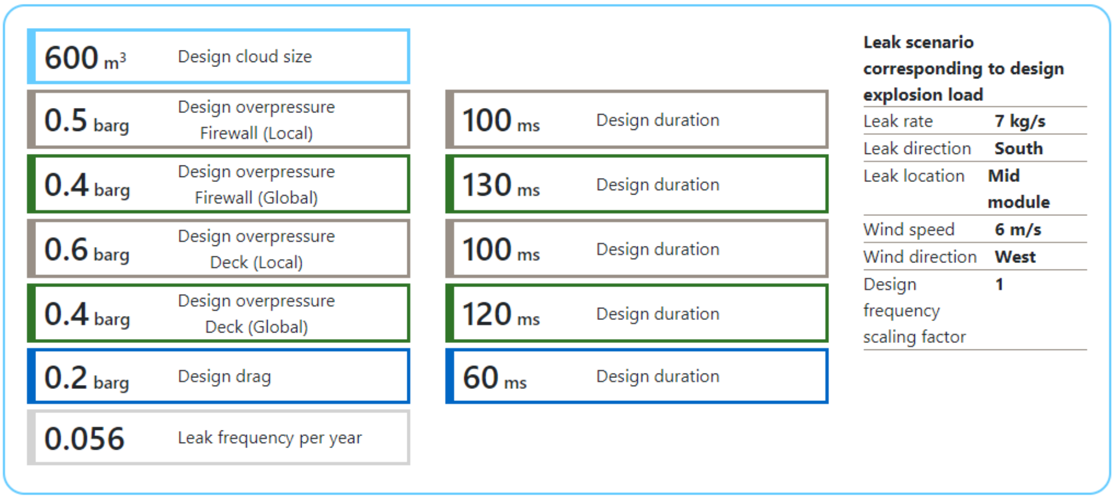
* RispEx is not valid for very congested areas or special geometries that will give high explosion loads. This should be a part of the assessment in HAZAN and need to be followed up throughout the development project

3 Definition of output parameters

3.1 Definition of output parameters

The key output field region of the RispEx tool contains Design explosion loads for the area as well as description of a typical scenario that are expected to result in consequences corresponding to the defined DeAL explosion:

Results



The key design explosion loads summarized in the introduction to this guideline are:

- **Design over-pressure Firewall (Local)** and associated **duration**
- **Design over-pressure Deck (Local)** and associated **duration**
- **Design over-pressure Firewall (Global)** and associated **duration**
- **Design over-pressure Deck (Global)** and associated **duration**
- **Design drag** and associated **duration**

Design cloud size is the equivalent stoichiometric ignited cloud size associated with the same return frequency as the design explosion loads.

The **Leak scenario for design explosion** is giving leak release rate, direction, location and wind condition for a leak event which is predicted to result in consequences (cloud size and overpressures/durations) in line with the Design explosion loads. Note that the leak rate is expressed in terms of an equivalent gas release rate.

The **Design cloud size** and the **Leak scenario for design explosion** can be used in development projects e.g. as part of Risk Management process. Guidance on the use of the leak scenario is provided in 3.2.

Several plots are given as output in addition to the design explosion loads and the defined leak scenario. The following plots are provided:

- The frequency vs ignited cloud size curve
- The relationship between the ignited cloud volume and the local explosion overpressure to walls
- The relationship between the ignited cloud volume and the local explosion overpressure to decks
- The relationship between cloud volume, equipment cross section area and drag
- The frequency vs local explosion overpressure to walls

- The frequency vs local explosion overpressure to decks
- The frequency vs point drag

Examples of these three figures are given in Figure 3-1, Figure 3-2, Figure 3-3 and Figure 3-4. As shown on the figures, it is possible to read off exact values on the curve by holding the mouse cursor above the plot.

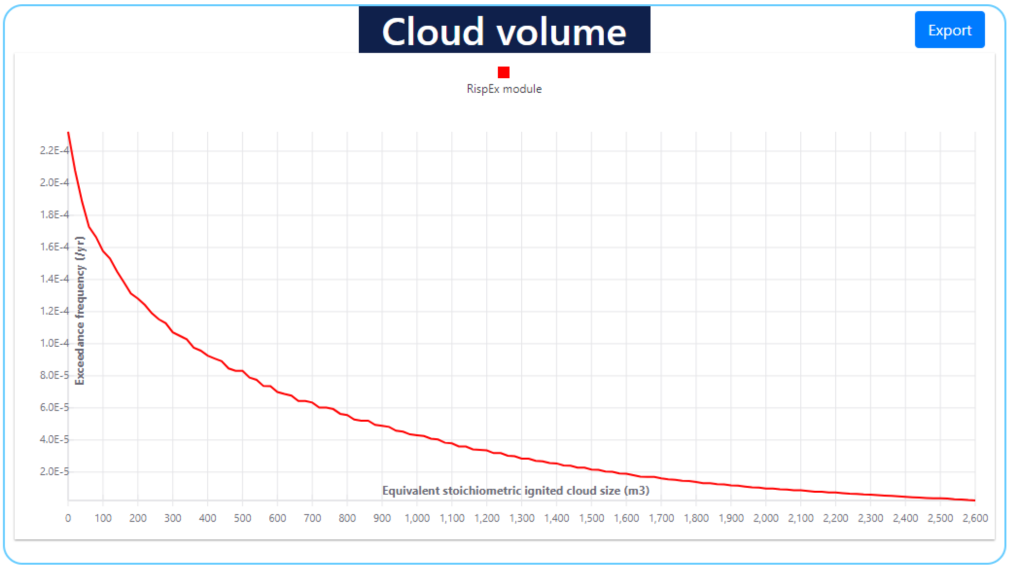


Figure 3-1 The frequency vs ignited cloud size curve estimated for the RispEx area

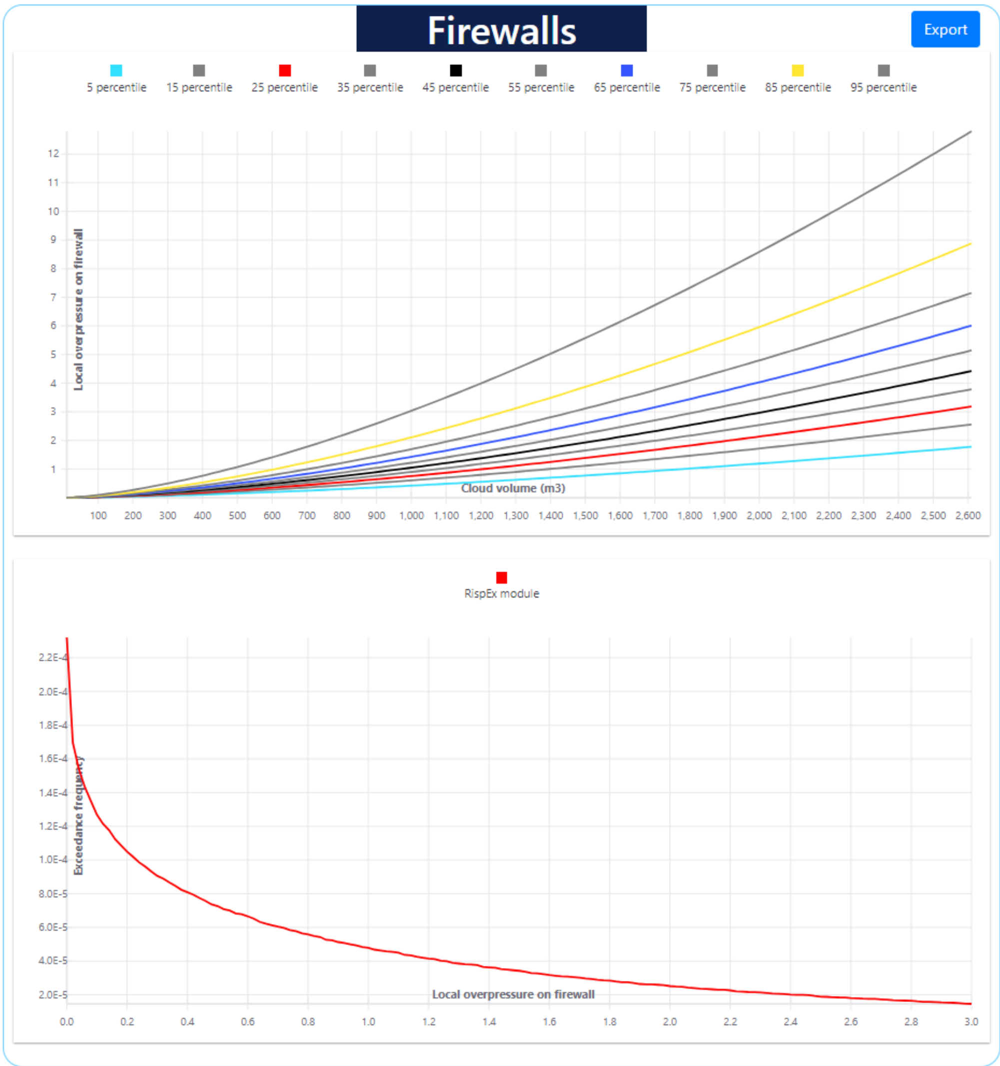


Figure 3-2 The relationship between the ignited cloud volume and the local explosion overpressure to walls (top) and the frequency vs local explosion overpressure to walls curve (bottom) estimated for the RispEx area

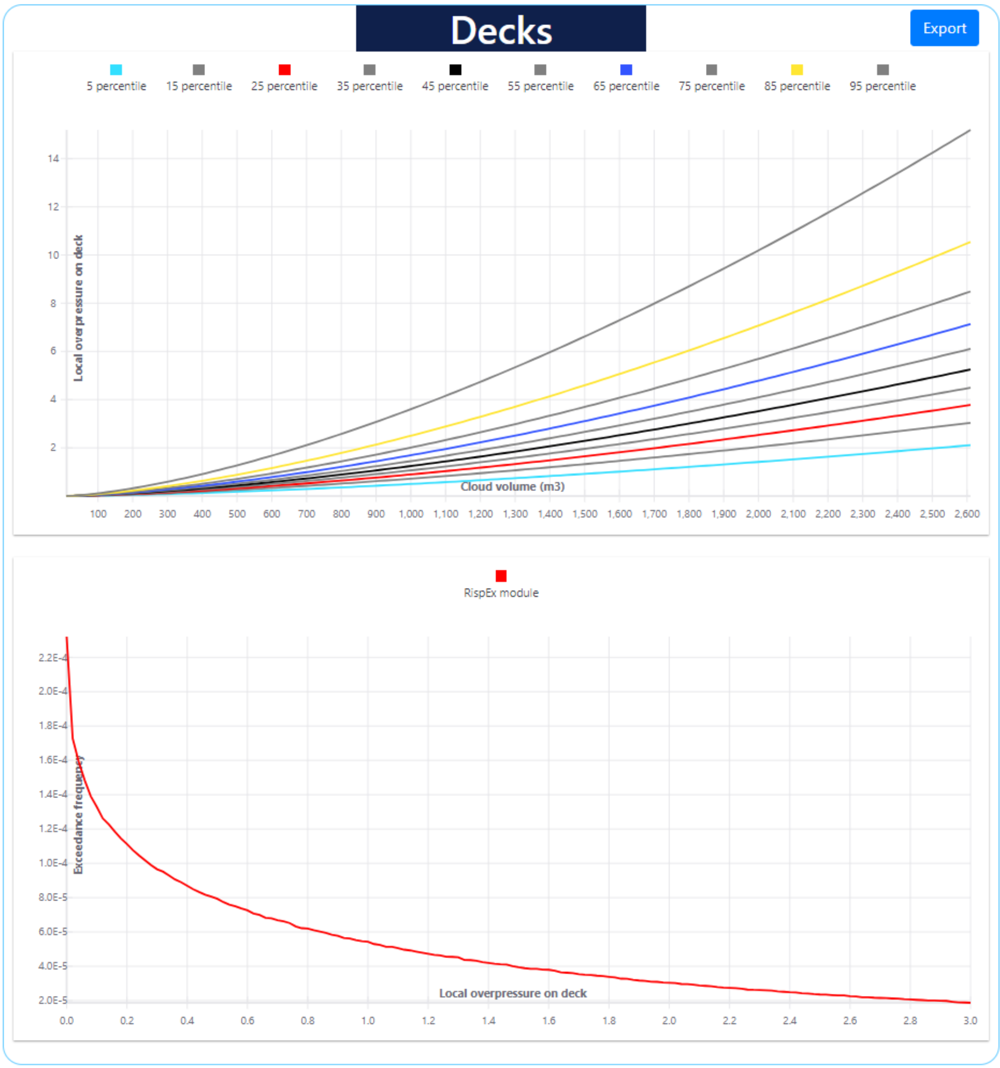


Figure 3-3 The relationship between the ignited cloud volume and the local explosion overpressure to decks (top) and the frequency vs local explosion overpressure to decks curve (bottom) estimated for the RispEx area

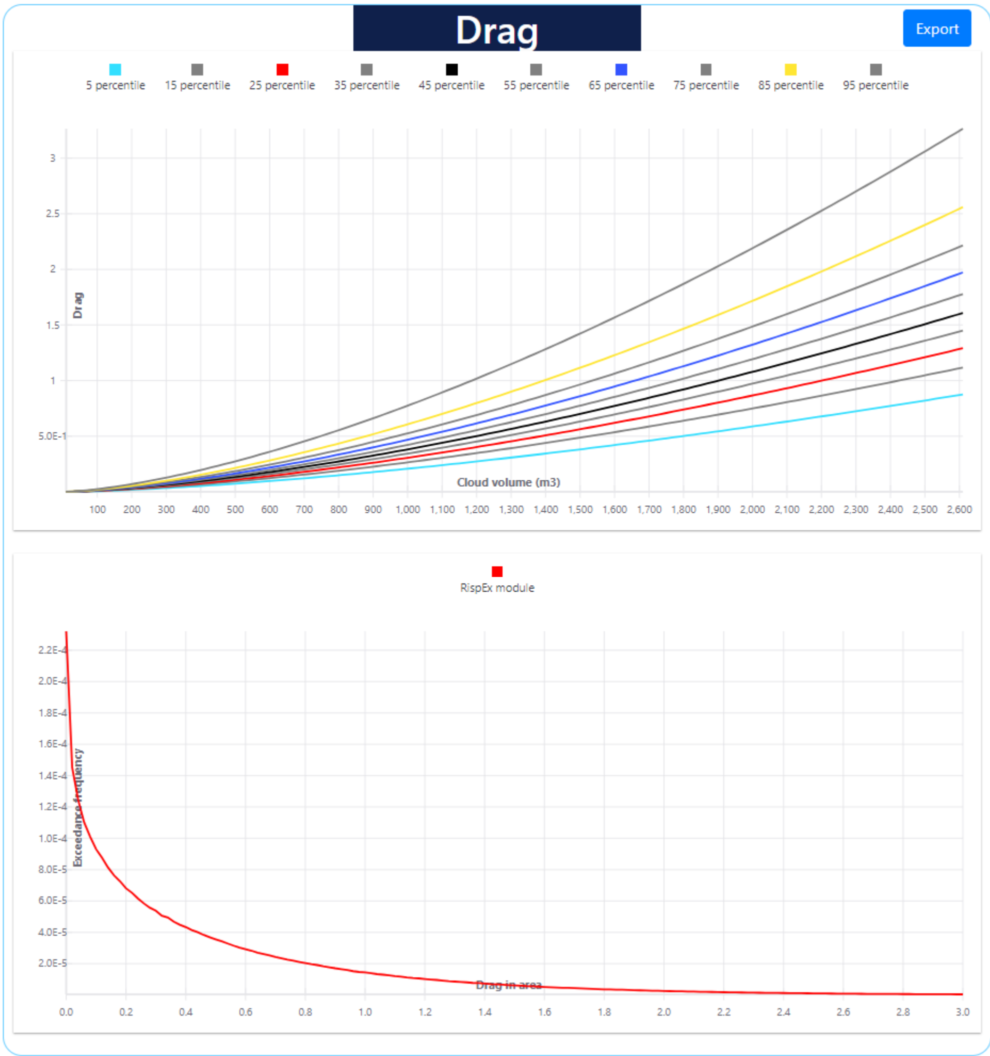


Figure 3-4 The relationship between the ignited cloud volume and the drag in the area (top) and the frequency vs drag in the area curve (bottom) estimated for the RispEx area

3.2 Use of design leak scenario and design cloud size

The exceedance curve generated by RispEx represents all potential wind conditions and releases scenarios. The **Leak scenario for design explosion** is one potential scenario which is found to likely result in a cloud volume comparable to the **Design cloud size.** The design cloud size will in turn on average produce the **Design over-pressure**.

Note that there are many other combinations of leak and wind conditions which could potentially generate a cloud with the design cloud size. Furthermore, there are many area specific factors that will affect the consequences upon ignition of this particular leak event. Hence, a perfect match towards the design explosion loads should not be expected on a regular basis.

As alluded to above the **Leak scenario for design explosion** is not guaranteed to generate the **Design cloud size.** The scenario may result in both larger or smaller cloud sizes. Similarly, the **Design cloud size** will not necessarily generate the **Design over-pressure** under all circumstances. Inversely, multiple different release scenarios may result in the **Design cloud size** and multiple different cloud sizes may produce the **Design over-pressure.**

In general, it is not appropriate to change the **Design cloud size** based on detailed gas dispersion simulations of the **Leak scenario for design explosion** or to change the **Design over-pressure** based on detailed gas explosion of **Design cloud size**. Exceptions to this are noted in section 4.

The **Leak scenario for design explosion** and **Design cloud size** are nonetheless valuable output from the RispEx model and should be used in the design of offshore facilities to minimize explosion risk.

Selected examples of where it would be appropriate to apply each are provided below:

Continuous design evaluation and improvement

Any project which applies RispEx to determine the overall explosion loads, must establish processes to ensure intrinsically safe design and that the principles of risk reduction (ALARP processes) are followed. To do this it may be necessary to perform detailed simulations to evaluate or provide input to design choices. In these situations it is recommended to perform simulations based on the RispEx **Leak scenario for design explosion** and **Design cloud size.** It may however be appropriate to modify the scenario slightly to ensure the simulated scenario is fit for purpose. E.g. if evaluating design choices that affect ventilation and gas dispersion in the north of a large module, it may be appropriate to simulate a release north-wards, even if the **Leak scenario for design explosion** specifies a leak southwards.

Management of change

If a change is considered which impacts the overall RispEx input, an update RispEx calculation must be performed to generate updated loads.

If a change is considered which does not impact the overall RispEx input, it may be appropriate to perform detailed simulations to evaluate the effect on the explosion risk level and determine the intrinsically safe option. In these situations it is recommended to perform simulations based on the RispEx **Leak scenario for design explosion** and **Design cloud size.** See guideline for Continuous design evaluation and improvement above.

Load on external targets

In some scenarios it may be required to provide explosion loads on wall or equipment not located within the RispEx area, but still potentially affected by an explosion within the area.

The **Design cloud size** may be used to evaluate the load on such targets. Note that as the overpressure from a gas explosion is highly dependant on local effects, it is in general recommended to perform a range of simulations with differing cloud and ignition positions, rather than a single simulation.

Load differentiation

In some scenarios layout choice have been made which result in substantially different loads on some parts of the RispEx area. An example of this may be an area with a solid roof in the western half of the area, but open or grated in the eastern half. In such situation the average openness of the roof is typically used in the RispEx calculation, which may underpredict of the load in the western half.

The **Design cloud size** may be used to evaluate the above example. By performing a range of detailed explosion simulations the average pressure on each of the walls may be compared and the design load on the eastern wall may be adjusted upwards accordingly. In general it is not appropriate to reduce the load on eastern wall based on such simulations. Note that as the overpressure from a gas explosion is highly dependent on local effects, it is in general recommended to perform a range of simulations with differing cloud and ignition positions, rather than a single simulation.

Load direction

Drag loading during a gas explosion in an offshore module can usefully be split into two separate phases:

- The cold peak, where cold air is pushed ahead of the expanding explosion pressure wave
- The warm peak, where warm combustion products fare ventilated out of the module.

In typical offshore modules, the cold peak results in the highest drag magnitude, but due the relatively short duration of the cold peak, most of the total drag impulse is due to the warm peak.

While the magnitude and duration of the cold peak tends to be relatively similar in all directions, the warm peak may differ substantially between the different principal directions. This is particularly true for small two-ways ventilated modules, where the warm peak is nearly negligible in the direction towards the fire divisions. A project may therefore find it useful to differentiate drag loading between the different principal directions.

The **Design cloud size** may be used to differentiate drag loading between the different principal directions. By performing a range of detailed explosion simulations the drag load in each principal direction may be compared and the duration of the drag loading in some directions may be reduced. In general, it is not recommended to reduce the **Design drag** based on such explosion simulations, however for some geometries the resulting **Design drag duration** may be so short and carry so little impulse that it has no impact on piping or structural elements. If it is concluded that the Drag load has insufficient duration and impulse in a given direction to affect a structural element or pipe, the element/pipe does not need to be designed against drag loading from that direction.

3.3 Explosion risk analysis results not provided by RispEx

While RispEx provides the key output from the Explosion risk analysis in terms of design accidental loads, there are some results typically provided by an explosion risk analysis which are not directly provided by RispEx.

Ventilation rates

In accordance with NORSOK S-001, the probabilistic ventilation rate in an area should be computed. This is presently not provided by RispEx and must be determined through detailed simulations or model testing.

Wind chill temperature

In accordance with NORSOK S-002, the local wind chill temperature should be computed if the temperature in the area is sufficiently low. This is presently not provided by RispEx and must be determined through detailed simulations or model testing.

Dimensioning cloud volume

It should be noted that the **Design cloud size** differs from the "dimensioning gas cloud" specified in section 3.10 of NORSOK S-001. The dimensioning gas cloud is defined as:

the minimum stoichiometric gas cloud which, when ignited, can create an explosion resulting in an explosion pressure exceeding the dimensioning explosion load of the area

This can be estimated based on the 95th percentile local overpressure curves.

4 Limitations of RispEx

4.1 Ambiguous area definitions

In some cases the boundaries of an area are not well defined, and several potential area boundaries may be selected as input to RispEx. An example may be a compressor area on the roof of an installation, with a grated area hosting PSVs above and large firewall covering both the compressor area and compressor area to the west.

