Lloyd's Register

Working together
for a safer world

Modelling of ignition sources on offshore oil and gas facilities - MISOF(2)

Report for:
Norwegian Oil and Gas Association
(Equinor, ConocoPhillips and Total E&P Norge AS)

Report no: 107566/R2 Rev: Final
Date: 20 November 2018

Summary

Modelling of ignition sources on offshore oil and gas facilities - MISOF(2)

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

Report no:	Revision:	Report date:
107566/R2	Final	20 November 2018

Prepared by:	Reviewed by:	Approved by:
Ingar Fossan/Are Opstad Sæbø Senior Principal Consultant/ Principal Consultant	Olav Roald Hansen Senior Principal Consultant	Kristin Myhre Department Manager
Ingar Fossan Are O Sæbø	Olav Roald Hansen	Kristin Myhre

Entity name and address:
Lloyd's Register Consulting - Energy AS
Kokstadflaten 35
NO-5257 KOKSTAD
Norway

Client name and address:
Norwegian Oil and Gas Association
(Equinor, ConocoPhillips and Total E&P Norge AS)

Our contact:
Are Opstad Sæbø
T: +47 476 68 619
E: are.sabo@lr.org

Client contact:
Eli Bech/Marie Saltkjel
T: +47 915 43 176/+47 990 06 519
E: elgl@equinor.com/
MarieJudith.Saltkjel@conocophillips.com

Document history

Revision	Date	Description/changes	Changes made by
Draft A	26 October 2018	This report is a further development of the report 106634/R1 Draft B issued in December 2017	Are Sæbø, Ingar Fossan
Final	20 November 2018	Comments from Equinor are received and implemented	Are Sæbø, Ingar Fossan

Preface

Extensive work has been carried out during the recent years regarding models for estimating leak frequencies and ignition probabilities for offshore facilities at the Norwegian continental shelf (NCS). This has resulted in the PLOFAM (Process leak for offshore installations frequency assessment model) and MISOF (Modelling of Ignition Sources on Offshore oil and gas Facilities) 2018 models.

The developed models seek to give a realistic and unbiased prediction of hydrocarbon process leaks and ignitions for an average facility on the NCS for the coming years. Users of the models and their results should however be aware of the following aspects:

- PLOFAM (2) is tuned to give the same number of leaks >0.1 kg/s as observed in historical data for NCS in the period 2006 – 2017, and predicts significantly fewer leaks than previous models
- The MISOF (2) model will for most modules give higher ignition probabilities than previous models. It builds on few ignited events, and the statistical uncertainty is therefore relatively high. The contribution from external ignition may be essential in such regard

For some analysed offshore modules, the combined use of these models may result in no dimensioning loads (ref. PSA's Facility regulation §11). Each risk owner needs to decide how these aspects shall be considered in their risk management.

Executive summary

This report presents an ignition probability model for potential ignition sources located on offshore oil and gas installations. The model is named MISOF, which is short for Modelling of Ignition Sources on Offshore oil and gas Facilities. MISOF is aiming to be best practice in industry for use in quantitative risk analysis for offshore installations located in the North Sea. The model can be used in geographical locations other than the North Sea if the properties of the objects at the specific installation, or site, can be considered similar to what are found generally on North Sea installations.

The ignition probability is the product of two probabilities; the probability of a live ignition source being exposed to a flammable atmosphere and the probability of ignition given such exposure. The objective of MISOF is to define the ignition probability given exposure to a flammable atmosphere for the most significant potential sources of ignition present on offshore oil and gas facilities. Thus, in order to quantify the ignition probability based on MISOF, a model for the exposure probability is also required. The quality of the probabilistic exposure model is critical for the obtained accuracy of the ignition probability estimate. MISOF provides ignition source data for use in two ways. Firstly it can be used with an exposure model in which all ignition sources are distributed evenly in space. Alternatively the location of specific ignition sources may be included in the model. Guidelines are provided for compliance with the requirements of the exposure probability model, and these guidelines are dependent on the targeted level of detail in the analysis of the fire and explosion risk.

The model parameters are largely based on analysis of statistics of leaks and ignited events on installations in the North Sea from 1992 until end of 2017. An understanding of the physical properties of the ignition phenomena has been applied where such knowledge is available, but in general the parameters are set based on a statistical methodology.

It is important to consider that the fundamental basis for the validity of MISOF is that the observed data extracted from the installations that have been in operation during the period 1992 – 2017 is applicable to the future design of offshore installations and operational conditions in the years to come. Shifts in underlying casual factors (*e.g.* emerging unknown degradation mechanisms due to age or changing operational conditions) affecting the future trend in ignited leaks occurring on installations on the NCS and UKCS may affect the model parameters significantly. However, casual factors implying a trend have not been identified in the project.

Glossary/abbreviations

AIT	Auto-Ignition Temperature
BD	Blow down system
CFD	Computational Fluid Dynamics
DCS	Danish Continental Shelf
EQ	Equivalence ratio
ESD	Emergency Shutdown System
F&G	Fire & Gas System
HCR Database	Hydrocarbon Release Database (established and maintained by HSE in UK)
JIP model	Denotation of the JIP ignition model
LFL/LEL	Lower Flammability Limit/Lower Explosive Limit
LM 2500	General Electric LM2500 Gas Turbine (a typical gas turbine used for offshore power generation)
LRP	A data set of selected installations denoted as Lloyd's Register Population.
MISOF	Modelling of Ignition Sources on Offshore oil and gas Facilities
NCS	Norwegian Continental Shelf
OLF model	Denotation of previous ignition model (see Appendix A).
OCS	Outer Continental Shelf
P(E)	The probability for exposure of a live ignition source to a flammable atmosphere
P(I ✠ E)	The ignition probability given exposure of a live ignition source to a flammable atmosphere
PFD	Probability of Failure on Demand
Platform 5	A jacket platform located in the North Sea used as basis for benchmarking of the MISOF model parameters
PLOFAM	Process leak for offshore installations frequency assessment model
QRA	Quantitative Risk Analysis
RNNP	Risikonivå i norsk petroleumsvirksomhet (English: Risk level in the Norwegian petroleum activity)
SHLF model	Standardized Hydrocarbon Leak Frequency Model (Ref. /15/)
UFL/UEL	Upper Flammability Limit/Upper Explosive Limit
UKCS	United Kingdom Continental Shelf

Table of contents

Page

1 Introduction

This report presents an ignition probability model for potential ignition sources located on offshore oil and gas installations. The model is named MISOF, which is an acronym for Modelling of Ignition Sources on Offshore oil and gas Facilities. MISOF is aiming to be best practice in industry for use in quantitative risk analysis for offshore installations located in the North Sea. The model can be used in domains other than the North Sea if the properties of the objects at the specific installation or site can be considered similar to what is generally found at North Sea installations.

In order to quantify the ignition probability based on MISOF, a model for the probability of exposure of potential sources of ignition to flammable mixtures is required. The quality of the exposure probability model is critical for the accuracy of the ignition probability estimate. This means that a risk analysis model stating compliance with MISOF does not infer an unambiguous estimate of the ignition probability. The methodology implemented to combine the MISOF model parameters with a probabilistic exposure model is crucial for the accuracy of the ignition probability estimate. More importantly, implementation of a simplistic method, still in compliance with MISOF, will not enable the full potential of the model to investigate the importance of the various barrier elements affecting the fire and explosion risk picture. A key element is the representation of the location of rotating machinery and special sources of ignition such as gas turbine air intakes and hot work activities. If the probabilistic exposure model assumes that that the conditional ignition probability related to these units are uniformly distributed in space, the effects of the location of the leak sources and the ignition sources are not reflected.

Guidelines that are applicable to both a simplified and advanced methodology for estimation of the exposure probability are implemented. The selection of methodology should be aligned with the targeted level of detail in the risk analysis. In many cases, a simple exposure probability model is suffice, but the limitations of either approach must be described in the report (this applies to either model being used, *i.e.* simple or advanced).

It is important to note that the MISOF ignition model and the PLOFAM leak frequency model (Ref. /1/) are interlinked. To ensure that the best possible estimate of fire and explosion frequency on offshore installations is obtained, it is highly recommended that both models are applied together when modelling fire and explosion risk for offshore oil and gas installations. This is so that the barrier elements affecting the risk picture are reflected as accurately as possible. However, the conditional ignition probabilities presented in MISOF can be combined with alternative leak frequency models. The area of application is further discussed in Chapter 5.

It is emphasised that other sources of ignition than those covered explicitly by MISOF may be relevant for a given facility. This has to be clarified as part of the risk analysis process, for instance through the hazard identification analysis.

2 Objective

The objective of MISOF is to determine the ignition probability given the exposure of potential ignition sources present on offshore oil and gas facilities to flammable atmospheres.

3 Background

MISOF represents a major upgrade of the previous ignition probability models used in industry in Norway. The former models have been frequently denoted the 'JIP-model' (Ref. /2/) and the 'OLF-model' (Ref. /3/). However, various names have been associated with these models.