In this case there are two potential ways to define the RispEx area:

- A large area encompassing both the compressor area and the grated PSV area, fully open towards the air above.
- Two separate areas:
  - One area encompassing the compressors bounded by the grated deck above.
  - One area encompassing the PSV bounded by the grated deck below and fully open towards the air above

If the area definition is ambiguous, it is recommended to check both potential ways to defined the RispEx area and select the option which results in the highest overall dimensioning accidental load on the shared firewall. It is further recommended to document choice of area definition to ensure a consistent and traceable basis for design explosion loads.

4.2 Very open areas

The RispEx explosion model depends on the volume of the explosive cloud, the openness of the area and the volume of the area. It has been observed that the RispEx model may in some cases underestimate the explosion overpressure for very open areas, where congestion is the primary driver of explosion overpressure.

Due to the higher uncertainty for very open areas it is recommended to verify the following parameter in the Front End Engineering and Design (FEED) phase of any project where RispEx is used to determine design accidental loads and the "Total openness" of the area is greater than 0.3:

- Explosion overpressure of dimensioning cloud calculated by RispEx, compared with the overpressure calculated through the traditional explosion modelling approach with a recognized CFD based explosion modelling tool.

If the overpressure calculated by RispEx is found to be too low, it is recommended to increase the **Design over-pressure** and **Design drag**. These values should be scaled by the ratio between traditionally computed and RispEx calculated median overpressure on either the deck or the firewall. E.g. if the RispEx calculated **Design cloud size** is 500 m^3, the median pressure on the firewall calculated by RispEx for a 500 m^3 is 0.2 bar and the median overpressure on the firewall calculated through CFD simulations is 0.3 bar, the scale factor is 0.3 / 0.2 = 1.5. The following RispEx results should be scaled by this factor:

- **Design over-pressure Firewall (Local)**
- **Design over-pressure Deck (Local)**
- **Design over-pressure Firewall (Global)**
- **Design over-pressure Deck (Global)**
- **Design drag**

Note that in some cases the pressure at the target frequency (normally 7×10^{-5} per year) may be lower than the minimum thresholds. In such cases the pressure at the target frequency should be read from the exceedance curve used for scaling, rather than the **Design over-pressure.** If the scaling results in lower overpressure than **Design over-pressure**, the **Design over-pressure** generated by RispEx should be kept.

If scaling is necessary, the associated durations should be recalculated based on the CFD simulations.

It is not recommended to reduce the **Design over-pressure** and **Design drag** if the explosion simulations indicate that the RispEx calculated median overpressure is too high.

4.3 Ship shaped FPSOs

The RispEx model for ship shaped FPSOs is based on fewer installations than the model for fixed facilities. Furthermore, compared with the model for fixed facilities there has been less formal review and benchmarking of the model. Finally, the model has been used much less than the model for fixed facilities. Overall, this results in higher uncertainty in the RispEx model for ship shaped FPSOs, compared with the model for fixed facilities.

Due to the higher uncertainty in the model for ship shaped FPSOs it is recommended to verify the following parameters in the Front End Engineering and Design (FEED) phase of any floating ship shaped FPSO project where RispEx is used to determine design accidental loads:

- Overall leak frequency predicted by RispEx, compared with the overall leak frequency computed based on a parts count and traditional leak frequency analysis.
- Explosion overpressure of dimensioning cloud calculated by RispEx, compared with the overpressure calculated through the traditional explosion modelling approach with a recognized CFD based explosion modelling tool.

If the overall leak frequency predicted by RispEx is found to be too low it is recommended to change the **Design frequency scaling factor** to ratio between RispEx predicted and the traditionally calculated leak frequencies. E.g. if the frequency predicted by RispEx is 1.0 and the calculated frequency is 1.2, the **Design frequency scaling factor** should be set to 1.0 / 1.2 = 0.83. It is not recommended to change the **Design frequency scaling factor** if the RispEx predicted leak frequency is found to be too high.

If the overpressure calculated by RispEx is found to be too low, it is recommended to increase the **Design over-pressure** and **Design drag**. These values should be scaled by the ratio between traditionally computed and RispEx calculated median overpressure on either the deck or the firewall. E.g. if the RispEx calculated **Design cloud size** is 500 m^3, the median pressure on the firewall calculated by RispEx for a 500 m^3 is 0.3 bar and the median overpressure on the firewall calculated through CFD simulations is 0.5 bar, the scale factor is 0.5 / 0.3 = 1.67. The following RispEx results should be scaled by this factor:

- **Design over-pressure Firewall (Local)**
- **Design over-pressure Deck (Local)**
- **Design over-pressure Firewall (Global)**
- **Design over-pressure Deck (Global)**
- **Design drag**

Note that in some cases the pressure at the target frequency (normally 7 x 10^{-5} per year) may be lower than the minimum thresholds. In such cases the pressure at the target frequency should be read from the exceedance curve used for scaling, rather than the **Design over-pressure.** If the scaling results in lower overpressure than **Design over-pressure**, the **Design over-pressure** generated by RispEx should be kept.

If scaling is necessary, the associated durations should be calculated based on the CFD simulations.

It is not recommended to reduce the **Design over-pressure** and **Design drag** if the explosion simulations indicate that the RispEx calculated median overpressure is too low.

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

RispEx Appendix B – CFD simulations for representative areas

Report for:
RISP Participants, att: Equinor Energy AS

JIP: Risk informed decision support in development projects (RISP)		
RispEx-decision support for explosion design loads – Appendix B: CFD simulations for representative areas		
Security classification of this report:	Distribute only after client's acceptance	
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Prepared by: Sjur Helland, DNV	**Reviewed by:** Jens Johansson Garstad, DNV	**Approved by:** Unni Nord Samdal, Equinor

Document history

Revision	Date	Description/changes	Changes made by
Rev A	18.06.2020	Draft A	Jens Garstad, DNV Asmund Huser, DNV
Rev 0	17.08.2020	Updated based on comments	-
Rev 01A	19.10.2021	Updated with larger process areas	Sjur Helland, DNV Jens Garstad, DNV
Rev 01	15.11.2021	No changes	-
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Rev 03A	04.07.2023	Updated explosion table	Sjur Helland, DNV Jens Garstad, DNV
Rev 03	22.09.2023	Editorial changes	Sjur Helland, DNV

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1 Summary

This appendix contains CFD simulation case information used in probabilistic analysis performed for 26 conventional process areas, 5 FPSO process areas and 7 wellhead areas. The appendix also contains the key response surface parameters as identified based on FLACS ventilation, dispersion and explosion simulations. This appendix mainly contains data, see the main report for the description of the context and conclusions derived from the simulations.

2 Geometry modelling

38 representative RispEx geometry models are generated, mainly based on cut and paste of geometry regions from new representative CAD files. Summary of the key parameters of the representative RispEx areas are summarized in Table 2-1 for conventional process areas, Table 2-2 for FPSO process areas and Table 2-3 for conventional wellhead areas.

Plots showing the geometry layout configuration for some selected areas are provided in the following Figure 2-1 to Figure 2-9. Congestion levels for all areas are tabulated in the Main report.

Table 2-1 Summary of key parameters of representative RispEx conventional process areas

ID	Length (m)	Width (m)	Height (m)	Volume (m^3)	P_e (-)	P_s (-)	P_n (-)	P_{up} (-)	Confinement level
03	23	24.5	8	4508	0	0.85	0.8	0	0.16
04	30	28	5	4200	0	0.7	1	0	0.11
01	30	28	5	4200	0	0.5	0.5	0	0.07
05	30	28	5	4200	0.8	0.8	0.8	0	0.16
02	30	28	5	4200	0.5	0.8	0.8	0	0.14
08	32	32	8	8192	0	0.8	0.8	0	0.13
09	32	32	8	8192	0.7	0.9	0.8	0	0.20
10	32	32	8	8192	0.8	0.8	0.8	0.8	0.47
11	28.5	28	10	7980	0	0.8	0.8	0	0.17
06	28.5	28	10	7980	0	0.5	0.5	0	0.10
12	28.5	28	10	7980	0.8	0.8	0.8	0.8	0.48
07	28.5	28	10	7980	0.8	0.8	0.8	0.4	0.37
13	40	28	7	7840	0.8	0.8	0.8	0	0.19
14	40	28	7	7840	0.8	0.8	0.8	0.8	0.47
16	46.5	46	8	17112	0.8	0.8	0.8	0	0.15
17	46.5	46	8	17112	0.8	0.8	0.8	0.8	0.45
18	41	41	10	16810	0	0.8	0.8	0	0.13
15	41	41	10	16810	0	0.5	0.5	0	0.08
19	41	41	10	16810	0.8	0.8	0.8	0	0.20
21	41	41	10	16810	0.8	0.8	0.4	0	0.16
20	41	41	10	16810	0.8	0.8	0.8	0.8	0.47
22	57	28	10	15960	0.8	0.8	0.8	0	0.23
23	60.5	41	10	24805	0.8	0.8	0.4	0	0.16
24	60.5	41	10	24805	0.8	0.8	0.8	0	0.19
25	60.5	41	10	24805	0	0.8	0.8	0	0.13
26	60.5	41	10	24805	0.8	0.8	0.8	0.8	0.46

Table 2-2 Summary of key parameters of representative RispEx FPSO process areas

ID	Length (m)	Width (m)	Height (m)	Volume (m^3)	P_e (-)	P_s (-)	P_n (-)	P_{up} (-)	Confinement level
51	34	53	19	34238	0	0.6	0.8	0.5	0.26
52	34	53	19	34238	0.8	0.6	0.8	0.5	0.38
53	60	53	10.5	33390	0	0.6	0.8	0.5	0.28
54	60	53	19	60420	0	0.6	0.8	0.33	0.25
55	60	53	19	60420	0.8	0.6	0.8	0.5	0.38

Table 2-3 Summary of key parameters of representative RispEx conventional wellhead areas

ID	Length (m)	Width (m)	Height (m)	Volume (m^3)	P_e (-)	P_s (-)	P_n (-)	P_{up} (-)	Confinement level
71	21	26	7.5	4095	0	0.8	0.8	0	0.14
72	21	26	7.5	4095	0.8	0.8	0.8	0	0.23
73	20	28	13	7280	0	0.9	0.9	0	0.20
74	24	28	15	10080	0	0.9	0.9	0	0.22
75	24	28	15	10080	0.8	0.8	0.8	0	0.31
76	24	43	13	13416	0.7	0.8	0.8	0	0.23
77	24	43	13	13416	0	0.9	0.8	0	0.14

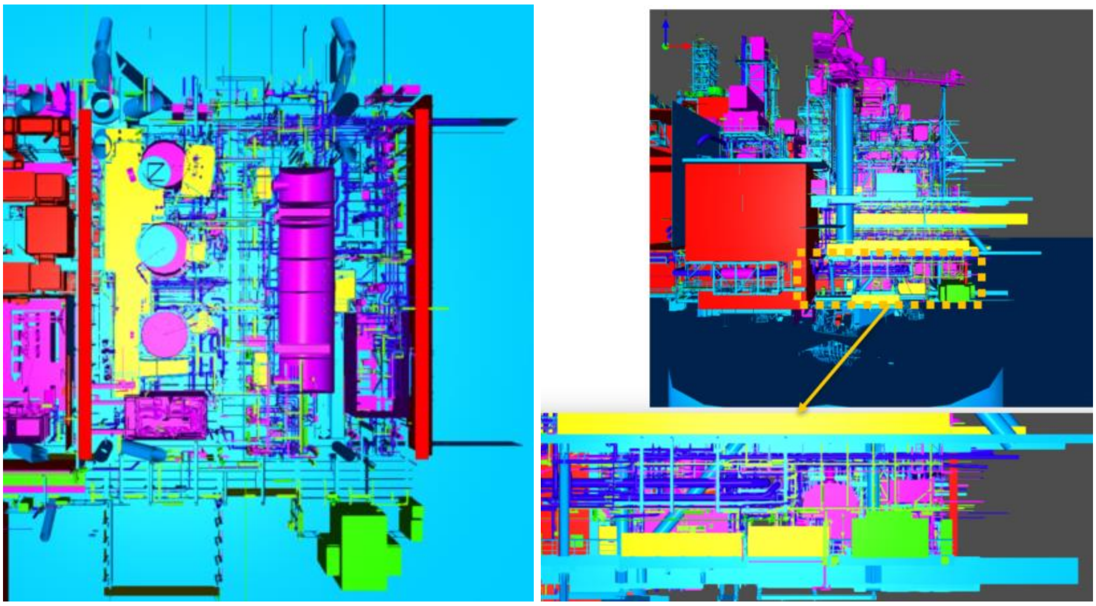

Figure 2-1 RispEx process area ID 3: 2-ways ventilated area with dimensions 23 x 23 x 8 m^3

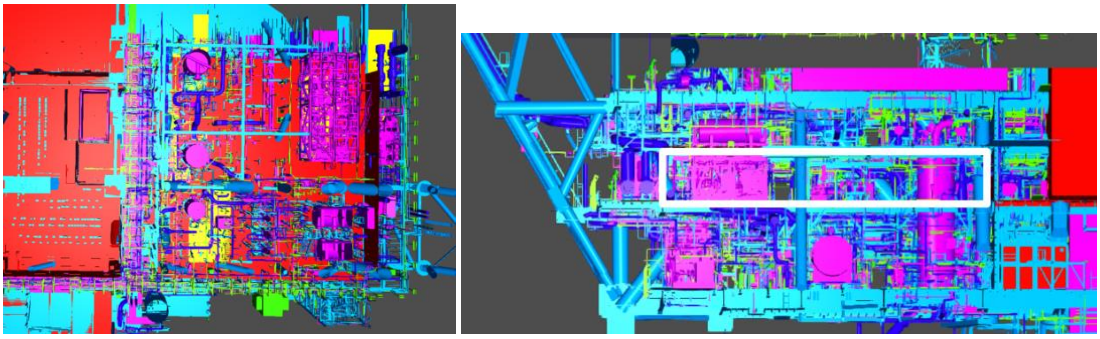

Figure 2-2 RispEx process area ID 4: 2-ways ventilated area with dimensions 30 x 23 x 5 m^3

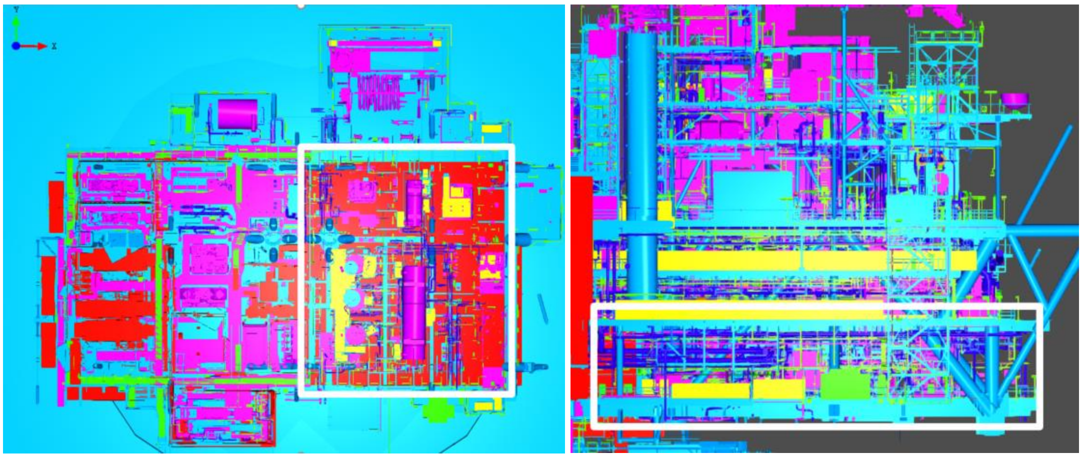

Figure 2-3 RispEx process area ID 9: 3-ways ventilated area with dimensions 32 x 32 x 8 m^3

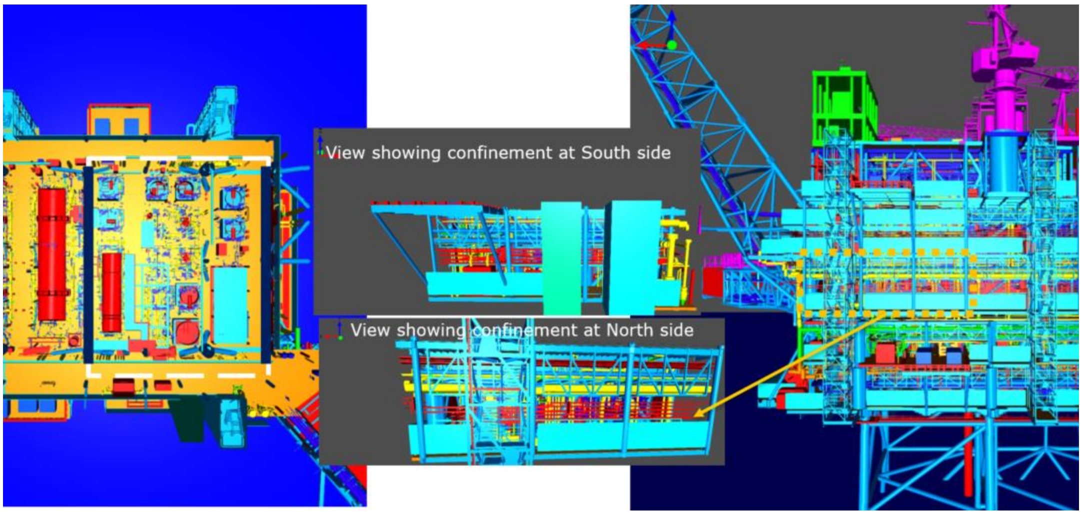

Figure 2-4 RispEx process area ID 11: 2-ways ventilated area with dimensions 29 x 28 x 10 m^3

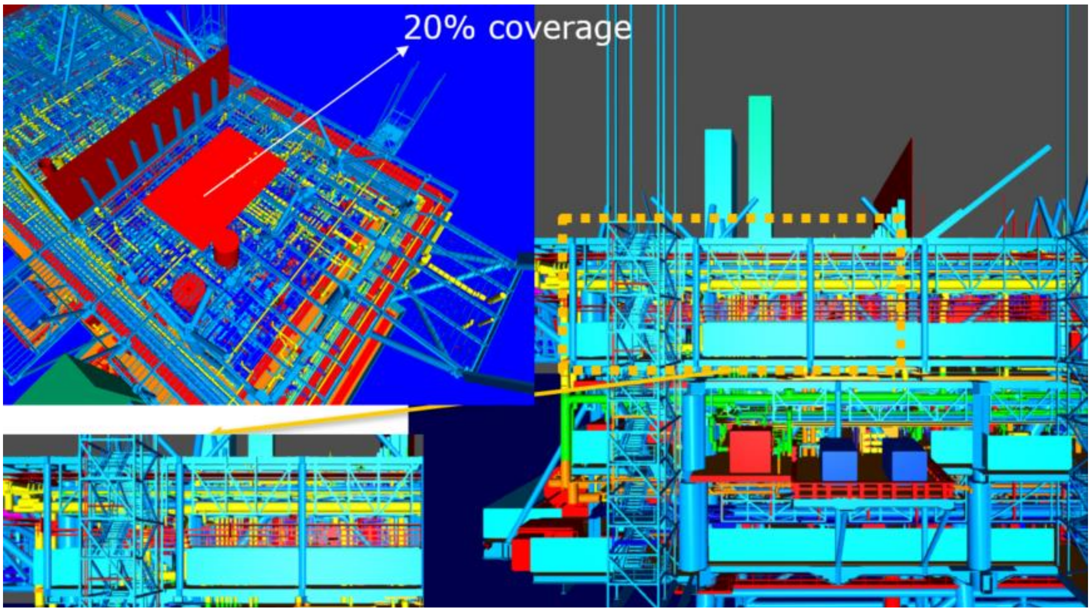

Figure 2-5 RispEx process area ID 12: 4-ways ventilated area with dimensions 29 x 28 x 10 m³. Similar to ID 11 but with East side and upwards ventilated as well.

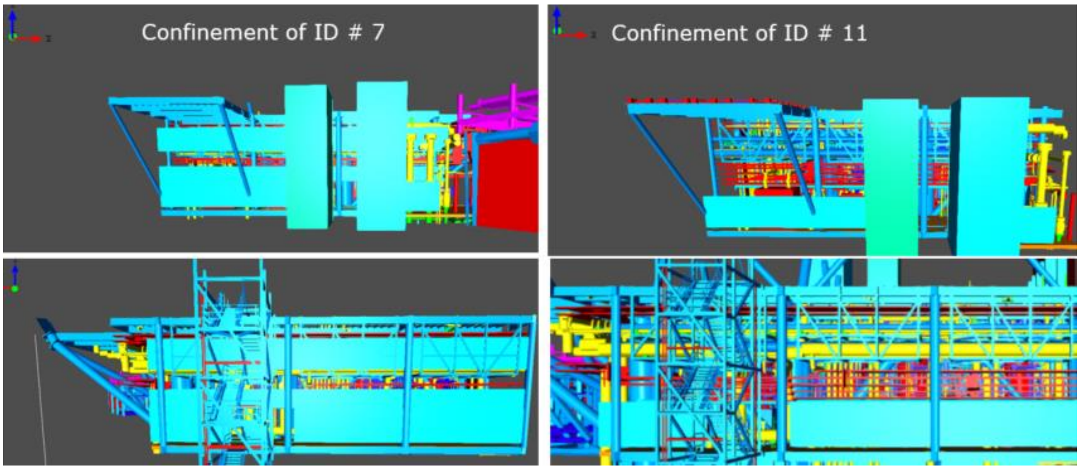

Figure 2-6 RispEx process area ID 7: 2-ways ventilated area with dimensions 29 x 28 x 10 m³. Similar to ID 11 but more confined

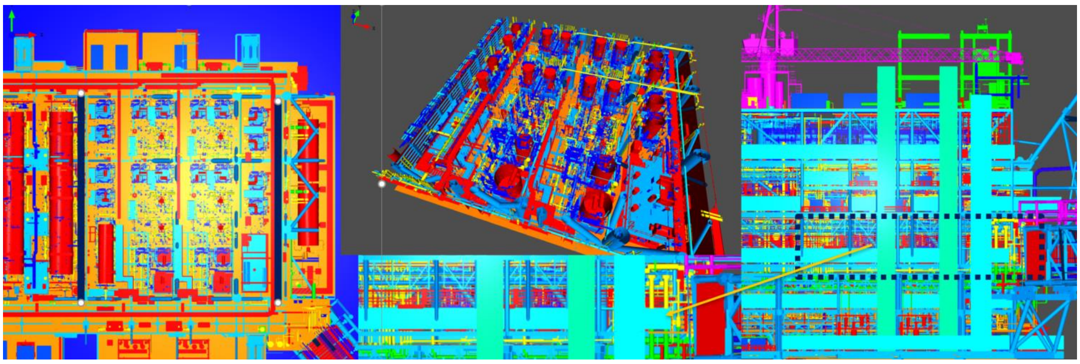

Figure 2-7 RispEx process area ID 18: 2-ways ventilated area with dimensions 40.5 x 41 x 10 m³.

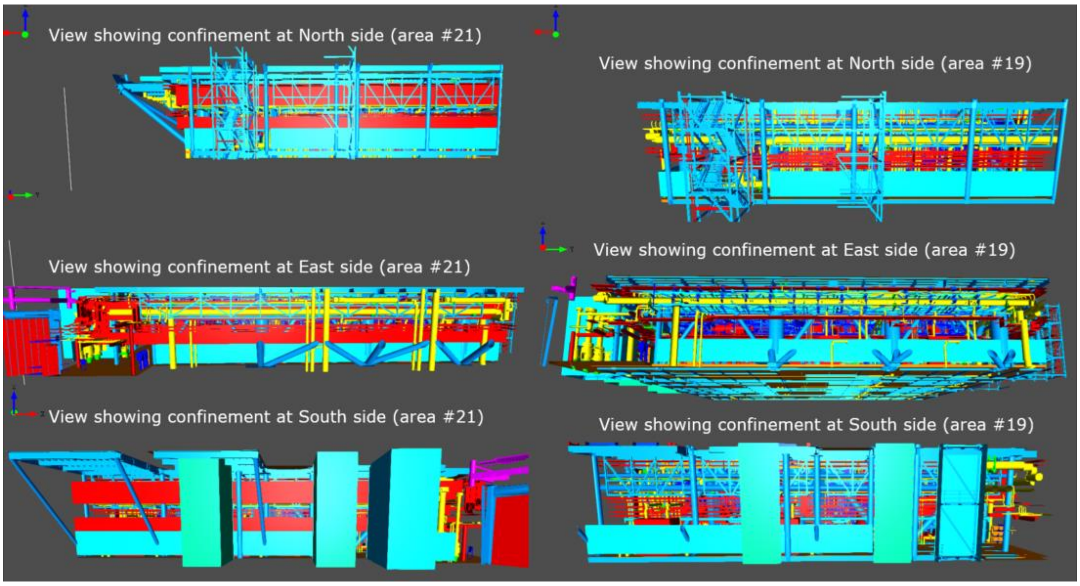

Figure 2-8 RispEx process area ID 19 vs ID 21: 3-ways ventilated area with dimensions 40.5 x 41 x 10 m^3 and high vs moderate confinement for the ventilated sides

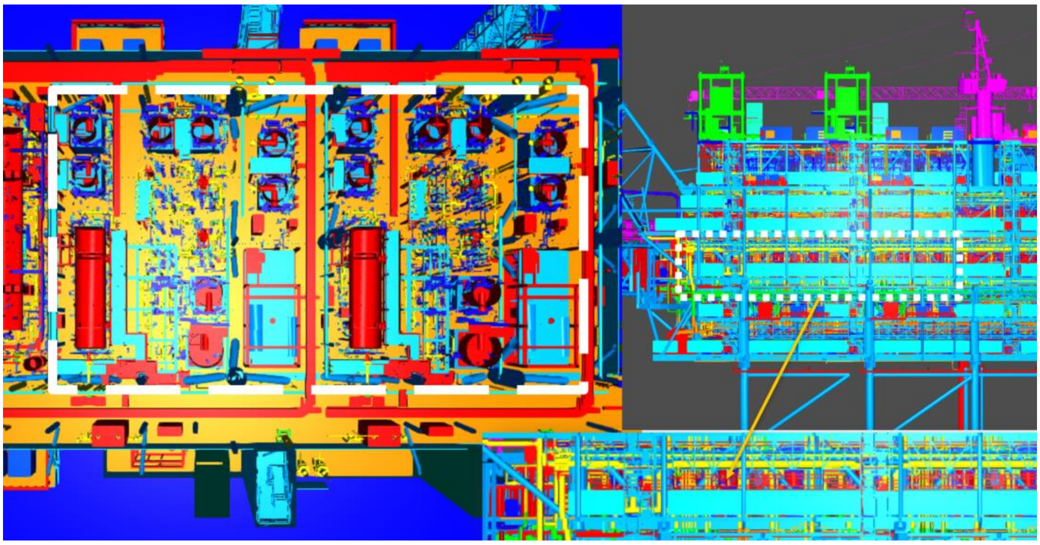

Figure 2-9 RispEx process area ID 22: 3-ways ventilated area with dimensions 57x 28 x 10 m^3.

3 Ventilation simulations

Eight ventilation simulations were carried out corresponding to wind directions N, NE, E, SE, S, SW, W and NW (in platform north coordinate system). The simulations were performed for a representative unobstructed wind speed of 6 m/s (10 meters above sea level). For FPSOs, the fraction of time with wind from prevailing direction is much higher due to weather vaneing. For this reason, more wind directions from FWD are selected. With denoting FWD direction "E - East", the simulated wind directions for FPSO is E, SEE, SE, S, W, N, NE, NEE.

The ventilation rate (m3/s) within the representative area with dimensions tabulated defined in the section above are recorded and summarized in Table 3-1 for conventional process areas, Table 3-2 for FPSO process areas and Table 3-3 for wellhead areas.

Table 3-1 Summary of ventilation rates [m³/s] for 6 m/s of representative RispEx conventional process area

ID	N	NE	E	SE	S	SW	W	NW
03	184	187	41	191	200	104	20	60.5
04	511	375	11	497	742	501	15	378
01	198	192	39	170	200	116	11	81
05	289	216	186	199	243	144	21	114
02	223	171	145	157	185	111	17	90
08	220	243	65	267	280	164	26	95
09	320	349	497	348	406	217	66	144
10	301	661	728	684	465	284	105	154
11	355	298	50	241	319	235	62	232
06	342	284	50	234	305	227	60	225
12	491	654	600.5	369.6	319.6	274	121	332
07	437	558	507	318	251	213	105	295
13	466	367	365	298	411	305	78	318
14	594	692	606	363	311	304	133	409
16	409	368	497	420	450	303	51	248
17	440	756	820	872	603	400	282	309
18	410	343	70	294	377	260	56	269
15	499	400	577	334	468	335	85	332
19	499	400	577	334	468	335	85	332
21	475	389	539	325	448	326	81	319
20	592	883	803	598	432	367	178	423
22	767	389	539	325	448	326	81	319
23	703	554	625	457	661	530	120	549
24	710	604	709	504	811	592	174	588
25	649	468	95	374	600	455	121	479
26	903	1190	985	796	692	663	644	756

Table 3-2 Summary of ventilation rates [m³/s] for 6 m/s of representative RispEx FPSO process areas

ID	E (FWD)	SEE	SE	S (Starb.)	W (AFT)	N (Port side)	W	NW
51	486	675	1196	1512	196	1710	1495	836
52	542	988	1508	1724	990	1848	1756	1088
53	693	755	1250	1647	377	1174	1014	710
54	664	1292	2360	3156	279	2932	2493	1390
55	691	1598	2674	3369	1258	3098	2712	1610

Table 3-3 Summary of ventilation rates [m³/s] for 6 m/s of representative RispEx conventional process areas

ID	N	NE	E	SE	S	SW	W	NW
71	71	189	115	15	136	136	126	11
72	72	244	239	360	193	174	139	58
73	73	265	219	30	191	200	168	32
74	74	437	397	87	390	412	165	57
75	75	627	445	632	474	501	159	141
76	76	87	297	359	324	511	354	454

4 Dispersion simulations

List of all dispersion simulations for all representative areas as well as key summary of the results are tabulated in Table 4-1 to Table 4-37. The results presented includes the simulated cloud size expressed as Q9 cloud size as well as the corresponding filling degree of the module (Vf/V). The last column presents the filling degree estimated based on the response surface parameters fitted to the simulation results.

Table 4-38 contains summary of key dispersion response surface parameters identified through simulations. Mean value A and amplitude B refers to A and B for Chartmax function as presented in the main report. See also main report for discussion of parameters C1 and P2.

Table 4-1 Summary of dispersion simulations for RispEx area ID #1

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	8	N	N	4	883	0.21	0.24
20102	8	N	W	12	584	0.14	0.12
20103	8	N	E	13	1227	0.29	0.33
20104	8	S	S	5	399	0.10	0.17
20105	8	W	S	4	458	0.11	0.24
20106	8	W	W	13	1200	0.29	0.29
20107	8	E	E	12	612	0.15	0.20
20108	5	Down	W	14	1214	0.29	0.23
20109	7	Down	S	4	400	0.10	0.16
20110	7	Down	E	12	654	0.16	0.23
20111	7	Up	E	12	803	0.19	0.27
20112	5	Up	W	14	1428	0.34	0.37
20113	3	N	W	10	634	0.15	0.17
20114	20	S	S	7	485	0.12	0.18
20115	3	W	W	10	592	0.14	0.33
20116	30	Down	S	12	210	0.05	0.17

Table 4-2 Summary of dispersion simulations for RispEx area ID #2

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	816	0.19	0.22
20102	12	N	W	10	486	0.12	0.12
20103	12	N	E	5	525	0.13	0.18
20104	12	S	S	5	540	0.13	0.19
20105	12	W	S	4	312	0.07	0.17
20106	12	W	W	10	994	0.24	0.25
20107	12	E	E	5	984	0.23	0.23
20108	10	Down	W	10	1205	0.29	0.30
20109	10	Down	S	4	299	0.07	0.17
20110	10	Down	E	4	502	0.12	0.15
20111	10	Up	E	4	627	0.15	0.17
20112	10	Up	W	10	1111	0.26	0.25
20113	3	W	W	10	620	0.15	0.30
20114	3	Up	W	10	772	0.18	0.29
20115	3	Down	W	10	706	0.17	0.32

20116	4	N	W	12	345	0.08	0.18

Table 4-3 Summary of dispersion simulations for RispEx area ID #3

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	8	N	N	4	792	0.18	0.20
20102	8	N	W	12	618	0.14	0.17
20103	8	N	E	13	549	0.12	0.14
20104	8	S	S	5	2235	0.50	0.23
20105	8	W	S	4	622	0.14	0.14
20106	8	W	W	13	644	0.14	0.15
20107	8	E	E	12	589	0.13	0.16
20108	5	Down	W	14	878	0.19	0.28
20109	7	Down	S	4	648	0.14	0.14
20110	7	Down	E	12	888	0.20	0.22
20111	7	Up	E	12	1111	0.25	0.23
20112	5	Up	W	14	544	0.12	0.13
20113	3	N	W	10	798	0.18	0.20
20114	20	S	S	7	543	0.12	0.30
20115	3	W	W	10	416	0.09	0.18
20116	30	Down	S	12	406	0.09	0.15

Table 4-4 Summary of dispersion simulations for RispEx area ID #4

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	8	N	N	4	317	0.08	0.11
20102	8	N	W	12	204	0.05	0.09
20103	8	N	E	13	306	0.07	0.08
20104	8	S	S	5	532	0.13	0.06
20105	8	W	S	4	249	0.06	0.07
20106	8	W	W	13	974	0.23	0.24
20107	8	E	E	12	572	0.14	0.12
20108	5	Down	W	14	1498	0.36	0.35
20109	7	Down	S	4	410	0.10	0.07
20110	7	Down	E	12	543	0.13	0.11
20111	7	Up	E	12	630	0.15	0.14
20112	5	Up	W	14	1431	0.34	0.35

Table 4-5 Summary of dispersion simulations for RispEx area ID #5

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	419	0.10	0.19
20102	12	N	W	10	274	0.07	0.05
20103	12	N	E	5	252	0.06	0.09
20104	12	S	S	5	452	0.11	0.19
20105	12	W	S	4	239	0.06	0.11
20106	12	W	W	10	890	0.21	0.17
20107	12	E	E	5	668	0.16	0.20
20108	10	Down	W	10	1151	0.27	0.26
20109	10	Down	S	4	276	0.07	0.10

20110	10	Down	E	4	531	0.13	0.18
20111	10	Up	E	4	674	0.16	0.17
20112	10	Up	W	10	960	0.23	0.21
20113	3	W	W	10	446	0.11	0.23
20114	3	Up	W	10	752	0.18	0.25
20115	3	Down	W	10	702	0.17	0.29

Table 4-6 Summary of dispersion simulations for RispEx area ID #6

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	5	N	W	10	647	0.08	0.15
20102	5	S	W	10	675	0.08	0.12
20103	5	E	W	10	565	0.07	0.10
20104	5	E	S	6	492	0.06	0.07
20105	5	W	W	10	2218	0.27	0.25
20106	5	Down	W	12	2020	0.24	0.20
20107	5	Down	S	6	373	0.05	0.08
20108	5	Up	S	12	166	0.02	0.03
20109	10	N	N	6	1648	0.20	0.15
20110	10	N	S	6	479	0.06	0.06
20111	10	N	NW	12	743	0.09	0.11
20112	10	Down	W	12	1653	0.20	0.25
20113	15	N	NW	10	1406	0.17	0.18
20114	15	Down	W	12	1550	0.19	0.25
20115	15	Down	S	7	868	0.11	0.16
20116	15	Down	E	12	2203	0.27	0.29

Table 4-7 Summary of dispersion simulations for RispEx area ID #7

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	6	640	0.08	0.11
20102	10	N	N	6	646	0.08	0.09
20103	10	N	S	6	451	0.05	0.05
20104	10	S	W	6	500	0.06	0.11
20105	10	E	W	6	84	0.00	0.00
20106	10	E	S	6	66	0.00	0.00
20107	10	W	W	6	1228	0.15	0.25
20108	10	Down	W	6	1093	0.13	0.15
20109	10	Down	S	6	832	0.10	0.14
20110	10	Up	W	6	525	0.06	0.12
20111	5	Down	W	6	878	0.11	0.14
20112	5	N	W	6	632	0.08	0.11
20113	20	N	N	6	1304	0.16	0.15
20114	20	N	S	6	398	0.05	0.04
20115	20	Down	S	6	823	0.10	0.16
20116	20	Down	E	6	2063	0.25	0.18

Table 4-8 Summary of dispersion simulations for RispEx area ID #8

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface

20101	12	S	S	4	2339	0.29	0.26
20102	12	S	W	12	655	0.08	0.13
20103	12	S	E	13	725	0.09	0.17
20104	12	N	N	4	1702	0.21	0.25
20105	12	W	S	4	351	0.04	0.10
20106	12	W	W	13	1689	0.21	0.17
20107	12	E	E	12	1413	0.17	0.22
20108	12	Down	W	13	1590	0.19	0.23
20109	12	Down	N	4	1407	0.17	0.17
20110	12	Down	E	12	905	0.11	0.12
20111	12	Up	E	12	780	0.10	0.13
20112	12	Up	W	12	1845	0.23	0.26
20113	4	N	W	10	51	0.00	0.00
20114	4	W	W	10	1401	0.17	0.20
20115	4	Up	W	10	0	0.00	0.00
20116	25	W	N	6	639	0.08	0.09

Table 4-9 Summary of dispersion simulations for RispEx area ID #9

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	S	S	4	2198	0.27	0.20
20102	12	S	W	12	580	0.07	0.14
20103	12	S	E	4	788	0.10	0.13
20104	12	N	N	4	1801	0.22	0.23
20105	12	W	S	4	442	0.05	0.09
20106	12	W	W	13	988	0.12	0.15
20107	12	E	E	4	1220	0.15	0.15
20108	12	Down	W	13	951	0.12	0.17
20109	12	Down	N	4	1929	0.24	0.23
20110	12	Down	E	4	926	0.11	0.14
20111	12	Up	E	4	615	0.08	0.11
20112	12	Up	W	12	1002	0.12	0.21
20114	30	S	S	5	1856	0.23	0.27
20115	30	Down	N	7	1145	0.14	0.26
20116	30	Down	E	5	672	0.08	0.17

Table 4-10 Summary of dispersion simulations for RispEx area ID #10

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	S	S	4	762	0.09	0.14
20102	12	S	W	8	522	0.06	0.13
20103	12	S	E	4	377	0.05	0.08
20105	12	W	S	4	371	0.05	0.09
20106	12	W	W	8	721	0.09	0.16
20107	12	E	E	4	498	0.06	0.09
20108	12	Down	W	8	704	0.09	0.16
20109	12	Down	N	4	590	0.07	0.12
20110	12	Down	E	4	697	0.09	0.08
20111	12	Up	E	4	205	0.03	0.05
20112	40	N	E	4	76	0.00	0.00
20113	40	S	E	4	439	0.05	0.09
20114	40	S	S	6	1028	0.13	0.16
20115	40	Up	E	4	195	0.02	0.05

20116	40	Down	E	4	346	0.04	0.09

Table 4-11 Summary of dispersion simulations for RispEx area ID #11

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	5	N	W	10	487	0.06	0.15
20102	5	S	W	10	489	0.06	0.12
20103	5	E	W	10	712	0.09	0.12
20104	5	E	S	6	867	0.10	0.07
20105	5	W	W	10	1246	0.15	0.20
20106	5	Down	W	12	1961	0.24	0.18
20107	5	Down	S	6	250	0.03	0.07
20108	5	Up	S	12	163	0.02	0.03
20109	10	N	N	6	1668	0.20	0.14
20110	10	N	S	6	392	0.05	0.07
20111	10	N	NW	12	667	0.08	0.11
20112	10	Down	W	12	1672	0.20	0.22
20113	15	N	NW	10	1299	0.16	0.17
20114	15	Down	W	12	1610	0.19	0.22
20115	15	Down	S	7	855	0.10	0.12
20116	15	Down	E	12	1915	0.23	0.26

Table 4-12 Summary of dispersion simulations for RispEx area ID #12

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	6	607	0.07	0.11
20102	10	N	N	6	617	0.07	0.08
20103	10	N	S	6	434	0.05	0.05
20104	10	S	W	6	355	0.04	0.11
20107	10	W	W	6	837	0.10	0.28
20108	10	Down	W	6	934	0.11	0.14
20109	10	Down	S	6	811	0.10	0.10
20110	10	Up	W	6	23	0.00	0.00
20111	5	Down	W	6	710	0.09	0.13
20112	5	N	W	6	551	0.07	0.11
20113	20	N	N	6	1274	0.15	0.14
20114	20	N	S	6	428	0.05	0.04
20115	20	Down	S	6	817	0.10	0.13
20116	20	Down	E	6	1898	0.23	0.15

Table 4-13 Summary of dispersion simulations for RispEx area ID #13

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	S	S	8	1214	0.15	0.10
20102	12	S	W	11	1784	0.23	0.26
20103	12	S	E	8	482	0.06	0.05
20104	12	N	N	7	1271	0.16	0.10
20105	12	W	S	6	175	0.02	0.07
20106	12	W	W	11	863	0.11	0.15
20107	12	E	E	8	1206	0.15	0.11
20108	12	Down	W	11	791	0.10	0.14

20109	12	Down	S	4	703	0.09	0.12
20110	12	Down	E	6	725	0.09	0.10
20111	12	Up	E	6	391	0.05	0.10
20112	12	Up	W	11	1684	0.21	0.24
20113	30	W	S	5	258	0.03	0.07
20114	30	S	S	6	1075	0.14	0.24
20115	30	S	E	6	416	0.05	0.04
20116	30	Down	E	6	623	0.08	0.11

Table 4-14 Summary of dispersion simulations for RispEx area ID #14

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	S	S	6	511	0.07	0.13
20102	12	S	W	6	492	0.06	0.09
20103	12	S	E	8	320	0.04	0.05
20104	12	N	N	10	82	0.01	0.04
20105	12	W	S	6	130	0.02	0.09
20106	12	W	W	7	130	0.00	0.00
20107	12	E	E	8	556	0.07	0.05
20108	12	Down	W	7	616	0.08	0.15
20109	12	Down	S	4	637	0.08	0.12
20110	12	Down	E	6	1227	0.16	0.06
20111	12	Up	E	4	28	0.00	0.00
20112	12	Up	W	7	21	0.00	0.00
20113	30	W	S	7	159	0.02	0.08
20114	30	S	S	7	760	0.10	0.16
20115	30	S	E	4	319	0.04	0.09
20116	30	Down	E	4	1180	0.15	0.09

Table 4-15 Summary of dispersion simulations for RispEx area ID #15

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	12	1884	0.11	0.13
20102	10	N	N	5	1723	0.10	0.13
20103	10	N	S	5	1093	0.07	0.08
20104	10	S	W	12	1803	0.11	0.15
20105	10	E	W	12	1867	0.11	0.04
20106	10	E	S	5	1303	0.08	0.10
20107	10	W	W	12	3760	0.23	0.31
20108	10	Down	W	12	1912	0.12	0.20
20109	10	Down	S	5	1895	0.11	0.12
20110	10	Up	W	12	1903	0.11	0.19
20111	5	Down	W	6	0	0.00	0.20
20112	5	N	W	6	2290	0.14	0.13
20113	20	N	N	5	1665	0.10	0.18
20114	20	N	S	5	765	0.05	0.07
20115	20	Down	S	6	1423	0.09	0.14
20116	20	Down	E	12	3739	0.23	0.27

Table 4-16 Summary of dispersion simulations for RispEx area ID #16

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	1127	0.07	0.15
20102	12	N	W	12	1795	0.10	0.16
20103	12	N	E	4	2797	0.16	0.14
20104	12	S	S	4	2395	0.14	0.14
20105	12	W	S	4	1306	0.08	0.10
20106	12	W	W	13	549	0.03	0.08
20107	12	E	E	4	867	0.05	0.07
20108	12	Down	W	14	1577	0.09	0.22
20109	12	Down	S	4	1697	0.10	0.20
20110	12	Down	E	4	1771	0.10	0.16
20111	12	Up	E	4	134	0.01	0.10
20113	40	N	E	6	1920	0.11	0.18
20114	40	S	S	6	2091	0.12	0.15
20115	6	W	W	8	838	0.05	0.08
20116	40	Down	S	7	10696	0.63	0.30

Table 4-17 Summary of dispersion simulations for RispEx area ID #17

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	N	4	226	0.01	0.08
20102	15	N	W	4	219	0.01	0.05
20103	15	N	E	4	345	0.02	0.07
20104	15	S	S	4	294	0.02	0.07
20105	15	W	S	4	200	0.01	0.04
20106	15	W	W	4	216	0.01	0.06
20107	15	E	E	4	421	0.02	0.06
20108	15	Down	W	4	553	0.03	0.14
20109	15	Down	S	4	534	0.03	0.11
20110	15	Down	E	4	678	0.04	0.10
20111	15	Up	E	4	52	0.00	0.01
20112	15	Up	W	4	53	0.00	0.02
20113	50	N	E	5	525	0.03	0.07
20114	50	S	S	6	386	0.02	0.06
20115	50	Down	S	6	474	0.03	0.11
20116	50	Down	E	5	842	0.05	0.13