MISOF represents a totally new model that supersedes the JIP-model and the OLF-model. It is not recommended to use either of the previous models for modelling of the fire and explosion frequency in quantitative risk analysis for offshore oil and gas installations. The updated statistical material results in a fundamentally different basis for the MISOF model opposed to the previous models. Furthermore, the JIP-model and the OLF-model does not reflect important new knowledge on the properties of the potential ignition sources as well as the behaviour of the ignition control barrier on offshore installations. For instance, the effect of isolation of equipment upon detection of a flammable atmosphere was not reflected appropriately in the previous models. Lastly, the previous ignition models are not aligned with the PLOFAM leak frequency model.

Some important changes to the model from the previous models are:

- The contribution from immediate ignition (ignitions occurring instantly upon release of flammable fluid to the atmosphere) is divided into 2 parts; one associated with leaks originating from hydrocarbon liquid pumps, and the other associated with all other leak sources. Both ignition probability parameters are independent of hole size and release rate. In the previous model, immediate ignition probability model possessed an increasing trend with the initial leak
- The ignition probability model for delayed ignition, due to exposure of equipment in classified areas, splits the ignition contribution into the three equipment categories; 'Rotating machinery', 'Electrical equipment' and 'Other'. This split on equipment category resembles the building blocks in the JIP-model. Alternative models have been developed for each of the categories 'Rotating machinery' and 'Electrical equipment'. The appropriate model alternative is to be selected based on the available formation about the systems and objects, i.e. location and protection mechanism
- MISOF does not include correction factors for the general platform specific properties age, technology and manning level. In cases where such factors are considered relevant, the basis for the correction factors described in the OLF-model could be utilised. However, such correction factors must only be used if carefully justified

This version of the MISOF is an update of the version of MISOF issued in 2016 (Ref. /4/).

4 Methodology

The model parameters are largely based on analysis of statistics of releases and ignited leaks on installations in the North Sea from 1992 and until end of 2017. An understanding of the physical properties of the ignition phenomena has been applied where such knowledge is available. For instance, the models for ignition, due to exposure to gas turbine air intakes and diesel air intakes, are based on an assessment of the behaviour of the machinery when exposed to flammable atmospheres.

The physics of ignition is fairly well understood, but very difficult to model accurately. Hence, a probabilistic approach is found to be more applicable for risk engineering purposes. The MISOF ignition model is therefore mainly about predicting the probability of ignition prevention barrier failure, and not about the modelling of ignition physics. This is illustrated in Figure 4.1. All terms used in the figure are explained in Chapter 5 and Chapter 6.

The model parameters are tested by applying the ignition model for three generic modules, and comparing the output with the historical ignition probability obtained from the established North Sea statistics. The test models are run using state of the art exposure models based on CFD.

It has been a clear objective for the project to establish a model where there is a consistent and transparent link between the statistical data material for the North Sea and the model parameters. This will provide the basis for effective updates of the model in the future. An update of the statistical data and classification of the future events in accordance with the methodology described in this report should lead to a transparent change of the parameter values. However, it is hard to account for new knowledge gained from the investigation of ignited events occurring in the future as well as new insights acquired through research within this subject area. New information would reduce the number of unknown factors, and thus imply a somewhat different model and/or methodology for assessment of the parameter values. For example;

- further analysis of the behaviour gas turbines ingesting combustible gas through the air intake will most certainly lead to a different ignition probability model
- in the process of deriving the model parameters, the fraction of the ignition probability related to delayed ignition versus immediate ignition is set based on scarce data. Additional understanding gathered through future incidents is believed to result in an improved basis for setting the model parameter values

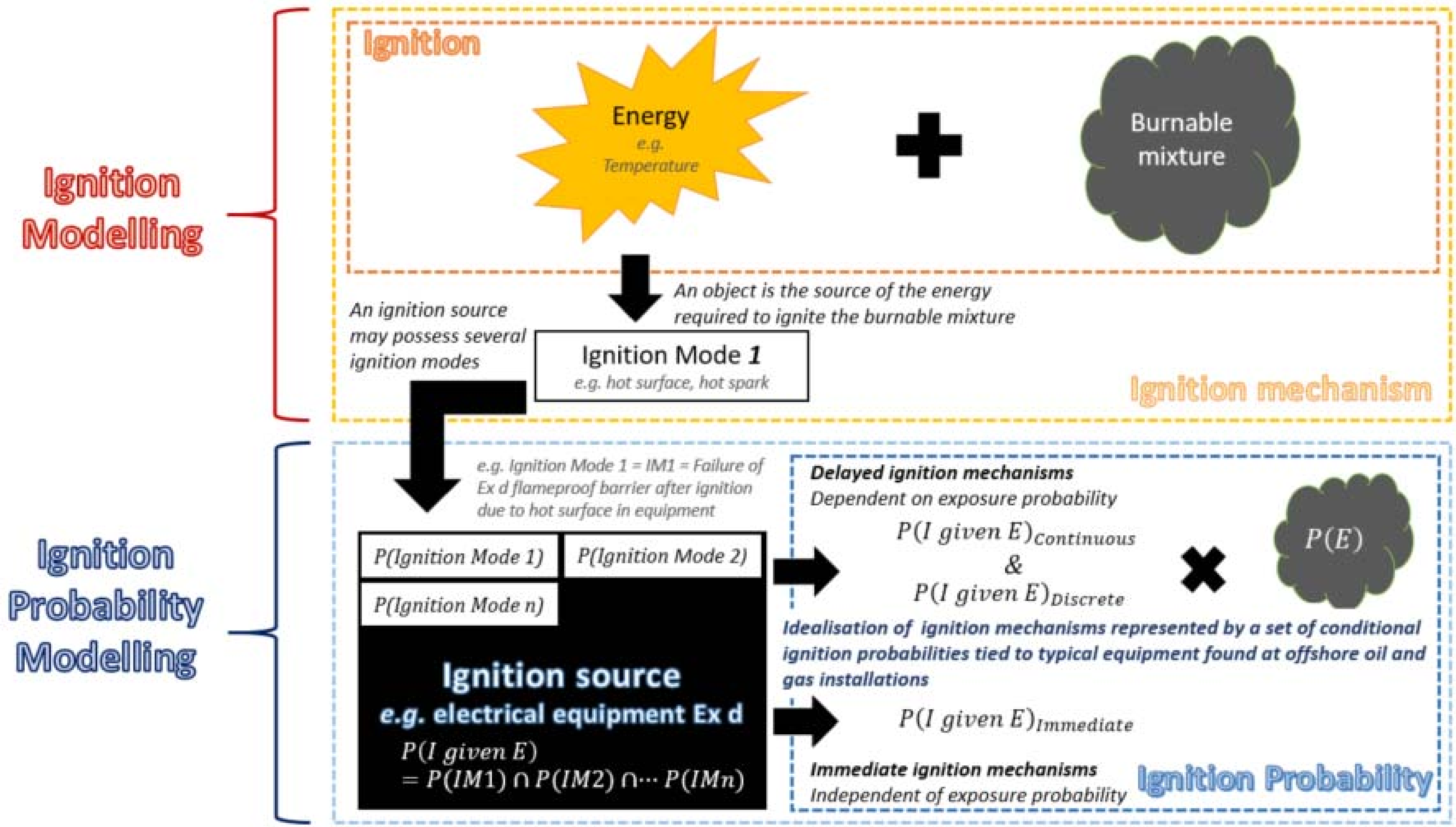


Figure 4.1 – Illustration of the fundamental difference between ignition modelling and ignition probability modelling. MISOF is covering idealised representation of ignition mechanisms by conditional ignition probabilities tied to typical equipment found on offshore oil and gas installations. See Chapter 5 and Chapter 6 for further description of terms and expressions used in this figure

5 Area of application

In general, the ignition probability, $P(I)$, is the product of two probabilities; the probability for exposure of a live ignition source to a flammable atmosphere, $P(E)$, and the ignition probability given such exposure, $P(I\ given\ E)$. Thus, the ignition probability, $P(I)$, can then be expressed as

$$P_{Ignition} = P(I) = P(E) \cdot P(I\ given\ E) \qquad (5.1)$$

Both $P(E)$ and $P(I\ given\ E)$ possess a time dependent behaviour.

The objective of the ignition model presented in this report is to define $P(I\ given\ E)$ for the most important potential sources of ignition present on offshore oil and gas facilities. Hence, $P(E)$ is not part of the ignition model described in this report. The capability of predicting the exposure probability is critical for the obtained accuracy of the ignition probability estimate. Guidelines including requirements of the exposure probability model are given in Chapter 10. The requirements are dependent on the level of detail targeted in the analysis utilising the MISOF model to investigate the fire and explosion risk.

It should be noted that the $P(I\ given\ E)$ is not dependent on the state of the hydrocarbon fluid causing the exposure (*i.e.* $P(E)$). The fluid could be in gaseous phase, liquid phase or a mixture of gas and liquid. This is to be covered as part of the modelling of $P(E)$. In general, an important challenge is to reflect the exposure of equipment resulting from liquid phase releases. The simplifications made when representing exposure to the liquid phase should be discussed in the analysis. Furthermore, it should also be noted that in MISOF the $P(I\ given\ E)$ is independent of the leak rate and the total exposed volume. This is discussed in Appendix A.