Table 4-18 Summary of dispersion simulations for RispEx area ID #18

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	12	1830	0.11	0.12
20102	10	N	N	5	1639	0.10	0.12
20103	10	N	S	5	1094	0.07	0.07
20104	10	S	W	12	1756	0.11	0.11
20105	10	E	W	12	1808	0.11	0.04
20106	10	E	S	5	1374	0.08	0.10
20107	10	W	W	12	3891	0.23	0.27
20108	10	Down	W	12	1883	0.11	0.15
20109	10	Down	S	5	1993	0.12	0.11
20110	10	Up	W	12	1868	0.11	0.19

20112	5	N	W	6	2199	0.13	0.12
20113	20	N	N	5	1647	0.10	0.17
20114	20	N	S	5	1063	0.06	0.06
20115	20	Down	S	6	1567	0.09	0.13
20116	20	Down	E	12	3682	0.22	0.24

Table 4-19 Summary of dispersion simulations for RispEx area ID #19

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	8	1770	0.11	0.18
20102	10	N	N	5	1260	0.08	0.09
20103	10	N	S	5	1180	0.07	0.08
20104	10	S	W	8	1394	0.08	0.12
20105	10	E	W	8	1196	0.07	0.08
20106	10	E	S	5	663	0.04	0.07
20107	10	W	W	8	3577	0.22	0.27
20108	10	Down	W	8	1597	0.10	0.14
20109	10	Down	E	5	3818	0.23	0.09
20110	10	Up	W	8	1594	0.10	0.19
20111	5	Down	W	5	377	0.02	0.15
20112	5	N	W	5	2639	0.16	0.18
20113	20	N	N	5	1209	0.07	0.14
20114	20	N	S	5	967	0.06	0.10
20115	20	Down	S	5	1294	0.08	0.13
20116	20	Down	E	5	1809	0.11	0.17

Table 4-20 Summary of dispersion simulations for RispEx area ID #20

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20102	12	N	W	5	1746	0.11	0.14
20103	12	N	E	4	2039	0.12	0.08
20106	12	W	W	5	1037	0.06	0.13
20107	12	E	E	4	0	0.00	0.00
20108	12	Down	W	5	601	0.04	0.06
20109	12	Down	S	4	763	0.05	0.07
20110	12	Down	E	4	311	0.02	0.08
20111	12	Up	E	4	1199	0.07	0.06
20113	40	N	E	4	1546	0.09	0.18
20114	40	W	S	7	2277	0.14	0.15
20115	40	Down	S	7	686	0.04	0.06
20116	40	Down	E	4	1541	0.09	0.13

Table 4-21 Summary of dispersion simulations for RispEx area ID #21

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	10	N	W	8	1814	0.11	0.19
20102	10	N	N	5	1210	0.07	0.10
20103	10	N	S	5	1328	0.08	0.09
20104	10	S	W	8	1450	0.09	0.12
20105	10	E	W	8	1393	0.08	0.10

20106	10	E	S	5	699	0.04	0.07
20107	10	W	W	8	3549	0.21	0.29
20108	10	Down	W	8	1629	0.10	0.15
20109	10	Down	E	5	3735	0.22	0.10
20110	10	Up	W	8	1668	0.10	0.19
20111	5	Down	W	5	628	0.04	0.15
20112	5	N	W	5	2674	0.16	0.19
20113	20	N	N	5	1248	0.08	0.14
20114	20	N	S	5	803	0.05	0.10
20115	20	Down	S	5	1315	0.08	0.13
20116	20	Down	E	5	1765	0.11	0.18

Table 4-22 Summary of dispersion simulations for RispEx area ID #22

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	S	S	4	4059	0.25	0.15
20102	15	S	W	12	1210	0.07	0.10
20103	15	S	E	4	1328	0.08	0.09
20104	15	N	N	4	1450	0.09	0.12
20105	15	W	N	4	1393	0.08	0.10
20106	15	W	W	11	699	0.04	0.07
20107	15	E	E	4	3549	0.21	0.29
20108	15	Down	W	11	1629	0.10	0.15
20109	15	Down	N	4	3735	0.22	0.10
20110	15	Down	E	4	1668	0.10	0.19
20111	15	Up	E	4	628	0.04	0.15
20112	15	Up	W	11	2674	0.16	0.19
20113	40	S	S	5	1248	0.08	0.14
20114	40	W	N	5	803	0.05	0.10
20115	40	Down	N	5	1315	0.08	0.13
20116	40	Down	E	6	1765	0.11	0.18

Table 4-23 Summary of dispersion simulations for RispEx area ID #23

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	W	12	1356	0.05	0.05
20102	15	N	N	5	1167	0.05	0.06
20103	15	N	S	5	1177	0.05	0.06
20104	15	S	W	12	1160	0.05	0.05
20105	15	E	W	12	934	0.04	0.05
20106	15	E	S	5	850	0.03	0.05
20107	15	W	W	12	3875	0.16	0.17
20108	15	Down	W	12	1343	0.05	0.25
20109	15	Down	S	5	1275	0.05	0.11
20110	15	Up	W	12	1428	0.06	0.08
20111	10	Down	W	6	7192	0.29	0.28
20112	10	N	W	6	1668	0.07	0.05
20113	30	N	N	5	1225	0.05	0.05
20114	30	N	S	5	897	0.04	0.05
20115	30	Down	S	6	1067	0.04	0.14
20116	30	Down	E	12	6507	0.26	0.12

Table 4-24 Summary of dispersion simulations for RispEx area ID #24

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	W	8	1543	0.06	0.18
20102	15	N	N	5	1149	0.05	0.08
20103	15	N	S	5	1145	0.05	0.07
20104	15	S	W	8	1466	0.06	0.07
20105	15	E	W	8	1382	0.06	0.06
20106	15	E	S	5	697	0.03	0.03
20107	15	W	W	8	4328	0.17	0.18
20108	15	Down	W	8	1617	0.07	0.11
20109	15	Down	E	5	5049	0.20	0.13
20110	15	Up	W	8	1556	0.06	0.09
20111	10	Down	W	5	2430	0.10	0.11
20112	10	N	W	5	5852	0.24	0.18
20113	30	N	N	5	1150	0.05	0.09
20114	30	N	S	5	829	0.03	0.09
20115	30	Down	S	5	1194	0.05	0.05
20116	30	Down	E	5	3914	0.16	0.23

Table 4-25 Summary of dispersion simulations for RispEx area ID #25

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	W	12	1595	0.06	0.09
20102	15	N	N	5	1598	0.06	0.09
20103	15	N	S	5	1156	0.05	0.06
20104	15	S	W	12	1356	0.05	0.09
20105	15	E	W	12	1233	0.05	0.02
20106	15	E	S	5	1281	0.05	0.06
20107	15	W	W	12	4983	0.20	0.19
20108	15	Down	W	12	1953	0.08	0.12
20109	15	Down	S	5	1611	0.06	0.08
20110	15	Up	W	12	2000	0.08	0.13
20111	10	Down	W	6	2138	0.09	0.12
20112	10	N	W	6	2583	0.10	0.09
20113	30	N	N	5	1497	0.06	0.11
20114	30	N	S	5	997	0.04	0.07
20115	30	Down	S	6	1300	0.05	0.10
20116	30	Down	E	12	4991	0.20	0.11

Table 4-26 Summary of dispersion simulations for RispEx area ID #26

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	N	4	1161	0.05	0.04
20102	15	N	W	5	1297	0.05	0.05
20103	15	N	E	4	1105	0.04	0.06
20104	15	S	S	4	732	0.03	0.04
20105	15	W	S	4	839	0.03	0.03
20106	15	W	W	5	550	0.02	0.03
20107	15	E	E	4	624	0.03	0.03
20108	15	Down	W	5	1611	0.06	0.04
20109	15	Down	S	4	1164	0.05	0.05
20110	15	Down	E	4	1512	0.06	0.04
20111	10	Up	E	4	164	0.01	0.05
20112	10	N	N	5	967	0.04	0.04
20113	30	N	E	4	879	0.04	0.06
20114	30	W	S	7	797	0.03	0.05
20115	30	Down	S	7	994	0.04	0.04
20116	30	Down	E	4	1190	0.05	0.05

Table 4-27 Summary of dispersion simulations for RispEx area ID #51

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	E	E	5	2324	0.07	0.11
20102	12	E	SE	5	2552	0.07	0.07
20103	12	E	S	5	2366	0.07	0.05
20104	12	W	W	5	1466	0.04	0.05
20105	12	Up	NE	5	620	0.02	0.04
20106	12	Down	E	5	2149	0.06	0.13
20107	12	Down	SE	5	2249	0.07	0.06
20108	12	Down	S	5	1390	0.04	0.05
20109	12	Down	NE	5	1825	0.05	0.05
20110	12	Down	NEE	5	1611	0.05	0.09
20111	12	N	NEE	5	1269	0.04	0.06
20112	20	N	N	7	2877	0.08	0.05
20113	40	E	E	7	3067	0.09	0.12
20114	40	E	SE	7	3130	0.09	0.14
20115	40	Down	E	7	3971	0.12	0.15
20116	40	Down	NEE	7	2153	0.06	0.14
20117	8	E	SEE	7	1167	0.03	0.05
20118	8	Down	NEE	7	0	0.00	0.04

Table 4-28 Summary of dispersion simulations for RispEx area ID #52

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	E	E	5	2584	0.08	0.11

20102	12	E	SE	5	2797	0.08	0.05
20103	12	E	S	5	2884	0.08	0.04
20104	12	W	W	5	246	0.01	0.03
20105	12	Up	NE	5	612	0.02	0.02
20106	12	Down	E	5	3204	0.09	0.11
20107	12	Down	SE	5	1977	0.06	0.05
20108	12	Down	S	5	1238	0.04	0.04
20109	12	Down	NE	5	2121	0.06	0.04
20110	12	Down	NEE	5	2054	0.06	0.07
20111	12	N	NEE	5	1556	0.05	0.05
20112	20	N	N	7	3027	0.09	0.05
20113	40	E	E	7	3399	0.10	0.12
20114	40	E	SE	7	3060	0.09	0.13
20115	40	Down	E	7	3480	0.10	0.14
20116	40	Down	NEE	7	2966	0.09	0.12
20117	8	E	SEE	7	1616	0.05	0.03

Table 4-29 Summary of dispersion simulations for RispEx area ID #53

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	E	E	5	2540	0.08	0.11
20102	12	E	SE	5	1663	0.05	0.06
20103	12	E	S	5	1381	0.04	0.04
20104	12	W	W	5	3036	0.10	0.11
20105	12	Up	NE	5	79	0.00	0.07
20106	12	Down	E	5	2663	0.08	0.10
20107	12	Down	SE	5	1022	0.03	0.06
20108	12	Down	S	5	1022	0.03	0.04
20109	12	Down	NE	5	1792	0.06	0.07
20110	12	Down	NEE	5	1566	0.05	0.10
20111	12	N	NEE	5	1477	0.05	0.05
20112	20	N	N	7	885	0.03	0.04
20113	40	E	E	6	1183	0.04	0.14
20114	40	E	SE	6	946	0.03	0.12
20115	40	Down	E	6	6404	0.20	0.13
20116	40	Down	NEE	6	2274	0.07	0.13
20117	8	E	SEE	7	1233	0.04	0.05
20118	8	Down	NEE	7	839	0.03	0.05

Table 4-30 Summary of dispersion simulations for RispEx area ID #54

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	E	E	5	3087	0.05	0.09
20102	12	E	SE	5	2664	0.04	0.03
20103	12	E	S	5	2160	0.04	0.02
20104	12	W	W	5	5181	0.09	0.10
20105	12	Up	NE	5	216	0.00	0.01
20106	12	Down	E	5	3670	0.06	0.08
20107	12	Down	SE	5	2644	0.04	0.03
20108	12	Down	S	5	1794	0.03	0.02
20109	12	Down	NE	5	2905	0.05	0.03
20110	12	Down	NEE	5	2972	0.05	0.05
20111	12	N	NEE	5	1290	0.02	0.04

20112	20	N	N	7	2578	0.04	0.03
20113	40	E	E	7	3184	0.05	0.10
20114	40	E	SE	7	2711	0.04	0.07
20115	40	Down	E	7	3690	0.06	0.09
20116	40	Down	NEE	7	2893	0.05	0.09
20117	8	E	SEE	7	1723	0.03	0.02

Table 4-31 Summary of dispersion simulations for RispEx area ID #55

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	E	E	5	2919	0.05	0.07
20102	12	E	SE	5	2831	0.05	0.02
20103	12	E	S	5	2339	0.04	0.02
20104	12	W	W	5	3351	0.06	0.06
20105	12	Up	NE	5	216	0.00	0.02
20106	12	Down	E	5	3164	0.05	0.09
20107	12	Down	SE	5	2778	0.05	0.03
20108	12	Down	S	5	2099	0.03	0.02
20109	12	Down	NE	5	3276	0.05	0.02
20110	12	Down	NEE	5	3065	0.05	0.04
20111	12	N	NEE	5	1452	0.02	0.05
20112	20	N	N	7	2746	0.05	0.03
20113	40	E	E	7	3190	0.05	0.10
20114	40	E	SE	7	2807	0.05	0.06
20115	40	Down	E	7	3156	0.05	0.13
20116	40	Down	NEE	7	2907	0.05	0.08
20117	8	E	SEE	7	1784	0.03	0.02

Table 4-32 Summary of dispersion simulations for RispEx area ID #71

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	8	N	N	4	1101	0.27	0.29
20102	8	N	W	13	227	0.06	0.31
20103	8	N	E	13	705	0.17	0.18
20104	8	S	S	5	1390	0.34	0.31
20105	8	W	S	4	311	0.08	0.13
20106	8	W	W	13	12	0.00	0.14
20107	8	E	E	13	738	0.18	0.22
20108	5	Down	W	13	1278	0.31	0.33
20109	7	Down	S	4	993	0.24	0.24
20110	7	Down	E	13	1401	0.34	0.37
20111	7	Up	E	13	1378	0.34	0.36
20112	2	Up	W	10	0	0.00	0.33
20113	2	N	W	10	1454	0.36	0.35
20114	3	W	W	10	0	0.00	0.18
20115	2	W	E	10	749	0.18	0.21
20116	2	Down	W	10	0	0.00	0.33

Table 4-33 Summary of dispersion simulations for RispEx area ID #72

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	8	N	N	4	835	0.20	0.20
20102	8	N	W	13	312	0.08	0.13
20103	8	N	E	13	383	0.09	0.09
20104	8	S	S	5	818	0.20	0.21
20105	8	W	S	4	632	0.15	0.15
20106	8	W	W	13	16	0.00	0.15
20107	8	E	E	13	1060	0.26	0.12
20108	5	Down	W	13	1197	0.29	0.31
20109	7	Down	S	4	1611	0.39	0.33
20110	7	Down	E	13	977	0.24	0.11
20111	7	Up	E	13	348	0.08	0.08
20112	2	Up	W	10	0	0.00	0.12
20113	2	N	W	10	0	0.00	0.12
20114	3	W	W	10	242	0.06	0.15
20115	2	W	E	10	982	0.24	0.31
20116	2	Down	W	10	0	0.00	0.19

Table 4-34 Summary of dispersion simulations for RispEx area ID #73

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	1735	0.24	0.23
20102	7	N	W	13	334	0.05	0.14
20103	7	N	E	13	929	0.13	0.15
20104	12	S	S	5	3110	0.43	0.33
20105	12	W	S	4	1055	0.14	0.17
20106	7	W	W	13	1057	0.15	0.19
20107	7	E	E	12	1545	0.21	0.28
20108	7	Down	W	12	1122	0.15	0.31
20109	12	Down	S	5	861	0.12	0.18
20110	7	Down	E	12	1042	0.14	0.27
20111	7	Up	E	12	839	0.12	0.45
20112	7	Up	W	12	2648	0.36	0.42
20113	4	E	E	9	2073	0.28	0.27
20114	4	Down	W	9	2184	0.30	0.30
20115	4	Up	E	9	3287	0.45	0.40
20116	4	Down	E	9	1805	0.25	0.27

Table 4-35 Summary of dispersion simulations for RispEx area ID #74

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	2536	0.25	0.20
20102	12	N	W	7	1620	0.16	0.15
20103	12	N	E	10	984	0.10	0.17
20104	12	S	S	7	1650	0.16	0.13
20105	12	W	S	7	720	0.07	0.09
20106	12	W	W	13	0	0.00	0.16
20108	12	Down	W	8	3312	0.33	0.34
20109	12	Down	S	5	773	0.08	0.14

20110	12	Down	E	9	2361	0.23	0.28
20111	12	Up	E	9	864	0.09	0.09
20112	12	Up	W	12	1328	0.13	0.19
20113	6	N	W	8	1389	0.14	0.17
20116	6	Down	W	8	3259	0.32	0.31

Table 4-36 Summary of dispersion simulations for RispEx area ID #75

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	15	N	N	4	2633	0.26	0.17
20102	15	N	W	7	884	0.09	0.13
20103	15	N	E	5	266	0.03	0.10
20104	15	S	S	7	1500	0.15	0.12
20105	15	W	S	5	593	0.06	0.09
20106	15	W	W	7	1131	0.11	0.13
20107	15	E	E	5	2678	0.27	0.15
20108	15	Down	W	8	2252	0.22	0.24
20109	15	Down	S	5	1067	0.11	0.12
20110	15	Down	E	5	885	0.09	0.10
20111	15	Up	E	5	732	0.07	0.09
20112	15	Up	W	8	1054	0.10	0.17
20113	30	N	E	5	501	0.05	0.13
20114	30	E	E	6	3799	0.38	0.25
20115	30	Down	E	5	1484	0.15	0.12
20116	30	N	N	5	2068	0.21	0.23

Table 4-37 Summary of dispersion simulations for RispEx area ID #76

Simulation no	Leak rate (kg/s)	Leak jet direction (to platform angle)	Wind dir. (from platform angle)	Wind speed (m/s)	Q9 (m3)	Vf/V from simulation	Vfpred/V from Responce surface
20101	12	N	N	4	1581	0.12	0.23
20102	12	N	W	7	742	0.06	0.09
20103	12	N	E	10	1122	0.08	0.08
20104	12	S	S	7	3411	0.25	0.10
20105	12	W	S	7	1365	0.10	0.08
20106	12	W	W	13	587	0.04	0.04
20107	12	E	E	12	1070	0.08	0.07
20108	12	Down	W	8	770	0.06	0.08
20109	12	Down	S	5	1139	0.08	0.09
20110	12	Down	E	9	1351	0.10	0.09
20111	12	Up	E	9	1743	0.13	0.10
20112	12	Up	W	12	768	0.06	0.05
20113	6	N	W	8	662	0.05	0.03
20114	30	S	S	6	4142	0.31	0.29
20115	30	W	S	6	792	0.06	0.12
20116	6	Down	W	8	425	0.03	0.03

Table 4-38 Summary of key dispersion response surface parameters for conventional process RispEx areas meanvalue A and amplitude B refers to A and B for Charmax function as presented in the main report. See also main report for definition of parameters C1 and P2.

Area ID		E	S	W	up	down	N		
03	meanvalue, A	0.13	0.10	0.15	0.13	0.16	0.13	C1	30.00
03	amplitude, B	0.06	0.05	0.14	0.02	0.05	0.07	P2	0.5
04	meanvalue, A	0.12	0.15	0.11	0.15	0.20	0.20	C1	35.00
04	amplitude, B	0.04	0.10	0.07	0.10	0.12	0.12	P2	0.5
01	meanvalue, A	0.20	0.15	0.10	0.23	0.25	0.15	C1	35.00
01	amplitude, B	0.04	0.05	0.06	0.08	0.10	0.08	P2	0.5
05	meanvalue, A	0.09	0.10	0.11	0.10	0.10	0.09	C1	35.00
05	amplitude, B	0.08	0.08	0.06	0.04	0.05	0.07	P2	0.5
02	meanvalue, A	0.16	0.13	0.14	0.15	0.20	0.15	C1	25.00
02	amplitude, B	0.05	0.08	0.03	0.10	0.05	0.01	P2	0.5
08	meanvalue, A	0.13	0.08	0.15	0.09	0.15	0.14	C1	35.00
08	amplitude, B	0.10	0.04	0.13	0.09	0.11	0.11	P2	0.5
09	meanvalue, A	0.13	0.09	0.13	0.08	0.11	0.15	C1	30.00
09	amplitude, B	0.12	0.08	0.12	0.04	0.07	0.10	P2	0.5
10	meanvalue, A	0.08	0.06	0.08	0.08	0.05	0.10	C1	30.00
10	amplitude, B	0.06	0.04	0.06	0.03	0.01	0.02	P2	0.5
11	meanvalue, A	0.14	0.15	0.11	0.15	0.11	0.11	C1	35.00
11	amplitude, B	0.08	0.04	0.04	0.06	0.07	0.09	P2	0.5
06	meanvalue, A	0.14	0.13	0.11	0.20	0.11	0.16	C1	35.00
06	amplitude, B	0.09	0.04	0.04	0.10	0.05	0.07	P2	0.5
12	meanvalue, A	0.10	0.04	0.10	0.15	0.02	0.11	C1	30.00
12	amplitude, B	0.06	0.03	0.06	0.07	0.02	0.09	P2	0.5
07	meanvalue, A	0.10	0.04	0.10	0.15	0.09	0.14	C1	30.00
07	amplitude, B	0.06	0.03	0.06	0.07	0.02	0.11	P2	0.5
13	meanvalue, A	0.14	0.11	0.14	0.07	0.11	0.11	C1	30.00
13	amplitude, B	0.13	0.09	0.13	0.03	0.01	0.01	P2	0.5
14	meanvalue, A	0.08	0.06	0.08	0.06	0.03	0.10	C1	30.00
14	amplitude, B	0.06	0.02	0.06	0.02	0.00	0.03	P2	0.5
16	meanvalue, A	0.15	0.04	0.13	0.08	0.10	0.20	C1	30.00
16	amplitude, B	0.01	0.02	0.01	0.01	0.01	0.10	P2	0.5
17	meanvalue, A	0.05	0.04	0.04	0.04	0.02	0.10	C1	30.00
17	amplitude, B	0.02	0.02	0.02	0.02	0.01	0.03	P2	0.5
18	meanvalue, A	0.11	0.10	0.10	0.15	0.12	0.12	C1	30.00
18	amplitude, B	0.05	0.05	0.04	0.10	0.05	0.02	P2	0.5
15	meanvalue, A	0.12	0.10	0.14	0.20	0.12	0.13	C1	30.00
15	amplitude, B	0.05	0.05	0.01	0.10	0.05	0.05	P2	0.5
19	meanvalue, A	0.11	0.07	0.10	0.15	0.12	0.12	C1	30.00
19	amplitude, B	0.02	0.04	0.04	0.08	0.05	0.08	P2	0.5
20	meanvalue, A	0.13	0.07	0.12	0.12	0.09	0.09	C1	25.00
20	amplitude, B	0.05	0.04	0.05	0.01	0.02	0.04	P2	0.5
22	meanvalue, A	0.12	0.12	0.13	0.13	0.14	0.14	C1	30.00
22	amplitude, B	0.06	0.12	0.13	0.04	0.05	0.05	P2	0.5
21	meanvalue, A	0.11	0.07	0.10	0.15	0.12	0.12	C1	30.00
21	amplitude, B	0.02	0.04	0.04	0.08	0.05	0.08	P2	0.5
23	meanvalue, A	0.04	0.05	0.08	0.04	0.13	0.05	C1	25
23	amplitude, B	0.01	0.00	0.07	0.03	0.13	0.00	P2	0.5
24	meanvalue, A	0.03	0.065	0.08	0.04	0.05	0.04	C1	25
24	amplitude, B	0.025	0.04	0.08	0.04	0.05	0.04	P2	0.5
25	meanvalue, A	0.06	0.08	0.11	0.07	0.09	0.08	C1	25
25	amplitude, B	0.04	0.04	0.10	0.05	0.02	0.02	P2	0.5
26	meanvalue, A	0.03	0.075	0.025	0.04	0.04	0.05	C1	25
26	amplitude, B	0.00	0.015	0.015	0.02	0.03	0.00	P2	0.5

Figure 4-1 Summary of key dispersion response surface parameters for wellhead and FPSO RispEx areas (A and B for chartmax, and C1 and P2). All parameters are defined in the main report

Area ID	N	E	S	W	up	down	N		
51	meanvalue, A	0.08	0.095	0.075	0.04	0.05	0.1	C1	40
51	amplitude, B	0.075	0.075	0.07	0.01	0.03	0.02	P2	0.3
52	meanvalue, A	0.08	0.1	0.075	0.016	0.035	0.1	C1	40
52	amplitude, B	0.075	0.095	0.07	0.01	0.025	0.01	P2	0.3
53	meanvalue, A	0.03	0.06	0.04	0.08	0.055	0.055	C1	45
53	amplitude, B	0.01	0.057	0.02	0.01	0.04	0.052	P2	0.3
54	meanvalue, A	0.04	0.07	0.04	0.07	0.02	0.09	C1	45
54	amplitude, B	0.02	0.01	0.02	0.01	0.01	0.02	P2	0.3
55	meanvalue, A	0.04	0.06	0.04	0.05	0.02	0.09	C1	45
55	amplitude, B	0.035	0.04	0.03	0.03	0.01	0.05	P2	0.3
71	meanvalue, A	0.22	0.13	0.22	0.12	0.22	0.22	C1	30
71	amplitude, B	0.15	0.09	0.12	0.06	0.09	0.09	P2	0.5
72	meanvalue, A	0.12	0.18	0.12	0.12	0.12	0.32	C1	35
72	amplitude, B	0.08	0.14	0.08	0.02	0.05	0.16	P2	0.5
73	meanvalue, A	0.13	0.13	0.2	0.15	0.4	0.16	C1	30
73	amplitude, B	0.09	0.12	0.17	0.02	0.02	0.13	P2	0.5
74	meanvalue, A	0.155	0.1	0.2	0.1	0.12	0.16	C1	30
74	amplitude, B	0.145	0.05	0.18	0.05	0.05	0.155	P2	0.5
75	meanvalue, A	0.12	0.15	0.15	0.08	0.1	0.12	C1	30
75	amplitude, B	0.115	0.05	0.12	0.04	0.05	0.1	P2	0.5

5 Explosion simulations

K value corresponding to the best curve fit per representative module are tabulated in Table 5-1. See main report for definition of K, as included in the function:

$$\frac{P}{P_0} = \Phi \cdot K \cdot V_f^{p_{eV}}$$

Table 5-1 Summary of key parameters of representative RispEx conventional process areas

	K paramteter predicted by simulations		
Area ID	Vertical divisions, K_W	Horizontal divisions, K_D	Drag, K_{Drag}
3	1.0E-04	9.0E-05	2.1E-05
4	1.1E-04	8.5E-05	2.2E-05
1	1.2E-04	9.3E-05	2.2E-05
5	1.1E-04	8.5E-05	2.2E-05
2	1.2E-04	9.2E-05	2.2E-05
8	7.8E-05	7.0E-05	1.6E-05
9	7.7E-05	6.9E-05	1.6E-05
10	1.3E-05	1.4E-05	2.8E-06
11	7.7E-05	6.6E-05	1.6E-05
6	7.7E-05	6.6E-05	1.6E-05
12	2.4E-05	2.3E-05	5.2E-06
7	5.4E-05	5.3E-05	1.3E-05
13	4.9E-05	4.5E-05	9.3E-06
14	1.6E-05	1.6E-05	2.9E-06
16	4.5E-05	5.9E-05	1.2E-05
17	6.8E-06	8.5E-06	1.2E-06
18	6.7E-05	7.4E-05	2.0E-05
15	6.7E-05	7.4E-05	2.0E-05
19	6.7E-05	7.4E-05	2.0E-05

21	6.7E-05	7.4E-05	2.0E-05
20	2.4E-05	3.1E-05	7.1E-06
22	8.5E-05	7.6E-05	1.7E-05
23	7.5E-05	8.7E-05	2.1E-05
24	7.5E-05	8.7E-05	2.4E-05
25	7.5E-05	8.7E-05	2.6E-05
26	3.0E-05	3.9E-05	1.4E-05
51	2.5E-05	3.5E-05	3.1E-05
52	1.3E-05	3.7E-05	9.9E-06
53	7.2E-06	2.8E-05	8.1E-06
54	8.4E-06	3.3E-05	8.9E-06
55	4.3E-06	2.9E-05	8.9E-06
71	1.6E-04	1.1E-04	3.1E-05
72	1.6E-04	1.1E-04	3.2E-05
73	9.2E-05	2.9E-05	1.6E-05
74	4.8E-05	2.9E-05	1.0E-05
75	4.6E-05	2.7E-05	9.8E-06

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

RispEx Appendix C – RispEx Source Code and look-up files

Report for:
RISP Participants, att: Equinor Energy AS

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

RispEx-decision support for explosion design loads – Appendix C: RispEx source code and look-up files

Security classification of this report:	Distribute only after client's acceptance

Report no:	**Revision:**	**Report date:**
DNV report no 2020-0628	Rev 03	22 September 2023
Prepared by:	**Reviewed by:**	**Approved by:**
Sjur Helland, DNV	Jens Johansson Garstad, DNV	Unni Nord Samdal, Equinor
____________________	____________________	____________________

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Rev 01A	19.10.2021	Update with process area types and larger process areas	Petter Vollestad, DNV Jens Garstad, DNV
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Rev 03A	28.06.2023	Updated to reflect new drag model.	Sjur Helland, DNV Jens Garstad, DNV
Rev 03	22.09.2023	Editorial changes	Sjur Helland, DNV

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1 Look-up files

The source code of the RispEx tool reads from look-up files which contains default interpolation parameters as derived in the main report and reference curves such as the cloud size probability curves for the representative areas. The reason for including these data in separate files is to make it easy to update or add reference curves that can be interpolated on when RispEx estimate the curves defining the calculated explosion risk for an area.

Table 1-1 contains a list of all look-up files and a description of what the files contain. For evaluation of specific cloud size probability curves or other data related to specific representative areas, the files can be opened and assessed manually. For this reason, all the relevant curves for the 33 RispEx representative areas are not plotted in this report or appendices.

Table 1-1: Summary of all RispEx tool look-up files

heading	Description and content
AreaKeyDataF	For FPSO representative process areas: • First colomn is reference to area ID from main report • Second colomn is volume of area • Third colomn is confinement level of area
AreaKeyDataP	For conventional representative process areas (at jacket / SPAR): • First colomn is reference to area ID from main report • Second colomn is volume of area • Third colomn is confinement level of area
AreaKeyDataW	For representative wellhead area (at jacket / SPAR): • First colomn is reference to area ID from main report • Second colomn is volume of area • Third colomn is confinement level of area
AreaNoF	For FPSO representative process areas: • First colomn contains representative area size per area size category (used in linear interpolation) • Second colomn contains the number of representative area for that particular size category
AreaNoP	For conventional representative process areas (at jacket / SPAR): • First colomn contains representative area size per area size category (used in linear interpolation) • Second colomn contains the number of representative area for that particular size category
AreaNoW	For representative wellhead area (at jacket / SPAR): • First colomn contains representative area size per area size category (used in linear interpolation) • Second colomn contains the number of representative area for that particular size category
ExplosionCurveMaxParam	Parameters used for capping total volume and openness in the explosion overpressure vs cloud volume calculations: • First two rows apply to FPSO process areas • Next to rows apply to process area (at jacket / SPAR) • Last two rows apply to wellhead area (at Jacket / SPAR)
ExplosionParam	Parameters used for estimation of explosion vs cloud size relation for firewall, and correlation parameters to find global pressure, as well as durations for explosion loads. See main report chapter 4 for definition and value of all parameters. • First colomn parameter set for representative process areas (at jacket / SPAR • Second colomn FPSO representative process areas • Third colomn representative wellhead area (at jacket / SPAR):

heading	Description and content
ExplosionParamDrag	Parameters used for estimation of drag vs cloud size relation, as well as durations for drag loads. See main report chapter 4 for definition and value of all parameters. • First colomn parameter set for representative process areas (at jacket / SPAR • Second colomn FPSO representative process areas • Third colomn representative wellhead area (at jacket / SPAR):
ExplosionParamHorizontal	Parameters used for estimation of explosion vs cloud size relation for decks, and correlation parameters to find global pressure, as well as durations for explosion loads. See main report chapter 4 for definition and value of all parameters. • First colomn parameter set for representative process areas (at jacket / SPAR • Second colomn FPSO representative process areas • Third colomn representative wellhead area (at jacket / SPAR):
FlashFrac	Flash fraction used
IntParam	Parameters used for interpolation of cloud size exceedance probabilities. See main report chapter 4 for definition and value of all parameters. • First colomn parameter set for representative process areas (at jacket / SPAR • Second colomn FPSO representative process areas • Third colomn representative wellhead area (at jacket / SPAR
LeakFreqParam	Parameters used for estimation of leak frequency per area based on volume of are a(process areas) or number of wells (wellhead areas). See main report chapter 4 for definition and value of all parameters.
PCloudSixeArrayLF	For FPSO representative process areas: • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from large leaks are given in this file (not that it is still not the probability given large leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArrayLP	For conventional representative process areas (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from large leaks are given in this file (not that it is still not the probability given large leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArrayLW	For representative wellhead area (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from large leaks are given in this file (not that it is still not the probability given large leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArrayMF	For FPSO representative process areas: • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from medium leaks are given in this file (not that it is still not the probability given medium leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArrayMP	For conventional representative process areas (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from medium leaks are given in this file (not that it is still not the probability given medium leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArrayMW	For representative wellhead area (at jacket / SPAR):

heading	Description and content
	• One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from medium leaks are given in this file (not that it is still not the probability given medium leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArraySF	For FPSO representative process areas: • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from small leaks are given in this file (not that it is still not the probability given small leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArraySW	For representative wellhead area (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from small leaks are given in this file (not that it is still not the probability given small leaks, it is the probability given any leak >0.1kg/s)
PCloudSixeArraySP	For conventional representative process areas (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given leak corresponding to the probability specified in the corresponding row in the file PProbArrayLF. Only contribution from small leaks are given in this file (not that it is still not the probability given small leaks, it is the probability given any leak >0.1kg/s)
PignitionLF	For FPSO representative process areas: • Ignition probability per representative area for large leaks
PignitionLP	For conventional representative process areas: • Ignition probability per representative area for large leaks
PignitionLW	For conventional representative wellhead areas (at jacket / SPAR): • Ignition probability per representative area for large leaks
PignitionMF	For FPSO representative process areas: • Ignition probability per representative area for medium leaks
PignitionMP	For FPSO representative process areas: • Ignition probability per representative area for medium leaks
PignitionMW	For conventional representative process areas (at jacket / SPAR): • Ignition probability per representative area for medium leaks
PignitionSF	For FPSO representative process areas: • Ignition probability per representative area for small leaks
PignitionSP	For FPSO representative process areas: • Ignition probability per representative area for small leaks
PignitionSW	For conventional representative process areas (at jacket / SPAR): • Ignition probability per representative area for small leaks
PProbArrayLF	Probability axis for PCloudSixeArrayLF curves
PProbArrayLP	Probability axis for PCloudSixeArrayLP curves
PProbArrayLW	Probability axis for PCloudSixeArrayLW curves
PProbArrayMF	Probability axis for PCloudSixeArrayMF curves
PProbArrayMP	Probability axis for PCloudSixeArrayMP curves
PProbArrayMW	Probability axis for PCloudSixeArrayMW curves

heading	Description and content
PProbArraySF	Probability axis for PCloudSixeArraySF curves
PProbArraySP	Probability axis for PCloudSixeArraySP curves
PProbArraySW	Probability axis for PCloudSixeArraySW curves
WCloudSixeArraySW	For well events in representative wellhead area (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given 2 kg/s blowout corresponding to the probability specified in the corresponding row in the file WProbArraySW
WCloudSixeArrayMW	For well events in representative wellhead area (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given 2 kg/s blowout corresponding to the probability specified in the corresponding row in the file WProbArraySW
WCloudSixeArrayLW	For well events in representative wellhead area (at jacket / SPAR): • One colomn per representative area containing the cloud size exceeded given 2 kg/s blowout corresponding to the probability specified in the corresponding row in the file WProbArraySW
WignitionSW	For conventional representative wellhead areas (at jacket / SPAR): • Ignition probability per representative area for 2 kg/s blowouts
WignitionMW	For conventional representative wellhead areas (at jacket / SPAR): • Ignition probability per representative area for 10 kg/s blowouts
WignitionLW	For conventional representative wellhead areas (at jacket / SPAR): • Ignition probability per representative area for 50 kg/s blowouts
WProbArraySW	Probability axis for WCloudSixeArraySW curves
WProbArrayMW	Probability axis for WCloudSixeArrayMW curves
WProbArrayLW	Probability axis for WCloudSixeArrayLW curves

2 Source code

The complete Source code including look-up files are included in the zip file RispEx_v2.zip (may also be published to github upon request).

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

RispEx Appendix D – Comparison with PLOFAM/MISOF analysis

Report for:
RISP Participants, att: Equinor Energy AS

JIP: Risk informed decision support in development projects (RISP)		
RispEx-decision support for explosion design loads – Appendix D: Comparison with PLOFAM/MISOF analysis		
Security classification of this report:	Distribute only after client's acceptance	
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Page

1 Introduction

1.1 General

As part of the testing and validation process of RispEx, a comparison with available PLOFAM2/MISOF2 analysis has been performed.

When comparing explosion analysis performed by different consultant companies with RispEx, it is expected to see a variance in the results. Similarly, a variance would be expected if two different consultant companies (with two different tools) performed an explosion analysis of the same module. Since the complex methods for calculating explosion loads includes subjective evaluations, deviations are expected also on individual level independent of tools etc.

The goal of the comparison is to investigate whether there are systematic overestimation or underestimation in the different steps of RispEx when comparing to the available PLOFAM/MISOF analysis.

The comparison has been performed for the different steps in the explosion analysis (if they were available):

- Leak frequency
- Frequency – ignited cloud relation
- Ignited cloud – pressure relation
- Overpressure – frequency relation

Modules from 5 different installations have been included, and in addition the MISOF test modules are included. For confidentiality reasons, the installations have been anonymized.

1.2 Updated versions of RispEx

No additional benchmarking was performed when updating RispEx to support larger process areas and different area types. The benchmarking documented in this report was performed as part of the development of the initial version of RispEx (Version 1.0). The benchmarking remains valid for "General process" process areas and for Wellhead areas.

2 Process areas

Modules from 5 installations: Installation A to D and the MISOF test modules are investigated in the present section. Some characteristics of the modules are given in Table 2-1 and geometrical properties are listed in Table 2-2. The confinement factor is also shown visually in Figure 2-1.

Comparisons with TRA values and RispEx calculations are provided in the proceeding subsections.

Table 2-1: Module description and fraction of gas leaks for process modules.

Installation	Module	Description	Gas fraction of leaks
Installation A	P10/20	NGL stab., glycol contactor, scrubber, gas metering, export compressor.	40 %
	P30/40	NGL stab., coolers, turboexpander, recompression, gas metering	100 %

Installation B	CP12/21	Process equipment	57% of the leaks are gas leaks at Installation B. Details are not known for the specific modules.
Installation C	M30D	Process equipment	50 % gas
	M30L	Process equipment	30 % gas
	M30W	Process equipment	20 % gas
MISOF test module	CM42EW	Generic modules	Leak frequency calculated in a similar way as RispEx.
	CM132EW		
Installation D	M1	Process equipment	63%
	M2		76%
	M3		95%
	M4		100%

Table 2-2: Module dimensions and confinement for process modules.

Installation	Module	Dimensions [m] (Length X Width X Height)	Module volume [m3]	Openness (N, E, S, W) (U, D)	Confinement factor
Installation A	P10/20	27 x 46 x 9,5	11 799	0.34, 0.24, 0.36, 0 0, 0	0.073
	P30/40	27 x 46 x 9,5	11 799	0.36, 0.26, 0.24, 0 0, 0	0.069
Installation B	CP12/21	15 x 33 x 9	4 455	0.8,0,0.4,0 0, 0	0.087
Installation C	M30D	32 x 27 x 7	6 048	0.2,0.9,0.8,0 0, 0	0.154
	M30L	32 x 27 x 9	7 776	1,0.9,0.6,0 0, 0	0.244
	M30W	14 x 27 x 9	3 402	1,0.9,0.75,0 0.3, 0	0.37
MISOF test module	CM42EW	16 x 30 x 8,25	3 960	1,0,1,0 0, 0	0.154

	CM132EW	25 x 52 x 10,25	13 325	1,0,1,0 0, 0	0.123
Installation D	M1	35 x 28 x 7	6 860	0.75, 0.75, 0.75, 0 0, 0	0.18
	M2	25 x 28 x 8	5 600	1, 0.85, 0.75, 0 0, 0	0.24
	M3	25 x 28 x 8	5 600	1, 1, 0.75, 0 0, 0	0.26
	M4	25 x 28 x 6	4 200	1, 0.75, 1, 0 1, 0	0.55

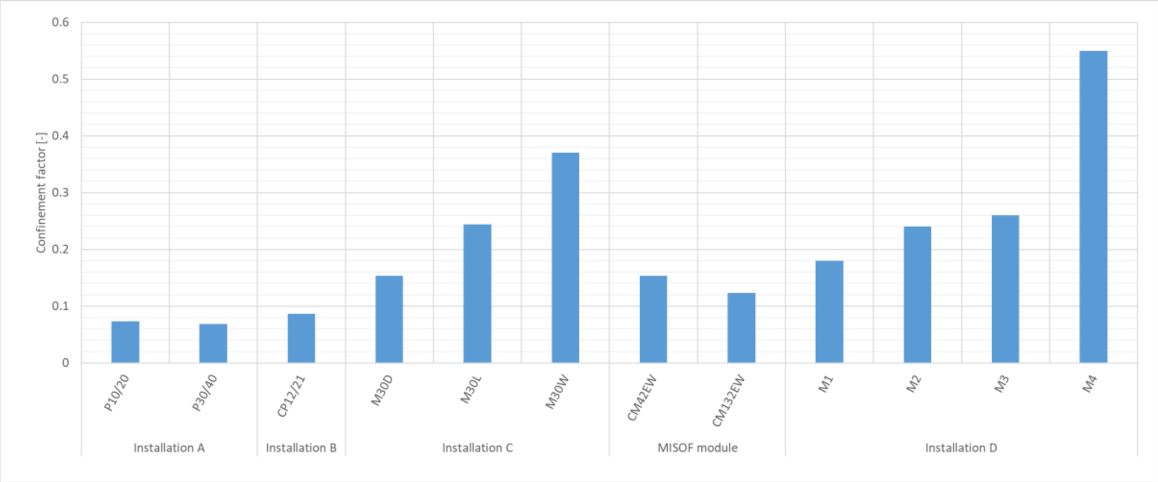

Figure 2-1: Confinement factors for the assessed modules.

2.1 Leak frequency

Figure 2-2 shows the relative difference between detailed approach in the TRAs and the model in RispEx for calculation of leak frequency. Note that the analysis of the MISOF test modules applies a similar approach to estimate leak frequency as RispEx. Hence, the results for the MSIOF test modules are close to identical to RispEx. Furthermore, Figure 2-3 elucidates the differences by providing the leak frequency per volume for each of the process modules.

It can be observed that the largest relative differences are found for the Installation A modules, and the leak frequency for all Installation A modules are overpredicted. The result is more mixed for the remaining modules.

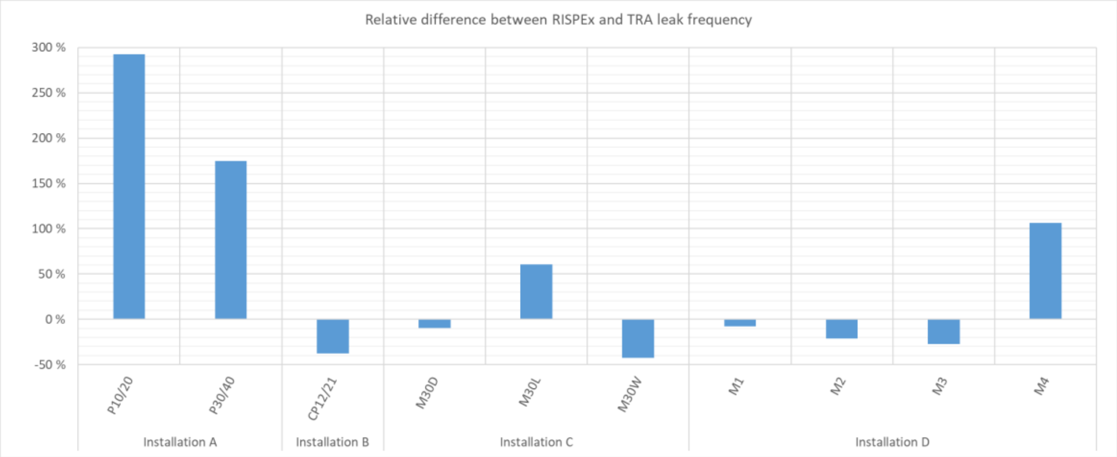

Figure 2-2: Relative difference between leak frequency predicted by RispEx and values calculated in TRAs.