The model of $P(I\ given\ E)$ in this report covers the following types of ignition sources:

1. Ignition due to exposure of objects intended for use in potentially explosive atmospheres. The model is split in two main categories with respect to ignition time; 'immediate ignition and 'delayed ignition'. Immediate ignition is an idealisation where the ignition probability is modelled directly without reflecting the exposure probability. This aspect of the model incorporates the fact that the main bulk of observed ignited leaks is believed to ignite within a very short time (< a few seconds) following the leak. Ignition sources contributing to 'delayed ignition' are categorised in terms of equipment type. Two specific object categories in addition to the category denoted 'Other', which accounts for unknown ignition mechanisms, have been established:
   - i) Rotating machinery
   - ii) Electrical equipment and instruments
   - iii) Other
2. Ignition due to exposure of objects not intended for use in explosive atmospheres. The objects included are:
   - iv) Gas turbine air intakes
   - v) Diesel engines
   - vi) Equipment in enclosures protected by a mechanical ventilation system
   - vii) Electrical equipment or instruments
   - viii) Supply vessels
   - ix) Hot work
   - x) Flare

As this model is based on releases of hydrocarbons from process equipment on North Sea offshore facilities, a consistent application of the model would imply that the model should be used only for such releases. Consequently, the ignition model should only be used for exposure of equipment used in the North Sea to flammable concentrations of hydrocarbons found on facilities in the North Sea. Furthermore, the immediate ignition probability is strictly applicable only for leaks of hydrocarbons from process equipment intended for use in potentially explosive atmospheres on facilities in the North Sea.

It is however reasonable to argue that the model is applicable to platforms and land based facilities where the object properties can be considered similar to those generally found on North Sea installations. For any other fluid than hydrocarbons, the model can be used as basis, but an assessment of any significant fluid properties or the properties of the equipment certified designed for exposure to the particular fluid must be carried out.

Correction factors should be used where appropriate to account for particular equipment properties and/or the fluid type considered. In such cases the validity of the model should be assessed and presented as part of the documentation for the basis for the risk analysis being performed. For example:

- For land based facilities, the general equipment density should be considered to reflect the difference relative to typical offshore installations (*i.e.* lower number of objects per volume potentially possessing a failure mode causing ignition if exposed to flammable atmosphere)
- The difference in physical properties of H_2 relative to hydrocarbons implies that the conditional ignition probabilities used to model both immediate and delayed ignition must be adjusted

It is emphasized that sources of ignition other than those mentioned above may be relevant for a given facility and must be clarified as part of the risk analysis being performed. It is recommended that this is covered in the hazard identification analysis, for instance through use of appropriate guide words in a HAZID workshop.

6 Important terms and key model parameters

In this chapter, important terms and model parameters used in the report are described. The bridge between ignition modelling and ignition probability modelling covered by MISOF is illustrated in Figure 4.1.

6.1 Ignition

Ignition occurs when an initiating combustion process in a flammable atmosphere is sustainable without external supply of energy. The heat generated by the chemical process is sufficient to support propagation of the combustion process throughout the combustible mixture. This does not mean that ignition necessarily will lead to combustion of the entire flammable mixture. Geometrical barriers or initiation of active systems may quench the flame or isolate some part of the flammable mixture from the ignited mixture, but these effects are to be analysed in the consequence analysis following the ignition modelling analysis.

6.2 Ignition mechanism

The term 'ignition mechanism' is used to describe the method of energy transfer between a specific ignition source and the combustible mixture that potentially results in ignition. In general, ignition is caused by energy transferred from the ignition source to the flammable atmosphere exposing the ignition source. The ignition mechanism can also be a pressure rise that may lead to explosion (in the extreme detonation) through generation of increased temperature. A typical situation is where hot parts of an object transfer heat by convection to the flammable mixture, causing the temperature of the flammable mixture surrounding the hot surface to rise above the auto-ignition temperature. The hot surface may also have a catalytic impact on the chemical reactions so that the temperature of the flammable mixture locally may be lower than the auto-ignition temperature. A concrete example discussed in the MISOF model is where combustible gas ingested by a gas turbine air intake ignited due to the flow of flammable gas across hot surfaces in the gas turbine film cooling system (see Chapter 9.2). In this case, the residence time is an important parameter (see below) in enabling the chemical process to be initiated. An example of an ignition mechanism resulting in instantaneous ignition is the release of a hot spark in the fluid (*e.g.* a switch being turned on or off), which for a short time, may generate plasma and raise the temperature of the flammable gas to several thousand degrees locally resulting in immediate ignition. The rise of pressure and increase of temperature may accelerate the chemical reactions, and thereby initiate ignition, but it is considered to be a rather special situation (this is the ignition mechanism in a diesel engine). A known physical process where this phenomenon is important is detonation of a combustible mixture.

In practice, the ignition mechanism is complex and challenging to describe in detail. A range of properties related to the object itself and a set of physical parameters affect the mechanism. Typical parameters include:

- Surface temperature
- Material
- Surface properties
- Spark energy
- Flow conditions (velocity and turbulence level)
- Fluid temperature and fluid pressure
- Fuel type
- Residence time of the fluid

6.3 Ignition mode

An ignition mode is a mode an object possesses where an ignition mechanism will materialise if exposed to combustible fluid. For objects intended for use in explosive atmospheres, equipment will only possess such a mode if the equipment is faulty (*e.g.* failure of Ex protection barrier of electrical equipment). For objects not intended for use in explosive atmospheres, the modes that facilitate ignition may be present when the object is functioning as normal.

There is a certain probability that an object may possess an ignition mode. An ignition source may possess one or several ignition modes. An object that cannot possess an ignition mode is not an ignition source.

6.4 Ignition source

An ignition source is an object that may possess one or several modes where an ignition mechanism may materialise if exposed to combustible atmospheres. For objects intended for use in explosive atmospheres, equipment will only possess such a mode if the equipment is faulty (*e.g.* failure of Ex protection barrier of electrical equipment). For objects not intended for use in explosive atmospheres, the modes that facilitate ignition may be present when the object is functioning as normal.

6.5 Live ignition source

The term 'live ignition source' is used to describe an ignition source that is operating as normal, *i.e.* not isolated or shut down, which means that any mode that may result in ignition may manifest itself upon exposure to flammable mixtures.

6.6 Potential ignition source

The term 'potential ignition source' is frequently used when there is a certain probability that a particular object is a live ignition source due to failure of a number of barriers to ultimately result in ignition. Hence, the object may possess a mode where an ignition mechanism may materialise if exposed to a combustible atmosphere.

6.7 Conditional ignition probability

The conditional ignition probability associated with an object is the probability for ignition by that object given exposure of the object to flammable atmospheres. This term incorporates the likelihood for the object possessing a mode where an ignition mechanism may materialise. This means that if the initial ignition occurs in the inside of an equipment (such as a faulty electrical unit), the conditional ignition probability includes propagation of the flame out of the object to the external atmosphere. One example is the model for gas turbine air intakes, where the conditional ignition probability includes ignition inside the turbine leading to ignition of the external gas cloud being ingested by the gas turbine. Another example is an electrical unit protected according to the Ex d protection concept (*i.e.* flame proof), where the conditional probability for this type of unit incorporates failure of the barrier suppressing propagation of the flame to the external environment.

An ignition source may possess several ignition modes. Hence, the conditional ignition probability for an ignition source equals the intersection of probability for each of the ignition modes the ignition source may possess.

The general expression used in MISOF for the conditional ignition probability is $P(I\ given\ E)$.

6.8 Exposure probability

The probability for exposure of an ignition source to a flammable atmosphere is denoted $P(E)$.

6.9 Ignition probability

The ignition probability is the product of two probabilities; the probability for exposure of ignition source to a flammable atmosphere, $P(E)$, and the ignition probability given such exposure, $P(I\ given\ E)$, see equation (5.1) in Chapter 5.

6.10 Free flow volume

V_{ff} is the free flow volume within the boundary of the area (*e.g.* module) being analysed.

Only the volume enveloping objects that may possess a failure mode causing ignition upon exposure should be considered. In practice, all geometrical objects within an area will be enveloped. This does not mean than all types of objects are considered to be a potential source of ignition (although it can be argued that all types of object, in principle, could facilitate an ignition mechanism; a general example is build-up of an electrostatic charge due to flow of combustible fluid across the object's surface). This approach will ensure that an ignition source introduced by activities in the vicinity of any equipment in the area is incorporated in the model.

In most cases V_{ff} is defined by the periphery of the walls and decks of the module being studied, minus the volume occupied by the objects in that volume. The guidelines for defining V_{ff} are given in Chapter 10.6.