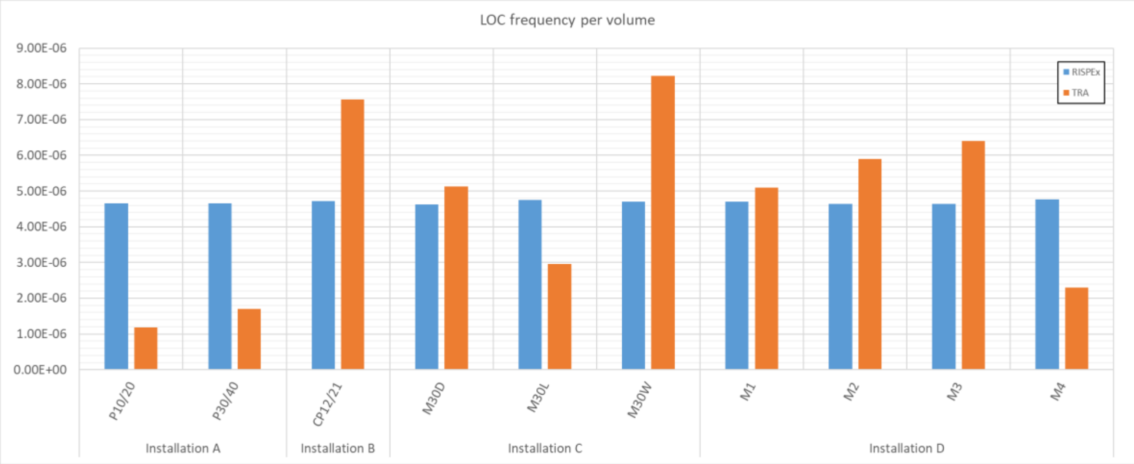

Figure 2-3: Leak frequency per volume for the analysed modules.

2.2 Installation A

Modules P10/20 and P30/40 are analyzed for Installation A. The ignited volume vs cumulative frequency for these modules are reported in Figure 2-4 and Figure 2-5 for both the RispEx prediction and the TRA calculations. A third curve is included which shows the results from RispEx when the leak frequency is adjusted to match the leak frequency in the TRA. It can be seen in Figure 2-4 and Figure 2-5 that the adjusted curve provides a good estimate.

Pressure exceedance curves from the comparison between the TRA and RispEx are given in Figure 2-6 and Figure 2-7. Note that, even if the adjusted cloud exceedance curve for P10/20 (Figure 2-4) is a good match, the adjusted pressure exceedance curve deviates slightly more. This is related to that RispEx predicts somewhat higher pressures than the Installation A TRA, ref. Figure 2-8.

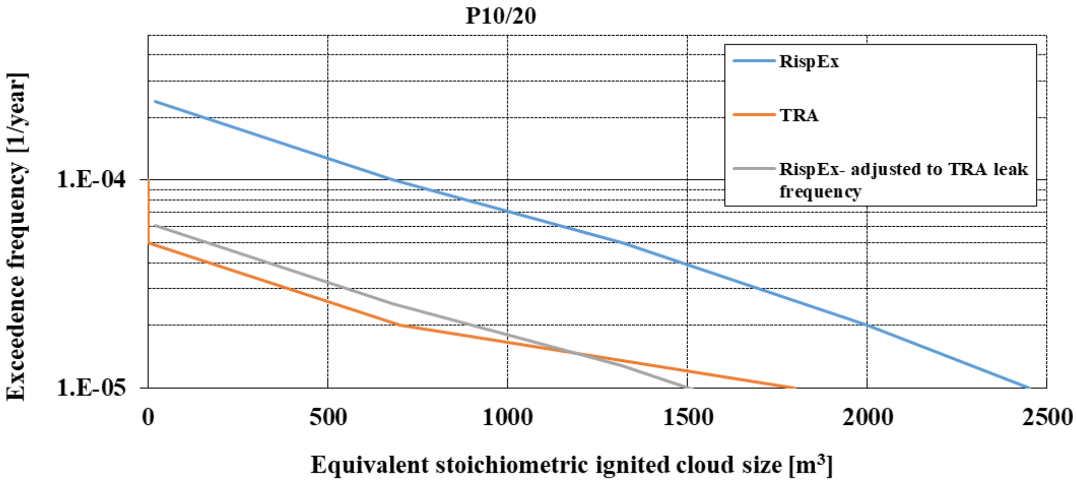

Figure 2-4: Cloud exceedance for the P10/20 module at INSTALLATION A.

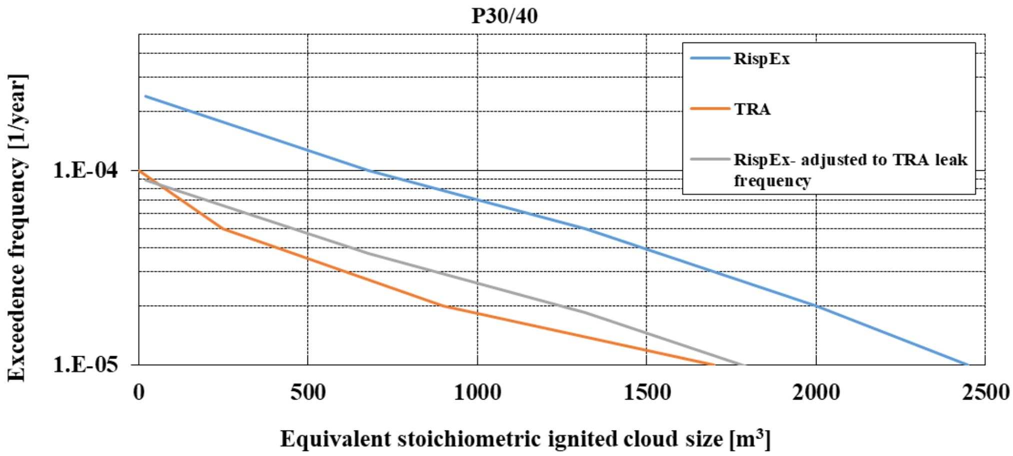

Figure 2-5: Cloud exceedance for the P30/40 module at INSTALLATION A.

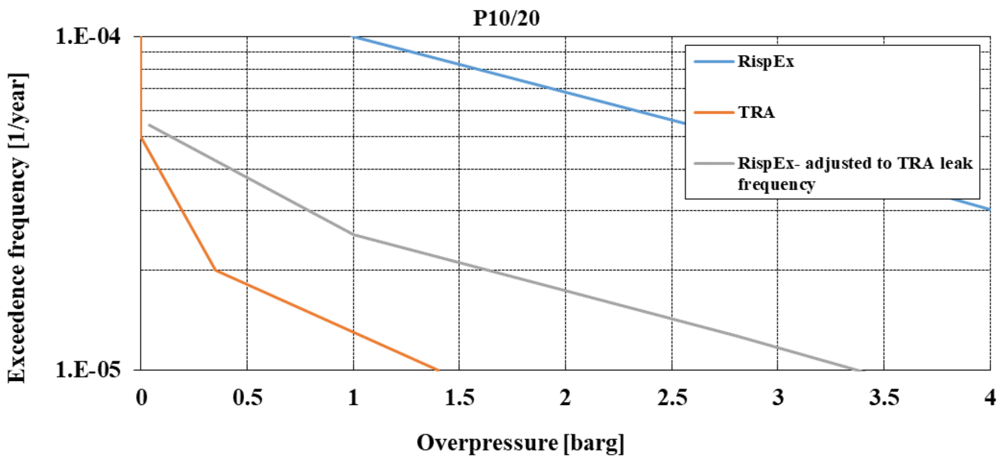

Figure 2-6: Pressure exceedance for the P10/20 module at INSTALLATION A.

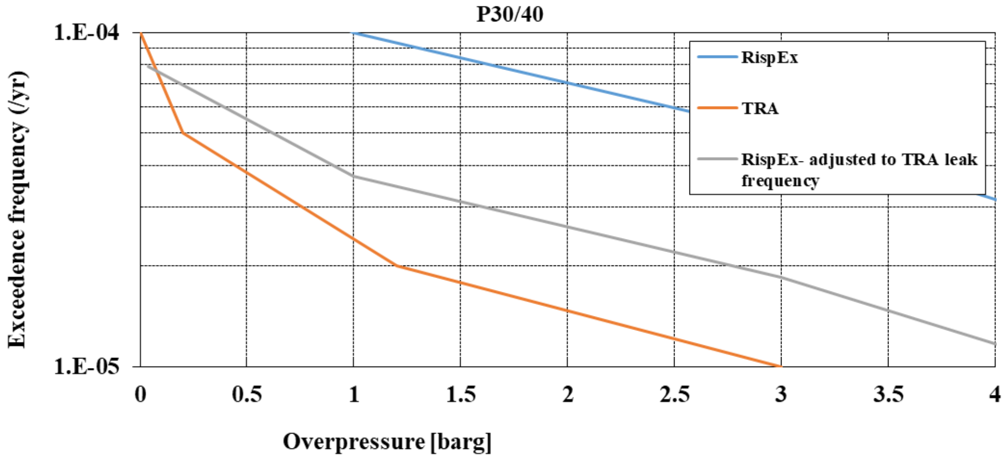

Figure 2-7: Pressure exceedance for the P30/40 module at INSTALLATION A.

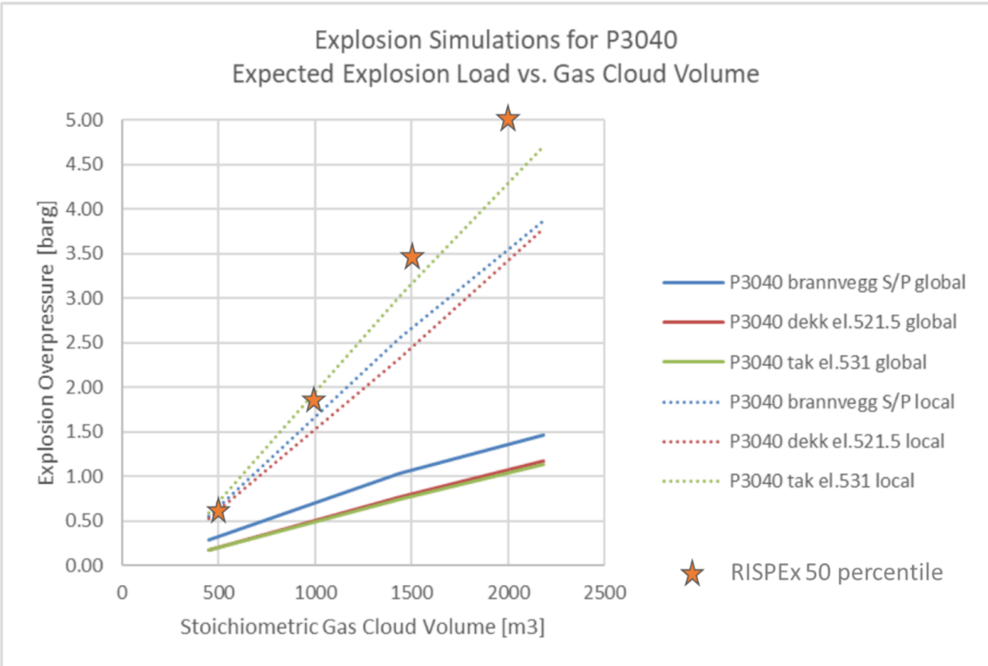

Figure 2-8: Explosion load as a function of ignited cloud volume for INSTALLATION A P30/40 (figure adopted from TRA and augmented with RispEx results).

Other modules on Installation A have also been compared, but not reported here. Worth mentioning is that modules from Installation A containing only/mostly liquid leakages, gets a significant overpredicted explosion load with RispEx. This is as expected, as the current leak frequency model in RispEx do not distinguish between liquid/oil and gas modules.

It is also worth mentioning that the modules on installation A are quite confined. The modules are equipped with pop-out panels, and RispEx has not currently this feature. These panels have therefore been modelled as fixed in RispEx, and based on this an overprediction of the explosions load for a given cloud size is expected.

2.3 Installation B

Benchmark results for the process area of Installation B are given in the present section, while results from the wellhead area are given in Sec. 3. For Installation B, the RispEx leak frequency is 40% lower than the one in the TRA. Hence, the predicted cloud sizes (Figure 2-9) are lower than the ones given in the detailed analysis. When the leak frequency is adjusted to the TRA level, the pressure exceedance curve is close to the one in the TRA. Also, the explosion load as a function of ignited cloud volume provides a good match in the most important cloud size region. This is shown in Figure 2-11.

Note that there is an air intake located in proximity to the CP12/21 area at installation B that gives a contribution to the ignition probability for large leaks, and consequently affects the calculated explosion risk. The external ignition probability for large leaks in the area as estimated in the QRA (0.7% for large leaks) is included in the RispEx calculation.

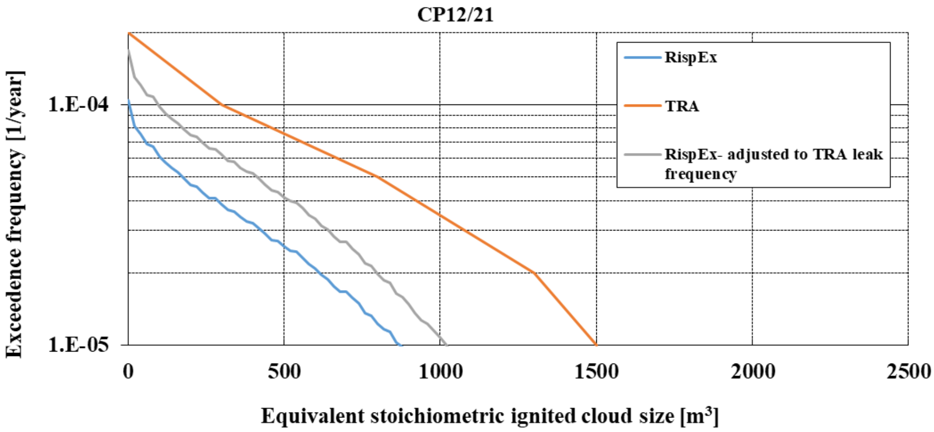

Figure 2-9: Cloud exceedance for the CP12/21 module at Installation B.

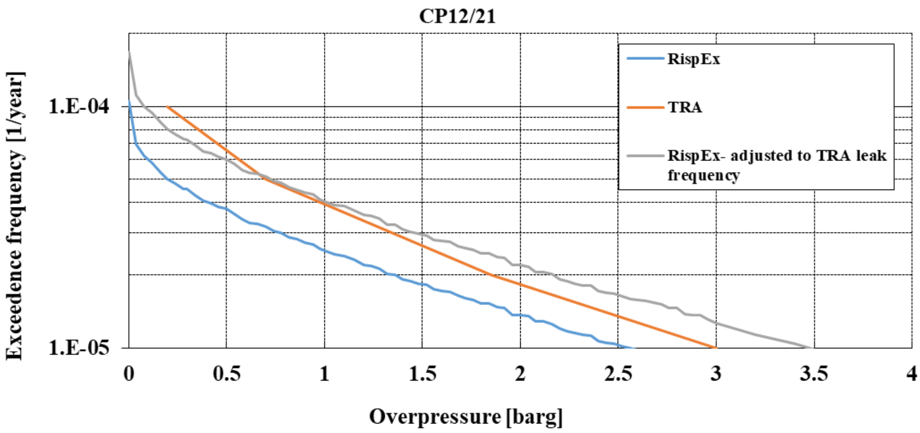

Figure 2-10: Pressure exceedance for the CP12/21 module at Installation B.

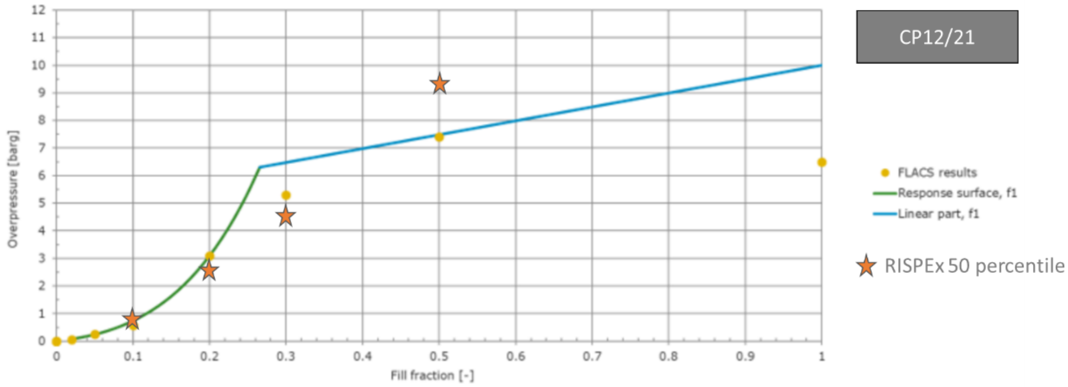

Figure 2-11: Explosion load as a function of ignited cloud volume for Installation B CP12/21 (figure adopted from TRA and augmented with RispEx results).

2.4 Installation C

TRA results for three modules at Installation C, i.e. M30D, M30L and M30W are compared with RispEx predictions below. The cloud exceedance curves are given in Figure 2-12, Figure 2-13 and Figure 2-14 and the pressure exceedance curves are provided in Figure 2-15, Figure 2-16 and Figure 2-17. One can observe that RispEx provides decent results.

The RispEx model for generated overpressure as a function of ignited cloud volumes is also in agreement with the detailed assessment of the TRA, see Figure 2-18, Figure 2-19 and Figure 2-20.

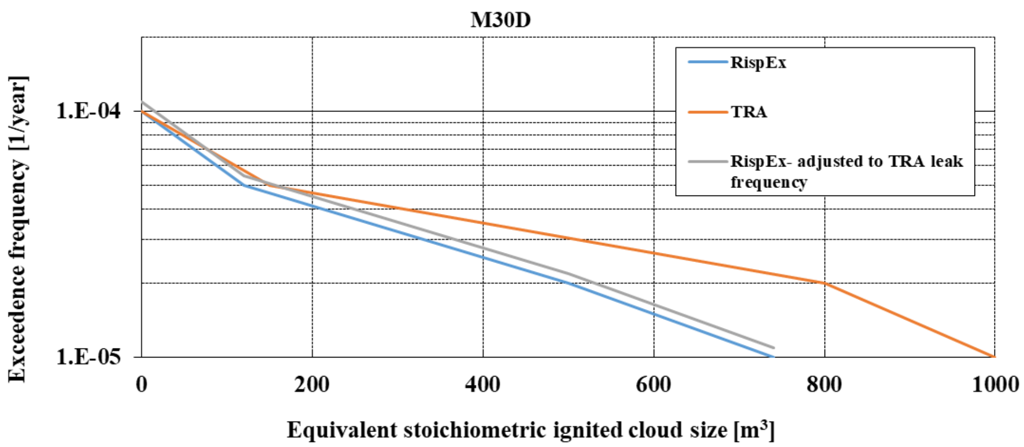

Figure 2-12: Cloud exceedance for the M30D module at Installation C.

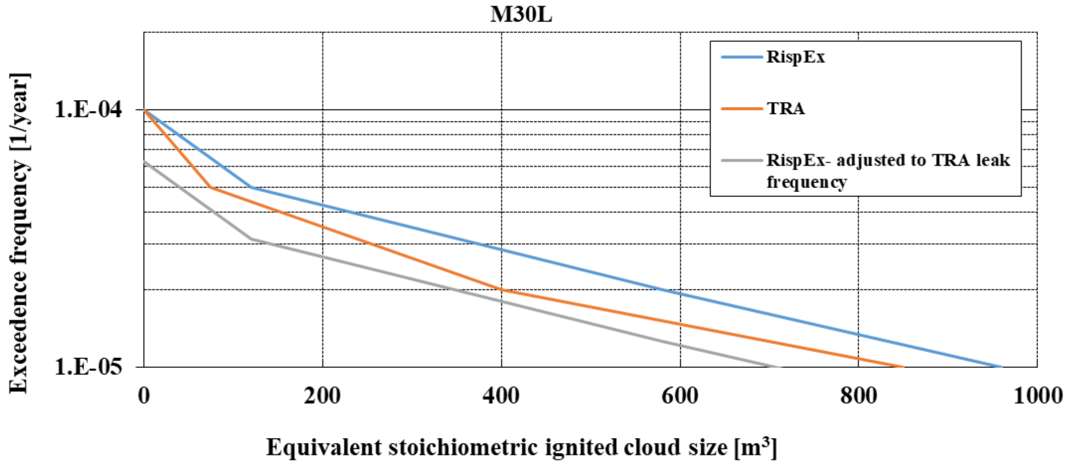

Figure 2-13: Cloud exceedance for the M30L module at Installation C.

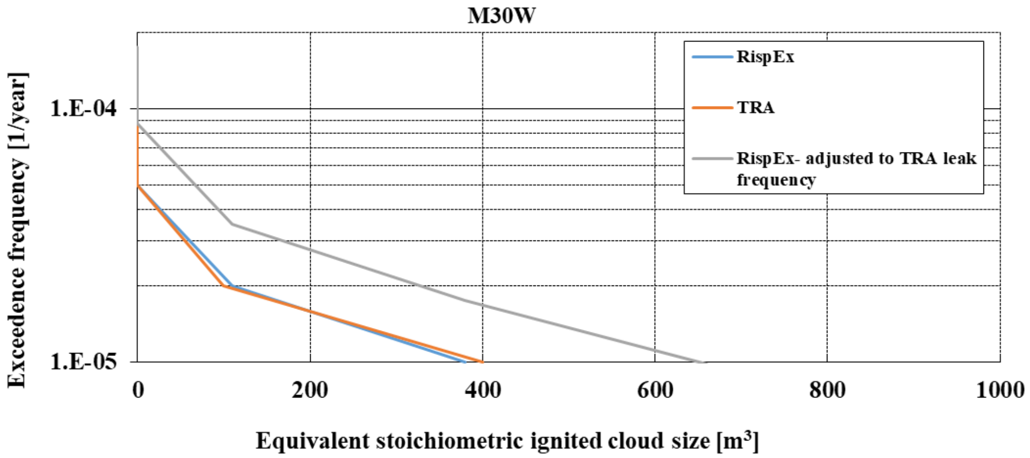

Figure 2-14: Cloud exceedance for the M30W module at Installation C.