6.11 Continuous and discrete ignition mechanisms

In order to model the time dependent behaviour of the phenomena, two different types of general ignition mechanisms, denoted continuous and discrete, have been defined. Both ignition mechanisms can be attributed to a specific ignition source.

The parameter describing continuous ignition mechanisms cover ignition mechanisms that are present continuously (such as a flame or a hot surface), and ignites the flammable atmosphere at the moment of first exposure. When estimating the ignition probability due to continuous sources according to equation (6.1) it is fundamental that the exposure probability model (*i.e.* $P(E)$) reflects this aspect. This means that the conditional ignition probability related to a given object can be disregarded after the first exposure to a combustible atmosphere has materialised.

Discrete ignition sources are only an effective ignition source at distinct moments in time. A discrete ignition source can, for example, be an electric spark due to static electricity or one could be generated by a switch being turned on or off. Another example is ignition sources introduced by activities performed by personnel (*e.g.* operation of equipment). The personnel may be present initially or they could enter the scene of the incident after the onset of the leak which exposes the flammable atmosphere. The time dependent stochastic nature of discrete sources must be incorporated in the ignition probability model reflecting the exposure probability appropriately. The resulting ignition probability due to the discrete ignition mechanism will be a function of the duration of the exposure to the flammable fluid, which is a function of the transient behaviour of the dispersing fluid.

It is important to note that the actual ignition mechanism is typically the same for both types of general ignition mechanism used for modelling purposes. A discrete ignition source is not considered as being intermittent in the sense of a repetitive source with a mean time between being active, but it is considered as an ignition source occurring at random intervals. The energy of the source is sufficient to ignite the flammable mixture, but short enough not to be considered as a continuous source from the time of occurrence. An intermittent source with a short mean time between being active and inactive compared to the rate of increase of the exposed volume, would in practice behave as a continuous source. The rational for the discrete ignition mechanism is mainly to capture the fact that sources of ignition may be introduced with some delay after onset of the leak scenario. This is an important element that must be captured in the ignition model to ensure that the explosion risk is not underestimated, and this is effectively incorporated in the model through the discrete ignition mechanism.

It must be noted that the idealisation of actual ignition mechanisms by use of the continuous and discrete ignition mechanism is uncertain. It is hard to establish statistical and technical basis for explicit modelling of ignition mechanisms incorporating the actual failure modes causing ignition. One important aspect is that ignition due to continuous sources is considered to materialise upon the very first exposure. In practice, there will be an ignition time delaying onset of the combustion process because it will take some time to elevate the temperature in the burnable atmosphere. The ignition time is typically a few seconds. Furthermore, dependent on the equipment and failure mode, time may be required for the combustible atmosphere to migrate to the component of the equipment providing the energy. For instance, a faulty encapsulation (Ex m) of an electrical equipment does not necessarily mean that the energy source is facing the external environment. It may take some time for the fluid to penetrate through the damaged barrier and expose the hot parts inside the equipment. The ignition delay time affects the ignition probability directly, but does also indirectly affect the potential energy taking part in the explosion or fire. Since the vapour cloud will have a time-dependent behaviour according to the leak feeding the unfolding scenario, delayed ignition implies that the chemical energy available for combustion will be different at various times throughout the history of the scenario. Large leaks generating rich gas clouds (considerable fraction of gas cloud constituted of atmosphere with too high fuel concentration for combustion to be initiated) may not ignite at all, or at a much later time as the concentration at the location of the ignition source must be diluted below the upper flammability limit before the combustion process can proceed in the external environment. Hence, there may be a significant dependency between the ignition time and the onset of the explosion or fire. It is recommended to address this problem in future work providing basis for enhancement of the model of ignition mechanisms.

6.12 Exposed volume

The term 'exposed volume' is used to denote exposure of free flow volume (see Chapter 6.10) to combustible mixture resulting from the leaks observed at installations in the UKCS and NCS. Two different parameters describing the exposed volume are used in the model. The term is used both to describe the exposed volume per leak scenario and to describe the aggregated volume for all leaks in a specified population (*e.g.* all leaks at all installations located in the NCS in the time period 2001-2017).

The two cloud parameters are described as follows

1) The total free flow volume exposed to combustible mixture at any point in time throughout the leak scenario. Disregarding drift of the gas cloud, this volume equals the maximum free flow volume exposed to a concentration above the LFL. This parameter is used to estimate $\lambda_{i,C}$ for the continuous ignition mechanism (see Chapter 6.11 and Chapter 6.2). The parameter is denoted $V_{LEL,max}$.
2) The time averaged volume of combustible mixture, which is the integral of the time dependent cloud volume with respect to time from start of the leak until the point in time where the generated flammable gas cloud from the leak can be considered negligible. This parameter is used to estimate $\lambda_{i,D}$ for the general discrete ignition mechanism (see Chapter 6.11 and Chapter 6.2). The parameter is denoted $VT_{LEL:UEL,avg}$.(or $V_{LEL:UEL,avg} \cdot t$) and possesses the unit 'm^3 x second'.

The methodology for estimation of the volumes is described in detail in Appendix A, Attachment A1, Chapter 3.

6.13 Immediate ignition mechanism

The term 'immediate ignition mechanisms' is used for ignitions that occur immediately upon start of the leak, *i.e.* at $t = 0$. The immediate ignition mechanism is an idealisation of the ignition mechanism where the ignition takes place before a flammable gas cloud has been formed. This is a special case where the ignition mechanism is related to the properties of the object that the release originates from and/or the fluid that is released. Hence, the likelihood of exposure to flammable atmospheres is disregarded in the estimation of the immediate ignition probability.

The rational for including immediate ignition in the model is that the main fraction of observed incidents is believed to have ignited within a marginal time delay after onset of the leak.

The incorporation of this ignition mechanism at start of the leak ($t = 0$) is in accordance with the definition used in NORSOK Z-013, Ref. /5/.

Ignition of a leak due to immediate ignition mechanisms will cause an immediate fire. In most cases, a gas jet fire or a spray fire will be formed. The formation of a pool fire will depend on the pressure in the process system feeding the leak and the geometrical situation determining the air supply to the combustion process.

6.14 Generic immediate ignition

The term 'generic immediate ignition', denoted P_{im}, is used for ignitions that occur immediately upon start of the leak originating from any type of equipment, except pumps.

Note that 'generic immediate ignition' has been denoted 'event ignition' in previous ignition models (*i.e.* Ref. /2/ and Ref. /3/).

6.15 Pump immediate ignition

Observed events have demonstrated that a faulty leaking pump can also cause ignition of a leak. Therefore, a specific ignition probability is included in the model for releases originating from pumps, denoted $P_{im,pump}$. The ignition occurs at $t = 0$, *i.e.* before a flammable gas cloud has been formed.

6.16 Delayed ignition

An ignition is considered 'delayed ignition' if the ignition takes place after start of the release allowing for formation of flammable mixture prior to ignition. Hence, the resulting ignition probability due to delayed ignition is dependent on the probability of exposure to the flammable fluid ($P(E)$) according to equation (5.1).

6.17 Ignition sources in the area

λ_i is the expected number of ignitions per volume unit. Hence it is a volumetric parameter representing the likelihood of having an effective ignition source in a classified area at a typical offshore installation, except those that are specifically modelled (such as hot work class A or a gas turbine air intake). Note that the parameter has the unit 'number of expected ignitions per m^3' and hence it is not a dimensionless ignition probability. However, unless the exposed volume is huge and/or the exposure time is very long, the expected value is an adequate approximation for the ignition probability per volume unit. λ_i is distributed according to ignition mechanism (see Chapter 6.11) and equipment category (see Chapter 6.19). See also Chapter 8.4.3 for derivation of λ_i per equipment category and ignition mechanism.

6.18 Duration of gas exposure

t_{exp} is the volume-averaged duration associated with the estimator for λ_i. Note that t_{exp} can be different from the actual duration of the leak t_{dur}. t_{exp} is used as a mean to estimate the time averaged volume of combustible mixture for leak scenarios where the complete time dependent history of the cloud is unknown. If the transient behaviour of the gas cloud is known (*e.g.* through a CFD simulation), the parameter t_{exp} is not required to estimate the time averaged volume. In this case, the time averaged volume is estimated from time integral of the time dependent cloud history. For further description, see also Appendix A, Attachment A1, Chapter 3.

6.19 Equipment categories

The following equipment categories are covered by the model:

i) Rotating machinery

All types of rotating equipment that may be exposed to flammable fluid. In practice this is pumps and compressors in most cases . The electrical drive is included in the conditional ignition probability set in the model. This model implies that the conditional ignition probability is considered to be equal for all types of pumps and compressors. The operating time of the units must be accounted for. For compressors, the provided figure applies per compressor stage. As the electrical drive is included in the basic figure, the contribution from the electrical drive is also included in the case of mechanical drive (gas turbine driving the compressor(s)). One consequence of this approach is that the fraction related to the electrical drive, which is unknown, is aggregated for each stage on one shaft. Hence, total conditional ignition probability may be somewhat conservative for cases with many stages on one shaft (*i.e.* small effect for typical cases with a few stages on one drive). In order to improve this approximation, more accurate population data is required (this is suggested as further work in Chapter 13)

ii) Electrical equipment

Any electrical equipment, *i.e.* both low and high voltage as well as instruments

iii) Other

The ignition mechanisms are unknown or irrelevant for the 'Rotating machinery' and 'Electrical equipment' categories.

Fractions of the parameter λ_i is distributed in these three categories such that the total equals the value of λ_i.

For the categories 'Rotating machinery' and 'Electrical equipment' there are developed model alternatives depending on the available information for the location and properties of the equipment. The high-level model is purely generic, *i.e.* there is no correlation between the value of the ignition parameter in the model and equipment properties/location. The detailed model allows for specific modelling in terms of location of the pieces of equipment for both categories as there is established a specific ignition probability for certain types of equipment. For the 'Electrical equipment' category, the level of protection and the protection method can be reflected. Intermediate models are suggested for both categories in cases where some information about the equipment properties and the layout is known.

The 'Other' category is a generic group of potential ignition sources that is not understood, and is not related to any specific type of equipment. These ignition sources are assumed to be homogenously distributed in the volume.

6.20 Probability for detection

The probability for detection of a gas leak and initiation of ignition source control is denoted P_{det}. P_{det} is dependent of the gas detector layout (location and type of detector), the set point of the detectors and the voting philosophy. The voting philosophy describes the combination of detectors required to initiate various effects. Examples of this are isolation of equipment representing potential sources of ignition (such as shutdown of electrical equipment, on-going hot work in area and/or non-essential electrical equipment), initiation of emergency shutdown and activation of blow down.

6.21 Effect of ignition source isolation

The effect of isolation of equipment on ignition probability is quantified using the parameter P_{iso}. P_{iso} = 0 means that the isolation of equipment has no effect with respect to ignition probability. P_{iso} = 1 means that isolation of equipment effectively eliminates all potential ignition mechanisms related to the particular equipment being isolated. The effect on continuous ignition sources, such as hot surfaces, is not immediate. This is taken into account by the parameter P_{hot} described below.

6.22 Ignition by hot surfaces after isolation

The continuous ignition mechanism, which typically represents a hot surface related to the ignition source, will not be eliminated effectively before the surface has cooled down below a critical temperature (in practice dependent on a complex set of parameters, see Chapter 6.1). To capture this effect, a general cooling time counting from the point the object has been shut down has been defined for the 3 equipment categories (see Chapter 6.19). The cooling time is defined as the half time for the conditional ignition probability.

An exponentially decreasing probability function versus time can be derived from the defined cooling time. This time dependent probability function is denoted P_{hot}. P_{hot} represents the remaining intensity of the isolated ignition source that can ignite the flammable mixture (A value 1 indicates no isolation effect, a value of 0.50 means intensity is reduced by factor of two). Ignition source is in this context either a specific piece of equipment, such as a pump or electrical equipment, or an entire group of equipment. The capability to represent a specific unit is enabled by an advanced exposure probability model reflecting the location of the unit. A simplistic exposure model can typically only consider a group of equipment homogenously distributed in the area studied.

P_{hot} is 1 prior to the point in time the ignition source is isolated. Hence, the probabilistic exposure model should be able to reflect the detection time (either probabilistic or deterministic per scenario) and include the delay time from detection until confirmed isolation of the unit.

Note that P_{hot} is different for the 3 equipment categories.

6.23 Hot work ignition

The probability for ignition due to exposure of flammable fluid to hot work activities is not accounted for in the P_{if} parameter. Hot work activities must therefore be reflected specifically when calculating the probability for ignition. The model describes how to reflect hot work activity in the ignition probability calculation (see Chapter 9.4).

It is important that the exposure probability model is able to reflect the geometrical layout. The location of the hot work activity relative to the location of the leak sources will have an important effect on the estimated ignition probability. For a limited amount of hot work activity, simplification by use of a model that assumes uniform distribution of the hot work activities relative to the location of the premixed cloud may be acceptable. For high activity periods, an advanced exposure model reflecting the geometrical situation is recommended.

7 Statistical Data Basis

7.1 Introduction

The updated data basis for the ignition model is presented in Appendix A where hydrocarbon leak statistics for the UK Continental Shelf (UKCS) and the Norwegian Continental Shelf (NCS) from 1992 to 2017 are presented. The main sources for these data are the HCR database for UKCS (Ref. /6/) and accident investigation reports, RNNP data and annual reports issued by the Norwegian Petroleum Directorate, Ref. /7/.

This chapter summarises the statistical data available for establishment of the model, and concludes that the population and corresponding observation period are to be used as a basis for the model parameters. Furthermore, the effect of randomness is discussed and a statistical model to account for such effects is presented.

For reasons presented in Chapter 7.5, the full data period (1992-2017) covering both NCS and UKCS is used to calculate the MISOF model parameters. For the sake of consistency in terms of data period it may be argued that data period used as basis for the PLOFAM leak frequency model should also form the basis for MISOF. To demonstrate the results using the same initial year as the basis for the model and for the PLOFAM leak frequency model (i.e. year 2001), the statistical data basis for the two data periods 1992 – 2017 and 2001-2017 is presented throughout this chapter and in Chapter 8.4.3. The latter period is given to show the result for the period being consistent with the PLOFAM(2) data period.

7.2 Observed ignited events

The updated statistical data has been scrutinised in order to determine if there are any ignited events relevant for quantitative modelling of fire and explosion risk. In the previous revision of the offshore ignition probability model, Ref. /3/, none of the registered events were found representative for a typical major accident hazard release scenario addressed in quantitative risk analysis of fires and explosions.

For an ignited release event to be deemed relevant in a quantitative risk analysis context, the following criteria must be fulfilled:

- A process leak according to the definition in PLOFAM (Ref. /1/) having an initial leak rate > 0.1 kg/s (see Table 7.2 definition of leak scenarios covered by PLOFAM)
- Either:
  - The ignition occurred by a gas cloud exposing an active ignition source inside a process module (relevant for estimating P_{if}), or
  - the leak and the ignition had a common cause, the leak itself caused the ignition and/or the time to ignition was very short reducing the importance of exposure probability for the materialisation of ignition (relevant for estimating P_{im} and $P_{im,pump}$)

Other ignited events are either considered not relevant (*e.g.* burning droplets from flare carryover) or are covered by other parts of the ignition model (*e.g.* hot work ignition, presented in Chapter 9.4).

Based on these criteria, three events from the statistical data at UKCS have been found relevant for the use in quantitative risk analysis. In addition, one leak at Rough B (located in the UKCS) in 2006 and one ignited leak in the DCS in 2001 are of particular interest, and are also included in the table below. It is considered likely that both these leaks ignited due to exposure to a gas turbine air intake, which demonstrates that ignition control of gas turbine air intakes must be addressed carefully in quantitative risk analysis of fires and explosions. Ignition due to the ingress of combustible gas in gas turbine air intakes is covered by a separate model in MISOF.

No relevant ignited events occurring on installations in the NCS have been recorded in the period after 1992. However, it is worthwhile mentioning that there was an ignition due to grinding at an installation located in the NCS in 1992, which underlines the importance of reflecting hot work appropriately in quantitative risk analysis. Hot work is to be modelled explicitly by a separate model in MISOF (see Chapter 9.4).

In Table 7.1, the ignited events are categorised with respect to the anticipated overall cause of the ignition corresponding to the main building blocks of the ignition model.

23 additional ignited leaks have been identified in the HCR database (presented in Table A3 2-1 in Attachment A3). These 23 ignited leaks are not considered relevant for modelling of the ignition probability in QRA's, but they are considered relevant for the understanding of the relative distribution between the main equipment categories (see Chapter 6.19) and generic ignition mechanisms (see Chapter 6.11 and Chapter 6.2).

If all release rates are considered (i.e. also PLOFAM leaks having a leak rate < 0.1 kg/s), there are 15 more ignitions that have occurred on UKCS installations. In total, including all leak rates and leaks from all systems (i.e. systems not considered a process system in QRA, such as leaks in diesel systems) the number of ignitions taken place on UKCS installations are 80.

Table 7.1 - Classification of historical events with respect to the main building blocks of the ignition probability model

Event	Immediate ignition	Delayed ignition due to gas exposure in hazardous area	Ignition due to exposure of gas turbine air intake	Assessment of event
Gorm C (DCS 2001) This event is not included in dataset used to set model parameters		X	X	Two possible ignition theories: • Gas turbine ingesting combustible gas resulting in ignition of external gas cloud • Delayed ignition, most likely continuous ignition mechanism (*i.e.* ignition upon initial exposure of source of ignition). See Chapter 6.11 for description of ignition mechanism
Centrica B (UKCS 2006)			X	Dispersed gas ingested by gas turbine resulting in ignition of external gas cloud
HCR ignition ID 164 (UKCS 2003)	X			Immediate ignition of leak from pump.
HCR ignition ID 208 (210-145)	X	X		Immediate ignition or delayed ignition (2 minutes delay according to available data). General ignition mechanism probably discrete (see Chapter 6.11).
HCR ignition ID 226 (210-145)	X			Immediate ignition of leak from pump

7.3 Observed leaks

The number of leaks occurring in the same time period at the same installations as the recorded ignited leaks is required to estimate the ignition probability. The number of relevant leaks according to the definition of a process leak in the PLOFAM leak frequency model (see Table 7.2) at installations in the UKCS and NCS is summarized in Table 7.3. Note that the number of leaks in the NCS in the period 1992-2000 is estimated based on various data sources (see Appendix A attachment A1).