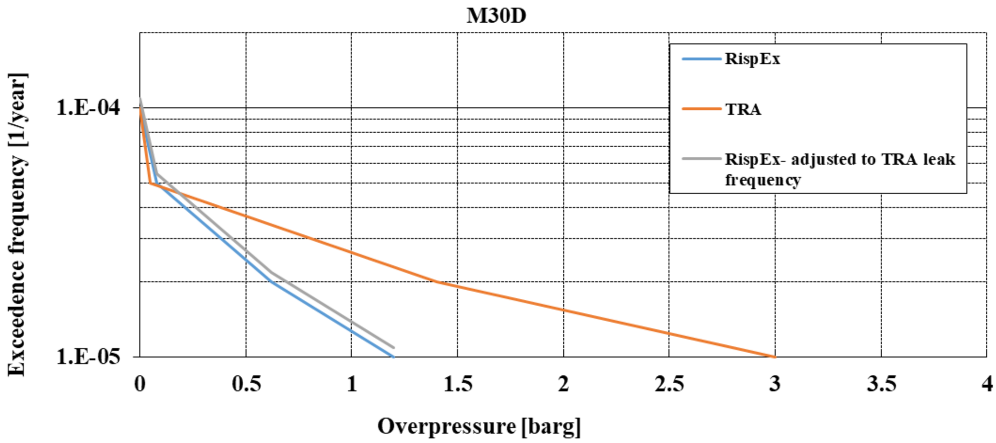

Figure 2-15: Pressure exceedance for the M30D module at Installation C.

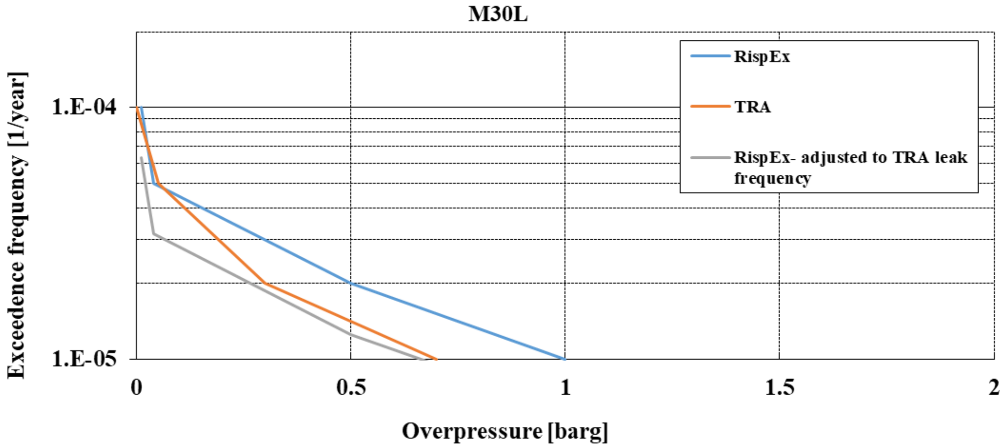

Figure 2-16: Pressure exceedance for the M30L module at Installation C.

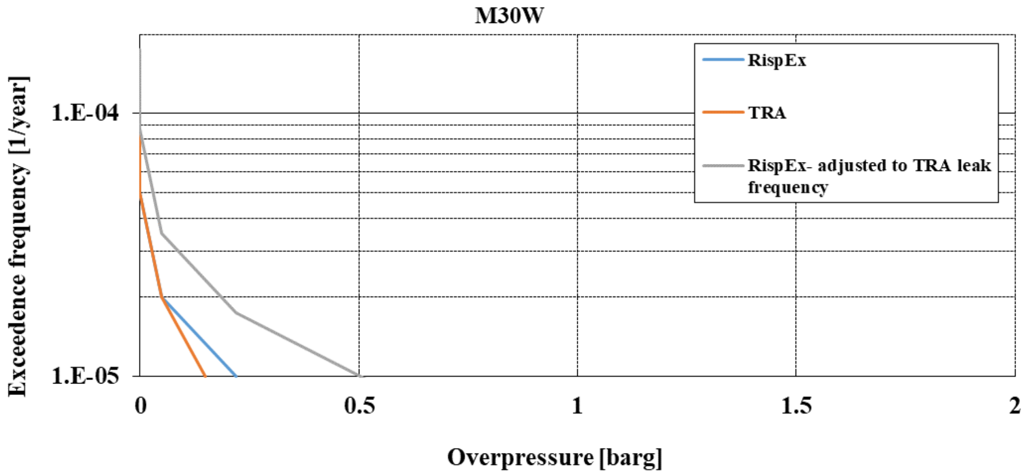

Figure 2-17: Pressure exceedance for the M30W module at Installation C.

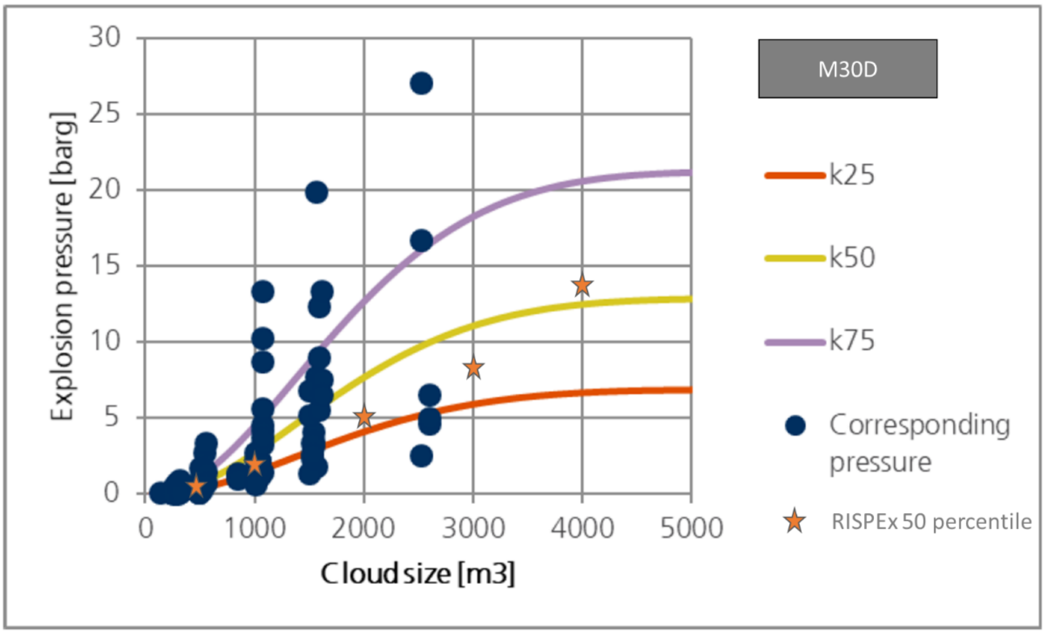

Figure 2-18: Explosion load as a function of ignited cloud volume for Installation C M30D (figure adopted from TRA and augmented with RispEx results).

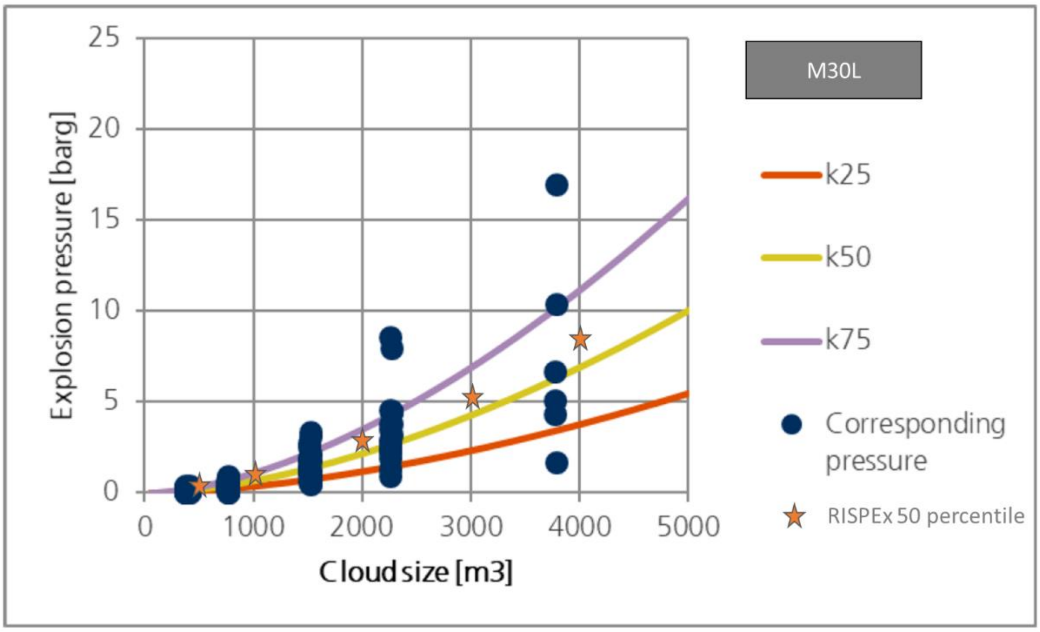

Figure 2-19: Explosion load as a function of ignited cloud volume for Installation C M30L (figure adopted from TRA and augmented with RispEx results).

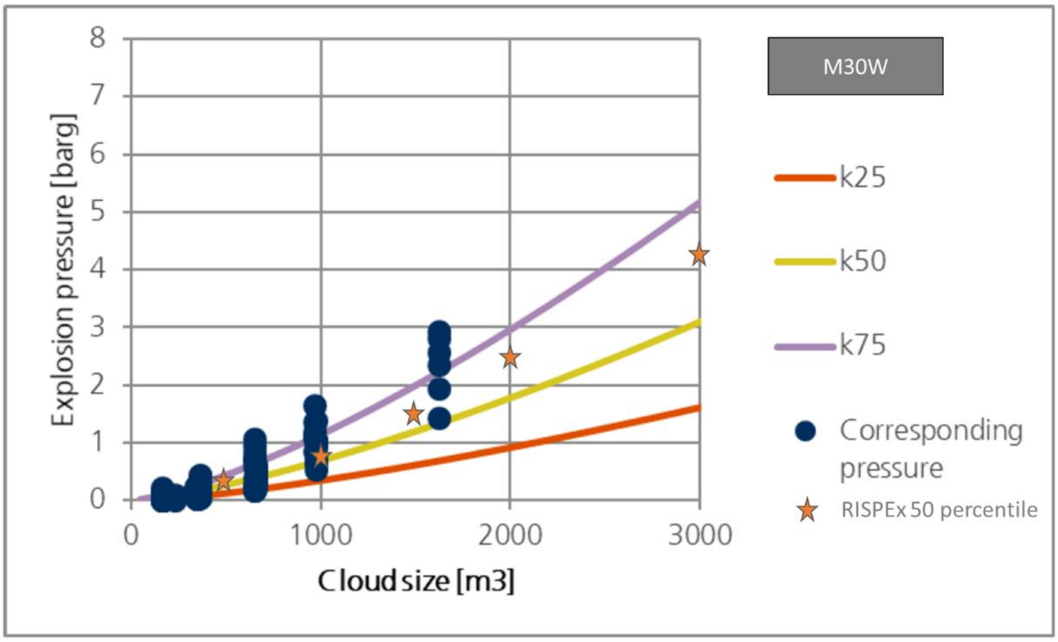

Figure 2-20: Explosion load as a function of ignited cloud volume for Installation C M30W (figure adopted from TRA and augmented with RispEx results).

2.5 MISOF test module

The analysis of the generic modules applies a similar leak frequency model as RispEx. Consequently, the predicted leak frequencies are very similar to RispEx. Adjusted RispEx curves for pressure and cloud volume, as given for, e.g., Installation C in section 2.4, is therefore not relevant here. Also, as the MISOF analysis uses a simplified approach to calculate explosion loads as a function of cloud volume, the pressure exceedance curves are not relevant to compare with. Hence, only the ignited cloud volume vs frequency is of relevance for these modules. The results can be seen in Figure 2-21 and Figure 2-22 and demonstrates a decent match between the two approaches.

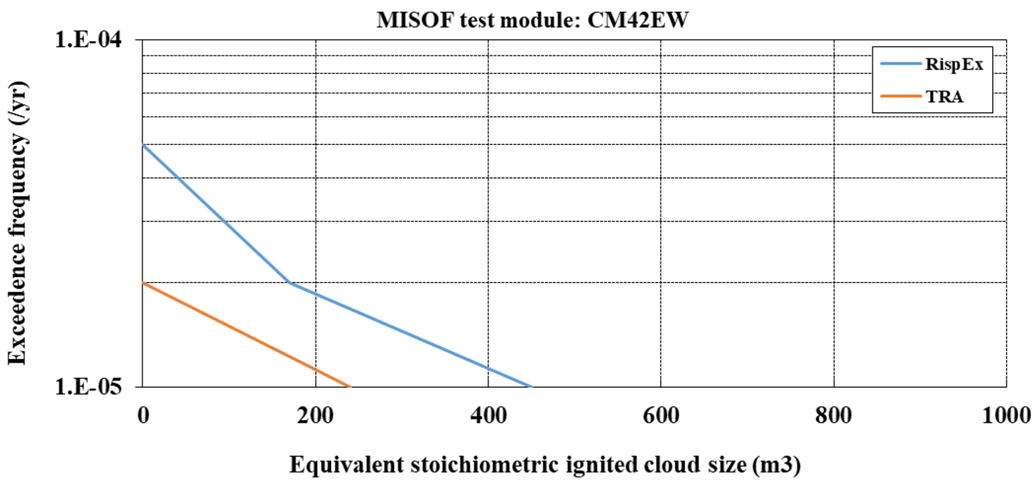

Figure 2-21: Cloud exceedance for the generic MISOF module CM42EW.

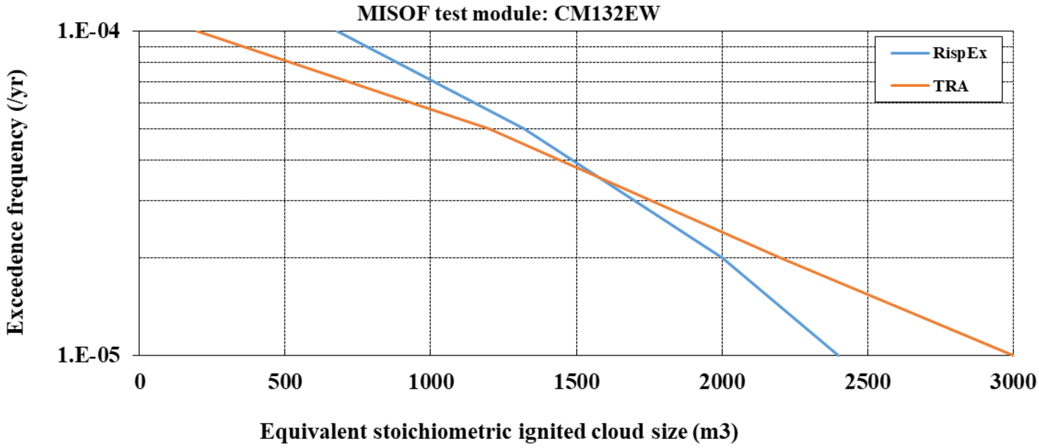

Figure 2-22: Cloud exceedance for the generic MISOF module CM132EW.

2.6 Installation D

The TRA results for four of the modules in the process area at Installation D (M1, M2, M3 and M4) are compared with RispEx predictions in this work. Individual results for each module are not available for this installation. However, the combined explosion load on the common barrier for these four modules is available, and it is this target that RispEx results are compared with. This curve is established by summing the contributions from the four individual modules. The resulting curve can be seen in Figure 2-23, and the RispEx model gives slightly higher loads compared to the TRA.

As an indication of how the RispEx model for explosion loads compares to the Installation D TRA, results from the analysis of one of the modules are given in Figure 2-24. In can be observed that RispEx predicts lower explosion load for a given cloud size that the TRA in this case, and this is because the modules on Installation D have a relatively high congestion.

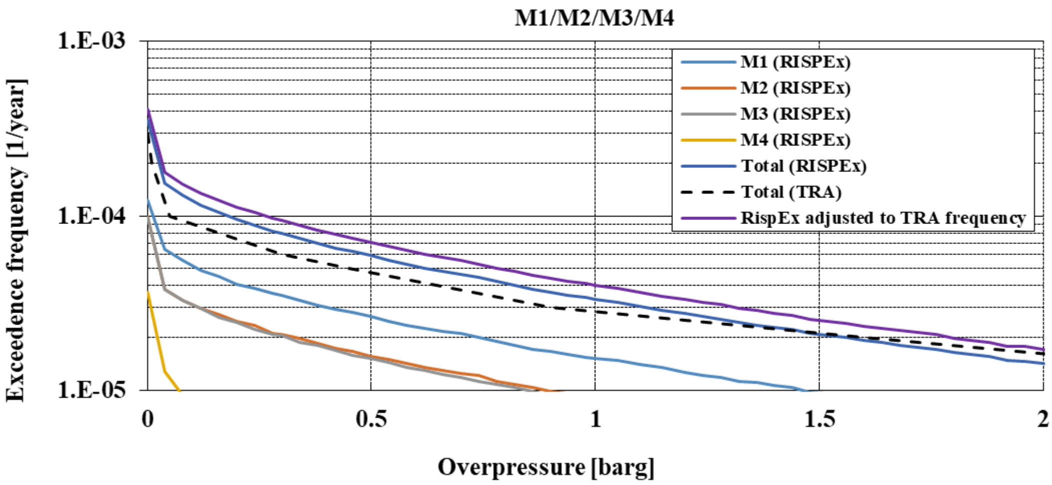

Figure 2-23: Explosion load vs frequency for the common fire wall for the modules M1, M2, M3 and M4 at Installation D. The TRA result is given as a dashed line. This line should be compared to the line dubbed “Total (RispEx)”.

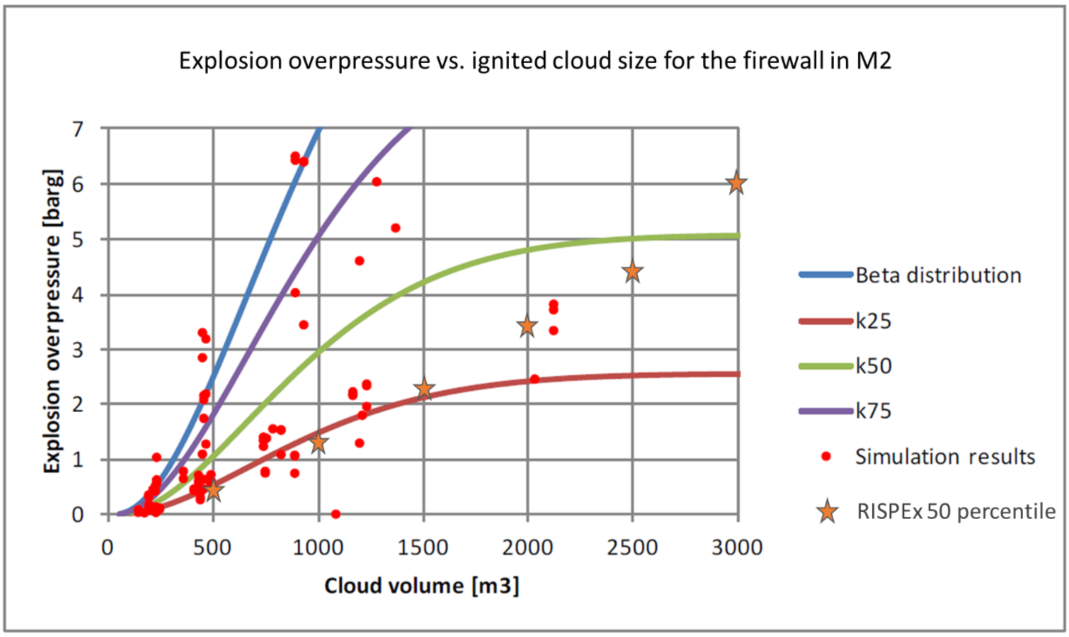

Figure 2-24: Generated pressure vs ignited cloud volumes for explosions in the M2 module at Installation D.

3 Wellhead areas

Three wellhead areas are included to compare with the RispEx model. These are Installation B, Installation C and Installation D. The module parameters are given in Table 3-1. Results from RispEx tests compared to the TRAs are provided in Figure 3-1 - Figure 3-3 (cloud exceedance curves) and Figure 3-4 - Figure 3-6 (pressure frequency curves). In all cases a high representative blowout rate has been selected in the RispEx input sheet.

It can be observed that RispEx predict higher explosion load than the TRA for most of the modules tested. This has not been investigated in detail, but some of it may be related to the activity level. A typical activity level is hard coded in RispEx, and if the activity level on the installation is low, this might give a significant difference in leak frequency.

Table 3-1: Module dimensions and confinement for wellhead areas.