Table 7.2 - Leak scenarios covered by the PLOFAM leak frequency model (Ref. /1/). They occur in well systems, process systems or utility systems (process leaks fed through utility systems). Scenarios that are not listed in this table are not covered by the PLOFAM model

Leak point in well system	Leak point in process system	Leak point in utility system
1. Producing well/Injection well: Topside well release where the inventory between DHSV and PWV is released during normal production. 2. Gas lift well: Topside well release where the inventory between the ASV and the barrier towards the process system is released. In cases where no ASV is present, the entire inventory in the gas lift annulus to the ASCV may be released. Assuming that the check valve ASCV is functioning, otherwise there is no barrier towards the reservoir. 3. Release of hydrocarbon fluid from annuli that are not used for gas lift.	4. Leak point in process system between PWV and topside riser ESDV/-storage ESDV. The fuel system is regarded as part of the process system.	5. Leak point in flare system (low pressure or high pressure flare system) 6. Excessive releases through flare tips and atmospheric vents that exceed the design specification and pose a fire and explosion hazard to equipment, structures or personnel. Such leaks are denoted vent leaks. 7. Leak point in utility systems that is fed by hydrocarbons stemming from process system. Systems covered by the model are: a. Open drain system b. Closed drain system c. Chemical injection systems.

Table 7.3 –The total number of leaks, the number of pump leaks and number of ignited leaks considered relevant for modelling in a QRA. The basis for the historical incidents is presented in Appendix A

Subset of leaks (initial leak rate > 0.1 kg/s)	2001-2017			1992-2017		
	UKCS	NCS	UKCS + NCS	UKCS	NCS	UKCS + NCS
Total number of observed leaks, including pump leaks ($M_{leak,all}$)	327	217	546	687	446[1)]	1,133
Number of observed leaks from pumps ($M_{leak,pump}$)	33	3	36	58	6.1[1)]	64.1
Number of ignited leaks due to immediate or delayed ignition in hazardous area (N)	3	0	3	3	0	3
Number of ignited leaks due to exposure to a gas turbine air intake (*i.e.* relevant for objects not intended for use in explosive atmosphere) [2)]	1	0	1	1	0	1

1) The leaks at installations on NCS in the period 1992-2000 are estimated based on various data sources. See Appendix A.

2) In addition, an incident in 2001 at the Gorm C platform located at the Danish Continental Shelf was likely due to gas ingestion by gas turbine air intake.

It is an important aim that the MISOF model is consistent with the PLOFAM leak frequency model. Hence, any premise put down as basis for the PLOFAM model that affect the estimation of the model parameters in MISOF must be reflected. In PLOFAM, the difference between the data of leaks gathered from installations in the UKCS and the NCS was discussed thoroughly. The following conclusion was established:

> *"A main overall conclusion obtained from running the parameterization and validation process is that the underlying hole size frequency distribution for equipment at installations located on the NCS is similar to the distribution for equipment located on installations on the UKCS. The differences may be explained by uncertainty related to both datasets (both the leaks and the population data), limitations of the mathematical formulations and uncertainty associated with the parameterization and validation methodology. Only a reduction of 20% (on average for all parameters) of the frequency parameter (F_{hist}) was necessary to fit the observed frequency of leaks at installations on the NCS (216 estimated with UKCS model versus 181 observed). The major difference between the estimated leaks and the observed data stems from difference in distribution in terms of type of equipment. Largely, the adjustment of the initial parameters established based on data from installations on the UKCS required to obtain a model that is able to describe the occurrence of leaks at installation on the NCS quite accurately can be considered to be minor."*

According to this statement, although a considerable difference in the distribution of leaks per equipment type is observed, it is not concluded that the hole size frequency distributions are different for an installation in the UKCS and the NCS. The quality of HCRD in terms of categorisation of leaks according to equipment type as well as the population data is not adequate to conclude that there is a difference between NCS and UKCS installations. More emphasis was therefore put on the data gathered from installations in the NCS to establish the joint hole size frequency distributions considered valid for both populations. One result of this is that the PLOFAM model for pumps generates a frequency for leaks from pumps in between the observed data for the NCS and UKCS, but closer to the NCS data than the UKCS data. A perception that the NCS data is more reliable than the UKCS data in terms of classification of leaks to equipment type explains this choice. A reason for the observed deviation could be that there is a tendency to classify leaks stemming from valves, flanges or instruments in the vicinity of pumps, to the pump itself because the accident investigation team concluded this was the case. Examples of such causes are (1) over pressurisation generated by the pump and (2) fatigue due to vibrations caused by the pump. A similar difference between UCKS and NCS data is observed for compressors, which could be explained in the same way as for pumps.

It is important that the risk model in a QRA balances the risk posed by loss of containment (*i.e.* the contribution from exposure to intolerable components due to toxic effects or asphyxiation) and fire and explosion loads following ignition of the leak. It is judged that PLOFAM generates the best estimate of the leak frequency for offshore installations in the North Sea. The PLOFAM model is able to reproduce the number of observed leaks, both occurring at installations in the NCS and UKCS, quite accurately. In order to ensure that the risk model in a QRA based on PLOFAM and MISOF also reproduces the number of ignited leaks, it is required to take the concluded properties of the hole size frequency distribution for pumps into account. Otherwise, the number of ignited leaks associated with pumps may be over- or underestimated (dependent on whether the NCS or UKCS population is being considered). The average fraction of leaks stemming from pumps resulting from the PLOFAM model can be taken from the PLOFAM validation model. The average fraction of leaks from pumps for the 86 installations in the validation model (*i.e.* 86 installations located in the NCS being in operation in the period 2006-2017) is 2.24%. Based on this figure, the number of estimated leaks from pumps for the various populations can be estimated. The result is presented in Table 7.4.

It is concluded that the adjusted number of pump leaks should be applied to set the ignition probability due to leaks from pumps. This will ensure that

- MISOF is consistent with PLOFAM
- A QRA based on MISOF and PLOFAM balances the risk posed by exposure to unignited and ignited leaks with the best possible accuracy
- The risk posed by fires associated with leaks from pumps is not underestimated

The parameterisation of the probability for immediate ignition ($P_{im,pump}$) due to leaks from pumps ($P_{im,pump}$) is quite sensitive to the population considered, which is discussed further in Chapter 8.4.3.

Table 7.4 –The number of pump leaks adjusted for the PLOFAM leak frequency model for pumps

Subset of leaks (initial leak rate > 0.1 kg/s)	2001-20172017			1992-20172017		
	UKCS	NCS	UKCS + NCS	UKCS	NCS	UKCS + NCS
Number of observed leaks, all ($M_{leak,all}$)	327	217	544	687	446	1,133
Number of observed leaks from pumps ($M_{leak,pump}$)	33	3	36	58	6.2[1)]	64.2
Number of estimated leaks from pumps adjusted for the PLOFAM model for pumps ($M_{leak,pump,PLOFAM} = M_{leak,all} \cdot 0.0224$)	7.3	4.9	12.2	15.4	10.0	25.4

1) Not a whole number because the number of incidents estimated based on equipment years. Decimals used to ensure consistency.

In order to perform an overall evaluation of the ignition probability, the total number of process leaks covering any leak rate is extracted from the HCR database. The result is presented in Table 7.5. The number of corresponding ignited events is given in brackets.

Table 7.5 –The total number of process leaks on UKCS installations covering any leak rate.

Subset of leaks	UKCS 1992-2017	
	Number of leaks with any initial leak rate	
	Total	Ignited
Leaks extracted from HCRD according to definition of a process leak in PLOFAM	3001	44

7.4 Exposed volume

From the updated statistical data on hydrocarbon leaks, the total free flow volume (see Chapter 6.10) exposed to flammable fluid (see Chapter 6.12) generated by the observed leaks is estimated. Two different volume parameters are derived in order to estimate the parameters relevant for continuous and discrete sources of ignitions (see Chapter 6.12). The resulting parameters are presented in Table 7.6. The values used as basis for the final model parameters are given in bold font. See also Appendix A for more details.

Table 7.6 – The cumulative gas cloud volumes $V_{LEL,max}$ and $VT_{LEL:UEL,avg}$ for leaks at UKCS and NCS in addition to the average duration. The basis for the numbers and the numbers themselves are given in Appendix A

	2001-2017			1992-2017		
Parameter	UKCS	NCS	UKCS + NCS	UKCS	NCS	UKCS + NCS
$V_{LEL,max}$	32 315	39 686	72 002	77 482	72 838	150 320
$VT_{LEL:UEL,avg}$	4 912 033	10 830 476	15 742 509	13 861 441	16 557 312	30 418 753
$t_{dur} = \frac{VT_{LEL:UEL,avg}}{V_{LEL,max}}$	219	219	219	202	202	202

7.5 Observation period

The main principles when selecting observation period as basis for the ignition model are:

- To use data considered representative for the systems the model is to be applicable for in the future
- To use data with acceptable quality

The quality of the UKCS data is considered consistent throughout the period from 1992 including 2017. The quality of the data gathered from installations in the NCS operating in the period after 2000 is considered to be very good. In the period between 1992 and 2000, there are some uncertainties associated with the data. The estimate of the total number of leaks having an initial leak rate > 0.1 kg/s is considered to be quite accurate. The main problem is related to the estimation of the exposed volume parameters. The initial leak rate, and hence the estimate of the aggregated exposed volume for all leaks in that period is somewhat uncertain, *i.e.* the leak rate is not known for each incident, but the number of leaks per leak rate interval is known. This is not sufficient information to generate a volume estimate per leak directly according to the methodology established for the leaks occurring after 2000. Therefore, the volume estimate has been scaled with the volume estimates for leaks after 2001 and the number of leaks before and after 2001 (see Appendix A), which is considered to result in an estimate with adequate accuracy. The estimate has been adjusted to account for an assumed lower number of very large leaks in the period before 2001 than for the period after 2001.

Based on the following, it is concluded to use the data gathered from installations in the NCS and UKCS in the period 1992 – 2017 as the main basis for the model:

- The quality of the data for both UKCS and NCS for the entire period 1992 onwards is considered acceptable. This applies to both the quality in terms of the recorded number of leaks and the number of ignited events. The estimate of the exposed volume (*i.e.* $V_{LEL,max}$ and $V_{LEL,max} \cdot t$) for the period before 2001 for NCS installations is also found to be acceptable
- No technical explanations are identified that should indicate that the performance of the ignition control barrier is different for UKCS and NCS installations. Hence, the same underlying ignition probability is believed to apply for both UKCS and NCS installations
- There is no time trend in the data with respect to ignition probability. A trend should be supported both by rational arguments and supported in the available data material. All relevant ignitions in the dataset, including the known ignited leak in the DCS, occurred after 2000. This indicates that there may be an underlying increasing trend with time (see Figure 7.8 in the following chapter). Although no conclusive technical or organisational factors are found to support such a time trend (*e.g.* such as insufficient maintenance in the population) it can be argued that such possible trends should be included in the model. However, in Ref. /8/, a decreasing trend in significant explosions from the 80's until the mid 90's was indicated, which supports that the observed trend may be due to stochastic effects (see also Attachment A.1). The stochastic effects are further scrutinised in Chapter 7.7.

The conclusion is that observing three ignitions after 2001 is not unlikely even if the underlying ignition probability is unchanged and based on the full data period. Based on this it is concluded that it is not possible to claim that there is an increasing ignition probability. Furthermore, no rational arguments have been identified to justify that there should be a trend in the underlying ignition probability, i.e. an increased ignition probability. In fact, there are arguments for a decreasing trend. Most importantly, the enforcement of the ATEX directive as of July 2003, likely improving the performance of ignition control of equipment in explosive atmospheres. Hence the best estimate for the underlying ignition probability is concluded to be the full data period.

- The parameters derived based on the entire observation period for UKCS and NCS is believed to generate a best estimate of the ignition probability for an installation provided that an appropriate exposure model (according to equation (5.1)) is used. The data does also provide basis for defining the upper and lower boundary for the underlying ignition probability quite accurately, which means that the risk analyst is enabled to effectively communicate the potential overestimation to the decision maker. This is important to ensure that a well-informed risk based decision is taken. The uncertainties associated with the estimation of the model parameters and an assessment of the interval for the underlying ignition probability is discussed in Chapter 11.2.

7.6 Exposure to combustible atmosphere versus initial leak rate and ignition probability

A fundamental property of the ignition model is the split between immediate and delayed ignition. An important basis for incorporating these two main building blocks is the correlation between exposure to combustible mixtures, leak rate and ignited events extracted from the observed data. Figure 7.1 displays the observed correlation for the entire data set including any leak rate (NCS and UKCS PLOFAM leaks for the period 1992-2017). The basis for the curves is 2902 leaks at UKCS installations and 209 leaks at NCS installations (see Appendix A). The number of ignited events is 43. Note that the NCS data includes only leaks >0.1 kg/s, while the UKCS data also includes leaks <0.1 kg/s. The curves show that an exposure to combustible atmosphere is not the dominant explanatory variable for the underlying historical ignition probability. This indicates that most emphasis should be put on parameters that are independent to the exposure probability when estimating the overall ignition probability. Furthermore, it indicates that a majority of ignited leaks are small. See also discussion of the figure and incorporated model features in the light of these curves in Appendix A.

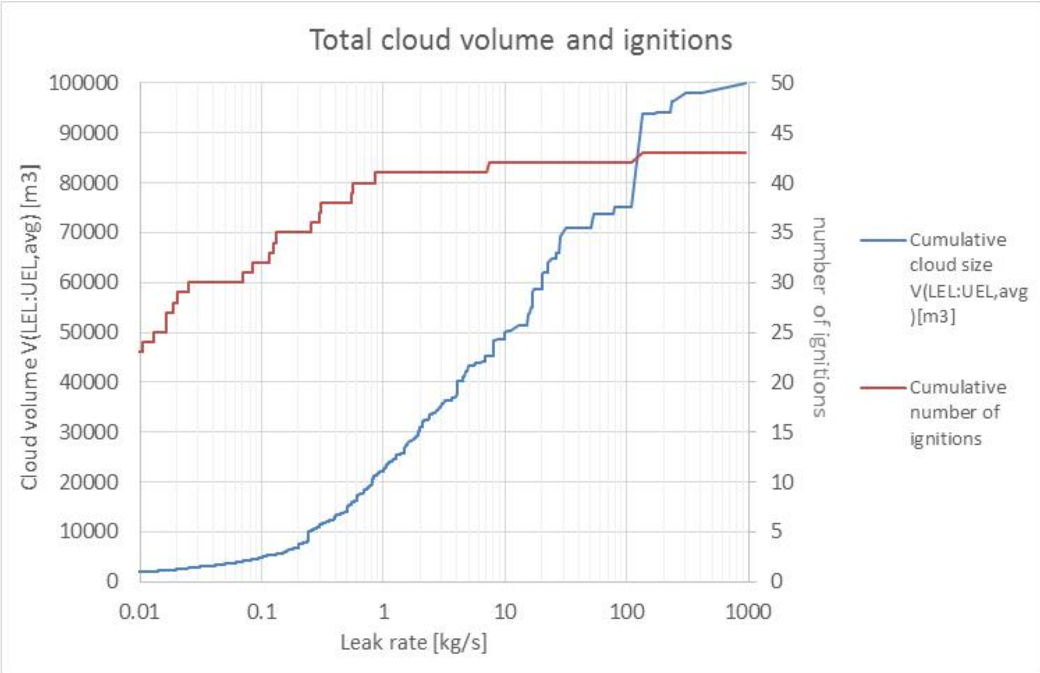


Figure 7.1 – Correlation between exposure to combustible mixtures, leak rate and ignited events extracted from the observed data (NCS and UKCS leaks in the period 1992-2017)

7.7 Interpretation of the historical data and effect of randomness

In order to derive the model parameters, it is important to evaluate how to interpret the observed data with respect to the underlying ignition probability for the population. The underlying probability that a leak ignites (*i.e.* the average ignition probability) is unknown, but it is reasonable to assume that the number of ignitions follows a binomial probability distribution for the following reasons:

- The data material consists of N repeated trials (the leaks)
- The repeated trials are independent. This assumption is not entirely true as known causes will tend to be rectified. For instance, following the huge gas leak at Visund in 2006, all knock out drums at installations in the NCS are equipped with deflection plates at the outlet where redesigned/removed. However, it is judged that assuming independence is a reasonable approach
- Each trial results in an outcome that may be classified as a success (ignited leak) or a failure (not ignited leak)
- The probability of success, denoted p, remains constant from trial to trial. This can be questioned with the same argument as above (*e.g.* technology improvement following lesson learnt from actual incidents). Also because each installation is different and is therefore associated with a unique probability of success (ignition), it may be claimed that the probability is not constant from trial to trial. In fact, there is a unique ignition probability associated with each leak (which is an important reason for developing the MISOF ignition model). In addition to the platform properties (*e.g.* layout and process system property such as composition, temperature, and pressure), the leak properties (*e.g.* geometry of hole) and the weather conditions affect the ignition probability. Hence, in our case, p describes the average ignition probability for all possible leaks (which in theory is infinite) at the various installations in the population (limited by geographical region (*i.e.* NCS or UKCS) and observation period (*e.g.* 1992-2016 or 2001-2016)), and represents the underlying average ignition probability for all possible leaks in the population before information is added to the scenario. As information is added, for instance leak location, leak rate and information about safety systems installed at the relevant installation, the estimate for the ignition probability will change, but this is not in contradiction to the assumption that the underlying ignition probability before information is added is constant from trial to trial It is considered a

reasonable approximation to assume that this average underlying ignition probability p is constant from trial to trial, even if it may have changed over time

Furthermore, it is judged that the quality of the data is good. Hence, all relevant process leaks as well as the ignited events can be considered to be known and described by the historic data presented in Appendix A.