Installation	Module	Number of wells	Dimensions [m] (Length X Width X Height)	Module volume [m3]	Confinement (N, E, S, W) (U, D)	Con-finement factor
Installation B	CW12/21/22	20	15x33x13	6 435	0.9, 0, 0.9, 0 0, 0	0.157
Installation C	Wellhead area	9	17.5x27x16	7 344	0.8, 0, 1, 0 0, 0	0.213
Installation D	Wellhead area	12	16x28x16	7 168	0.8, 0, 0.8, 0 0, 0	0.178

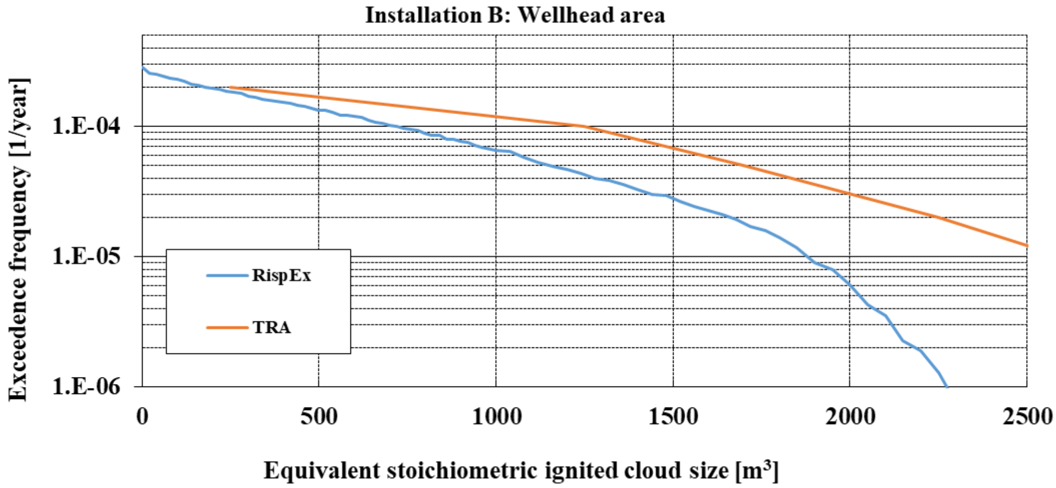

Figure 3-1: Cloud exceedance for the wellhead area at Installation B.

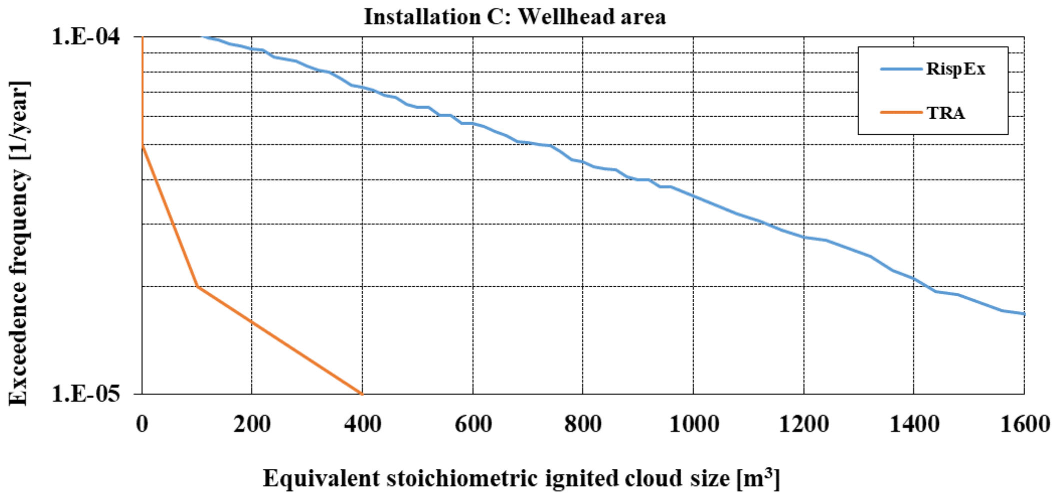

Figure 3-2: Cloud exceedance for the Installation C wellhead area.

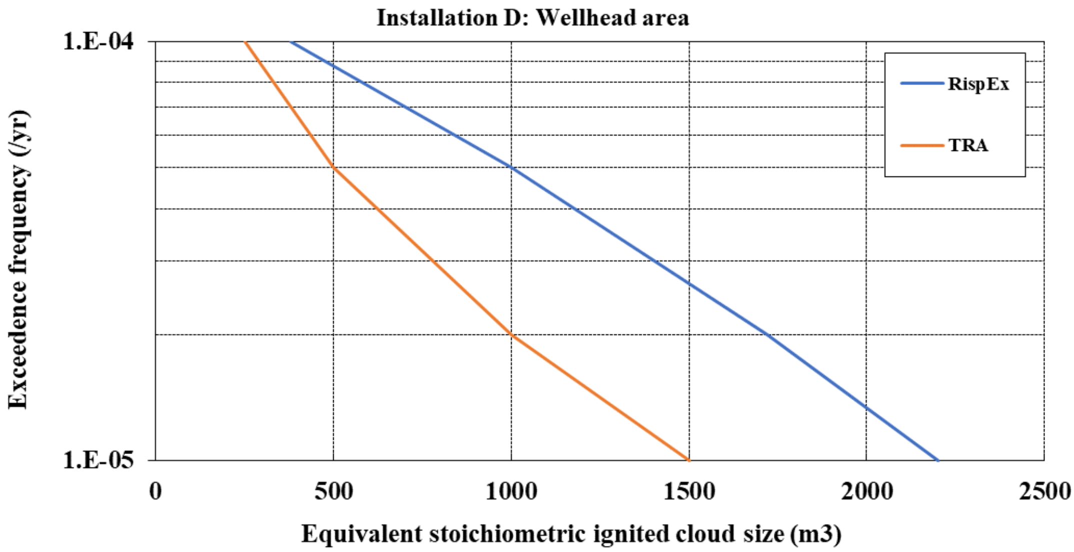

Figure 3-3: Cloud exceedance for the wellhead area at Installation D.

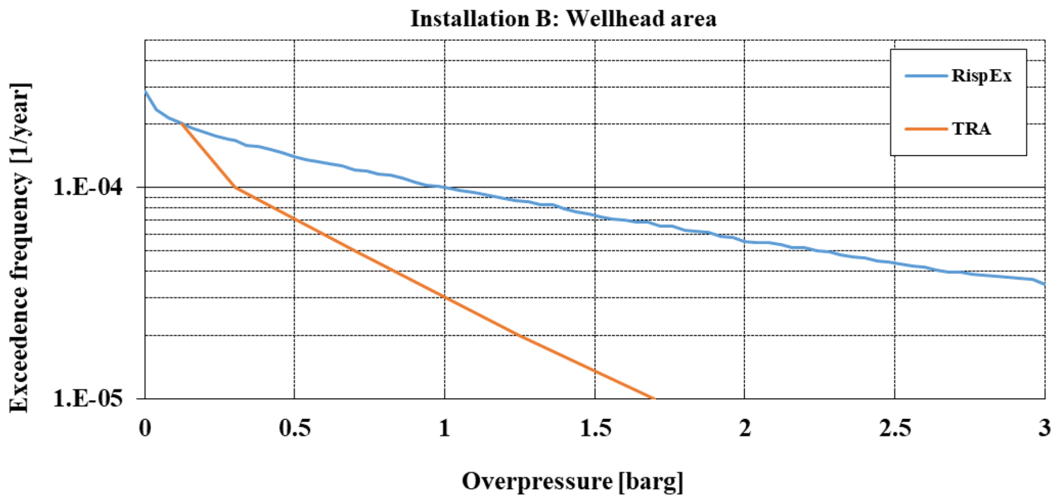

Figure 3-4: Pressure exceedance for the wellhead area at Installation B.

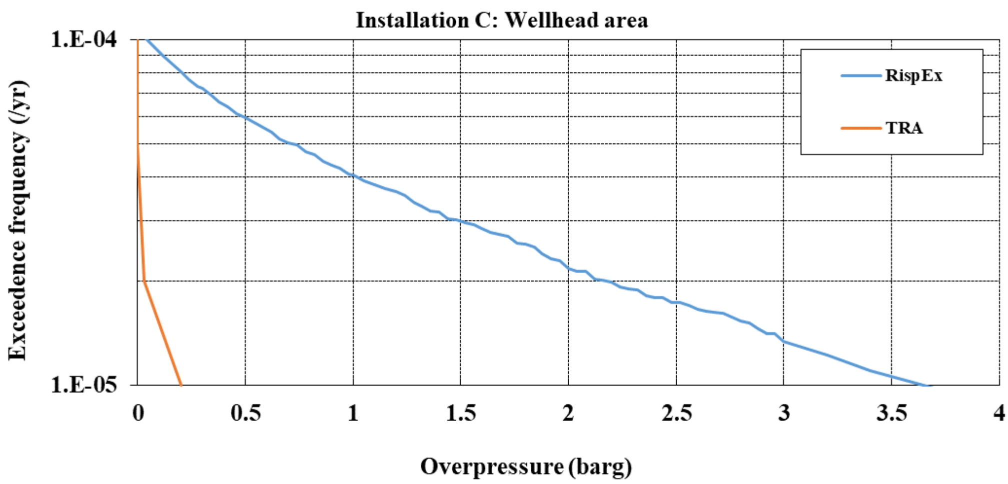

Figure 3-5: Pressure exceedance for the wellhead area at Installation C.

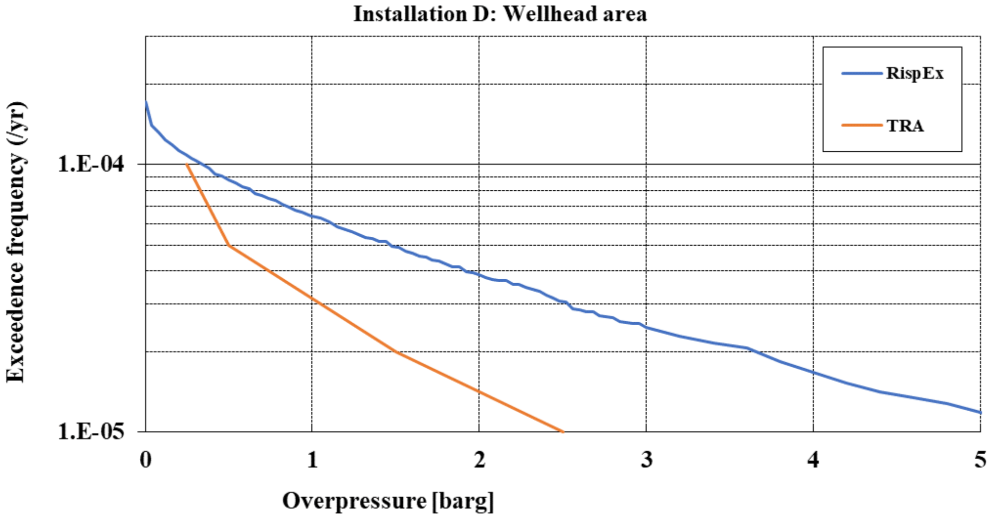

Figure 3-6: Pressure exceedance for the wellhead area at Installation D.

4 FPSO process area

The TRA of Installation E FPSO are applied as a spot check of the FPSO module in RispEx. The dimensions (L x W x H) of the process area is 110 x 34 x 11 m. It has open sides, with a degree of openness as given in Figure 4-1. It is also open towards the sky, but fully closed towards the cargo deck as shown in the side view in Figure 4-2.

Figure 4-3 shows comparative results for pressure vs cumulative frequency when applying RispEx FPSO model to Installation E. It can be seen from the figure that the non-adjusted RispEx curve provides an almost perfect match to the curve from the TRA. However, as RispEx gives an annual leak frequency of 0.08, which is approximately half of the TRA value, the leak frequency adjusted RispEx curves overshoots the TRA results.

Data for ignited cloud volume vs frequency and pressure as a function of ignited cloud volume are not available in the TRA. Therefor, only the pressure frequency dependency is addressed here.

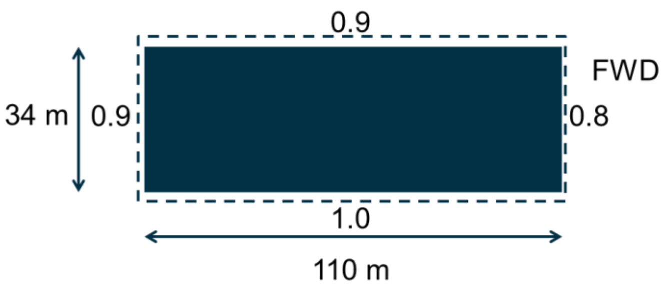

Figure 4-1: The dimensions of the process area at Installation E seen from above. The dimensions of the area and the degree of openness of each side are indicated.

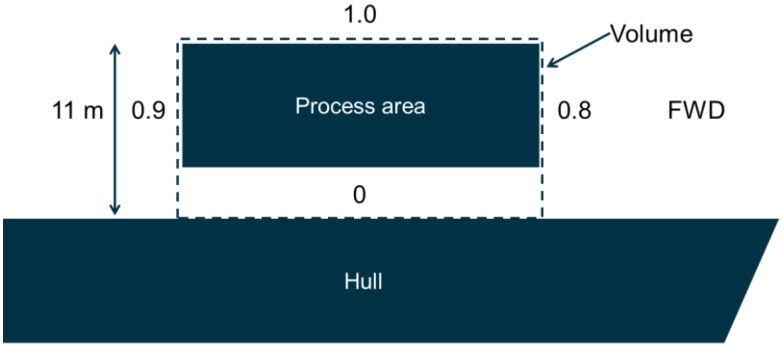

Figure 4-2: Schematic side view of the process area at Installation E with factors for openness.

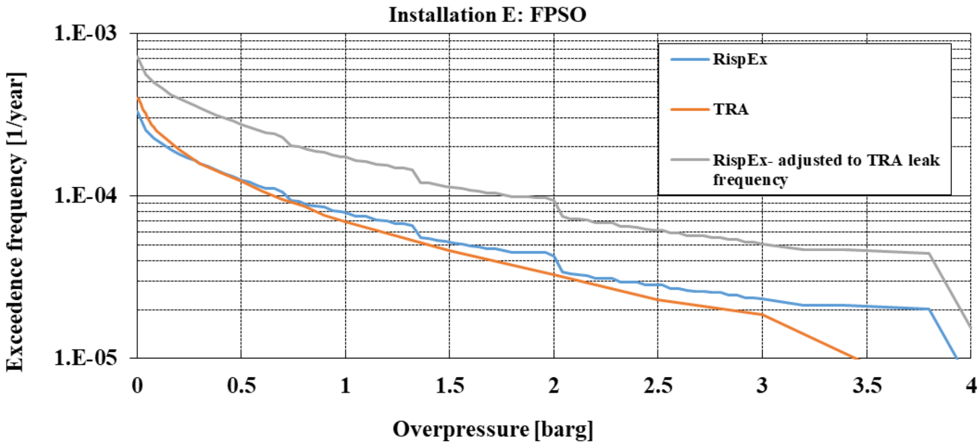

Figure 4-3: Pressure exceedance for the process area at Installation E.

5 Summary of comparison

In short, and perhaps as expected, RispEx will in some cases overpredict dimensioning explosion loads and in other cases underpredict them. There are three models in the tool that are more, or less, independent of each other. These are:

- Leak frequency model
- Probabilistic model to produce cloud exceedance
- Model for explosion overpressure as a function of ignited cloud volumes

For **process areas**, the established relationship between generated overpressure and ignited cloud volumes agrees relatively well with values computed in TRAs. The model for cloud exceedance also appears to behave as desired in the sense that when the leak frequency is adjusted to TRA levels, it tends to approach the TRA cloud exceedance results. At least this is the case when applied to modules with a relatively high fraction of gas leaks compared to liquid leaks.

The RispEx tool is best suited for modules with an overweight of potential gas leaks (e.g. gas compression areas). Hence, caution should be exercised when using the tool to predict loads in areas where one would expect a high liquid leak fraction. As input to further work one could consider refining the tool to be able to distinguish between different types of process modules. As an extension of this a more thorough approach to the leak frequency model could be taken.

For **wellhead areas** RispEx overpredicts the explosion loads for most of the modules tested. The reasons for this have not been investigated in detail, but it could be related to a relatively robust activity level defined in RispEx. Comparison with more modules is recommended to make a conclusion on this.

The **FPSO** model has only been tested with one area, and it is difficult to draw any conclusion based on this. For the FPSO tested, the RispEx results are on the conservative side.

In general, only a few PLOFAM/MISOF analysis have been available for benchmark, and it is recommended to more extensive testing /comparison as part of the future maturing of RispEx. Based on the testing/benchmark performed it has not been identified systematic over/underprediction that recommends adjustment of the RispEx model.

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

RispEx Appendix E – Uncertainty Assessment

Report for:
RISP Participants, att: Equinor Energy AS

JIP: Risk informed decision support in development projects (RISP)		
RispEx-decision support for explosion design loads – Appendix E: Uncertainty Assessment		
Security classification of this report:	Distribute only after client's acceptance	
Report no: DNV report no 2020-0628	**Revision:** Rev 03	**Report date:** 22 September 2023
Prepared by: Sjur Helland, DNV Linda Fløttum, Aker Solutions	**Reviewed by:** Jens Johansson Garstad, DNV Asmund Huser, DNV	**Approved by:** Unni Nord Samdal, Equinor

Document history

Revision	Date	Description/changes	Changes made by
Rev A	18.06.2020	Draft A	Linda Fløttum, AkerSolutions Asmund Huser, DNV
Rev 0	17.08.2020	Updated based on comments	Linda Fløttum, AkerSolutions Jens Garstad, DNV
Rev 01A	19.10.2021	No change	-
Rev 01	15.11.2021	No change	-
Rev 02A	19.12.2022	No change	-
Rev 03A	28.06.2023	No change	-
Rev 03	22.09.2023	Editorial changes	Sjur Helland, DNV

#ID	Description	Sensitivity i)	Competency ii)	Comments
1	Segment inventories	Low	Medium	Robust value for segment inventories used as hard coded input
2	Blowdown time	Medium	High	Relatively robust value used for blow down time. Validity envelope will restrict use of RispEx for longer blowdown times
3	Gas mol weight	High	High	Risk results sensitivie if gas is heavy. Validity envelope restrict use of RispEx for heavy gases
4	Leak initial conditions, and release modelling	Low	Medium	Standard modelling as used in probabilistic analysis
5	Gas detector density	Medium	High	Results are sensitive if the gas detector densitiy is very low. Validity envelope restricts use of RispEx for such cases (design according to S-001)
6	Time to isolation/ESD	Medium	Medium	Results are sensitive if the time to ESD is very long. Will be captured by validity enevelope (design according to S-001)
7	Failure probability safety systems	Medium	High	Result are sensitive if the failure probability is high. Robust value chosen in code and will also be handeled by validity envelope (design according to S-001)
8	Wind rose	Medium	Medium	Results are sensitivie if the wind rose is significantly different that the hard code windrose in RispEx. Typical wind rose for NCS is chosen.
9	Hot work per year	Low	Medium	This will be handled by the validity envelope
10	Congestion and detailed geometry of module	High	Medium	Results are sensitive to congestion and detailed geomerty of a module. Representative modules chosen to have a spread in congestion and to represent typical congestion levels for these designs.
11	Moderate number of gas dispersion simulations per module	Medium	Medium	Representative scenarios carefully selected due to low number of simulations. Shown to converge relatively fast in previous studies when this approach is applied
12	Moderate number of explosion simulations per module	Medium	Medium	Representative scenarios carefully selected due to low number of simulations. Shown to converge relatively fast in previous studies when this approach is applied
13	Variance between different probabilistic explosion models/tools	High	Medium	Due to different tools developed by the different safety consultant companies.
14	Only module volume and total confinement used in interpolation	Medium	High	Based on experience and knowledge, this is considered to be the main driving parameters. Experience has shown that complex models with effects of a large number of quantified has proven to be vulnerable to subjective/inconsistent evaluations
15	Total leak frequency estimation	High	Medium	Results are very sensitive for leak frequency model. A robust leak frequency model is chosen, that for most designs will overpredict the leak frequency.
16	Leak frequency rate distribution	Medium	Medium	Results are sensitive for leak rate distribution. Distribution (hard coded in RispEx) chosen based on best knowledge (PLOFAM 2)
17	Ignition model	High	Medium	Results are sensitive for ignition model. Ignition model represents best knowledge (MISOF2)
18	CFD modelling	Medium	Medium	CFD modelling is in general attached with some uncertainy. CFD modelling is perfomred according to best practice (DNVGL methods)
19	Interpolation scheme	Medium	High	Relatively short interpolation steps, interpolation region selected based on what is evaluated most relevant for realistic, future designs
20	Liquid leak frequency fraction	High	Medium	RispEx does not account for the fraction of liquid leaks vs gas leaks in an area. For areas with a large fraction of liquid leaks, RispEx will significantly overpredict the explosion risk.
21	Relalively few representative FPSO process areas included	Medium	Medium	To some extent dealt with in validity envelope.
22	Relalively few representative wellhead areas included	Medium	Medium	To some extent dealt with in validity envelope.

i) High = exponential; Medium = proportional; Lav = < proportional

ii) High = High integrity, possible to verify/refer to; Medium = Best estimate, trends ; Low = Unknown

Competency

	Sensitivity	Low	Medium	High
	High			
	Medium			
	Low			

	High criticallity	Not Robust
	Medium criticallity	Robust
	Low criticality	Very robust

#ID	Description	Sensitivity i)	Competency ii)	Criticality	Management of uncertainty iii)
1	Segment inventories	Low	Medium	Low criticality	
2	Blowdown time	Medium	High	Low criticality	
3	Gas mol weight	High	High	Medium criticality	
4	Leak initial conditions, and release modelling	Low	Medium	Low criticality	
5	Gas detector density	Medium	High	Low criticality	
6	Time to isolation/ESD	Medium	Medium	Medium criticality	
7	Failure probability safety systems	Medium	High	Low criticality	
8	Wind rose	Medium	Medium	Medium criticality	
9	Hot work per year	Low	Medium	Low criticality	
10	Congestion and detailed geometry of module	High	Medium	High criticality	Validitiy envelope to restrict use for very congested areas or special geometries that will give high explosion loads. Highligt this in user manual.
11	Moderate number of gas dispersion simulations per module	Medium	Medium	Medium criticality	
12	Moderate number of explosion simulations per module	Medium	Medium	Medium criticality	
13	Variance between different probabilistic explosion models/tools	High	Medium	High criticality	RispEx is based on DNVs probabilisc explosion tool, Express, which is a achknowledged tool
14	Only module volume and total confinement used in interpolatio	Medium	High	Low criticality	
15	Total leak frequency estimation	High	Medium	High criticality	The leak frequency model in RispEx will be robus for most designs. Further work are also proposed on leak frequency.
16	Leak frequency rate distribution	Medium	Medium	Medium criticality	
17	Ignition model	High	Medium	High criticality	RispEx is based on MISOF2 which represents the best available knowledge
18	CFD modelling	Medium	Medium	Medium criticality	
19	Interpolation scheme	Medium	High	Low criticality	
20	Liquid leak frequency fraction	High	Medium	High criticality	Proposed as further developmet of RispEx
21	Relalively few representative FPSO process areas included	Medium	Medium	Medium criticality	Possible future development
22	Relalively few representative wellhead areas included	Medium	Medium	Medium criticality	Possible future development

iii) Increse the level of competency or use a conservative approach