The binomial distribution is given by:

$$P(n\ out\ of\ N\ leaks\ ignite) = \binom{N}{n} \cdot p^n \cdot (1-p)^{N-n} \quad (7.1)$$

The resulting binomial distribution of the number of ignitions given 1133 leaks is shown in Figure 7.2 assuming that the observed ignition probability for the period 1992 - 2017 (3/1133 ~ 0.26%) represents the underlying ignition probability for ignition in hazardous areas (the basis for using this data set for exemplification can be found in the Chapter 7.5). The distribution shows that three ignited events is the most likely outcome in 1133 leaks. On the other hand, the distribution also demonstrates that observing a number of ignited events different from three is likely given that three out of 1133 represents the underlying ignition probability. Even observing no ignited events is quite likely.

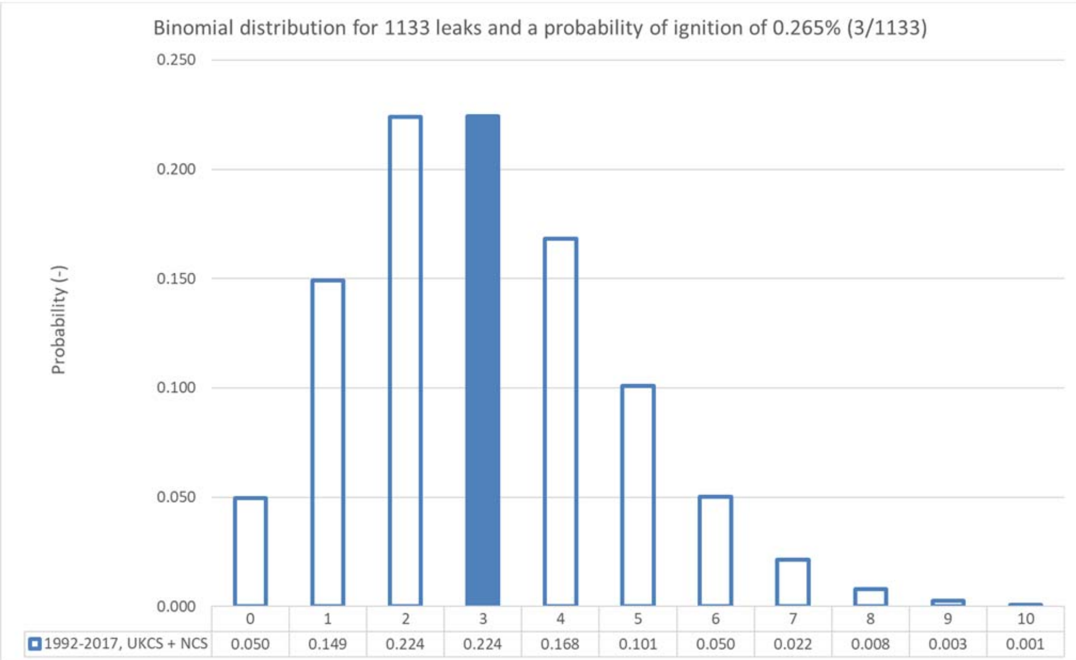


Figure 7.2 – Binomial distribution for 3 ignited leaks in hazardous area out of 1133 leaks occurring at installations located on UKCS and NCS in the period 1992 -2017 (see Table 7.3)

The binomial distribution that describes the possible outcomes suggests that a slightly different underlying ignition probability would also result in a significant probability for observing 3 ignited events in 1133 leaks. This is illustrated in Figure 7.3 where the number ignited events is increased by a factor of two (ignition probability set to 6/1133 ~ 0.53%). Hence, we need to establish a premise describing our interpretation of what we have observed (*i.e.* 3 ignited leaks out of 1133 leaks). This premise must incorporate the philosophy for risk management in terms of how uncertainty is to be accounted for in the model parameters.

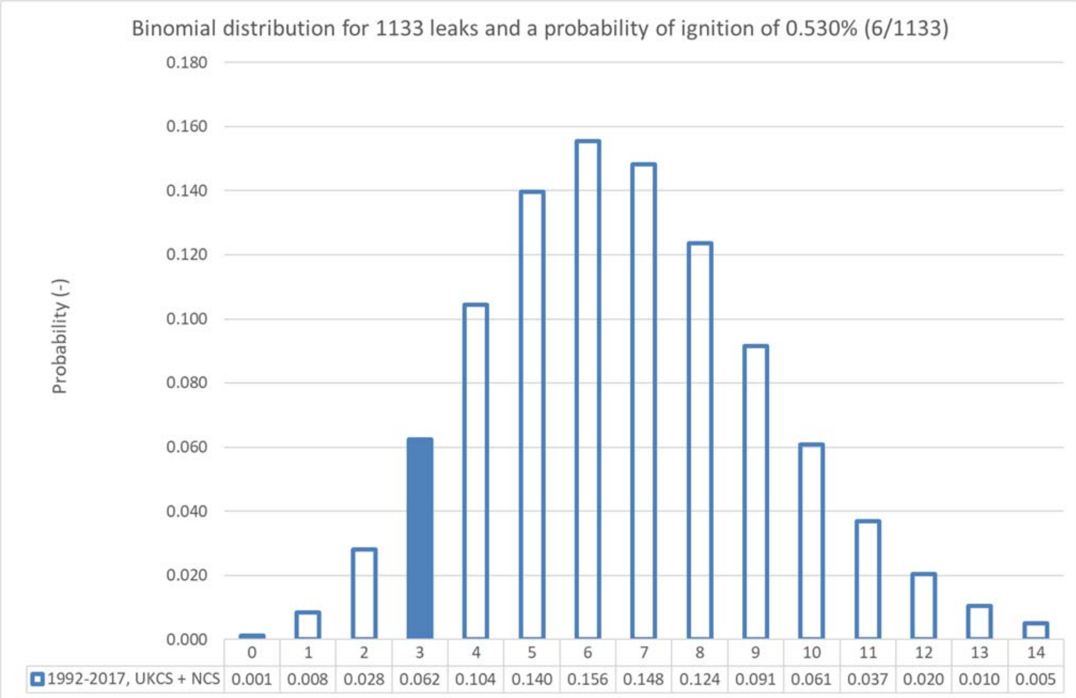


Figure 7.3 – Binomial distribution for 1133 leaks assuming ignition probability of 0.55% (6/1133)

For projects conducted in Norway, blowout frequency model and process leak frequency model are defined through establishing the best estimate of the frequency, but incorporating a model for the stochastic effects (*i.e.* randomness) when setting the model parameters. This is done so that the probability for generating a frequency for a particular event in the population below or above the true underlying frequency is equal. We do not know the underlying ignition probability, but we assume that the underlying probability result in equal probability for observing fewer or more ignited events than the number of expected ignited events corresponding to the underlying ignition probability. The following premise is established that is in line with this principle:

> The MISOF ignition probability, $P(I\ given\ E)$, corresponds to an underlying likelihood for the observed number of ignited leaks, or fewer, of 50%.

The resulting cumulative binomial distribution is shown in Figure 7.4 for the ignition of leaks from exposed equipment in hazardous areas. Because of the small number of observations (*i.e.* number of ignited events), the binomial distribution describing the occurrence of ignited events is skewed. Thus, the underlying ignition probability that satisfies the stated principle is slightly higher than the observed ignition probability (0.32% (3.67/1133) opposed to 0.26% (3/1133)). The result is in line with the use of the Gamma distribution describing the underlying frequency for a Poisson process in Ref. /1/ and Ref. /9/.

Table 7.7 shows the resulting ignition probability for various populations, denoted as the base ignition probability for equipment exposed to combustible fluids in hazardous areas. The number of ignited events as a proposition of the number of observed leaks is given in brackets. The same approach could be used to assess the randomness associated with exposure to gas turbine air intakes, but as the number of leaks that have exposed gas turbine air intakes is unknown, this is not possible. The conditional ignition probability for ingestion of flammable fluid by a gas turbine intake is therefore set based on an assessment of ignition mechanisms and not based on the observed historical data. The defined model parameters for gas turbines are however discussed in light of the gas exposure probability modelled for one specific platform (see Chapter 10.9 and Appendix C).

In Chapter 11, the binomial distribution is used to assess the uncertainty due to randomness associated with the parameter values in more detail. For instance, the effect of applying different interpretations of the observed historical data is discussed.

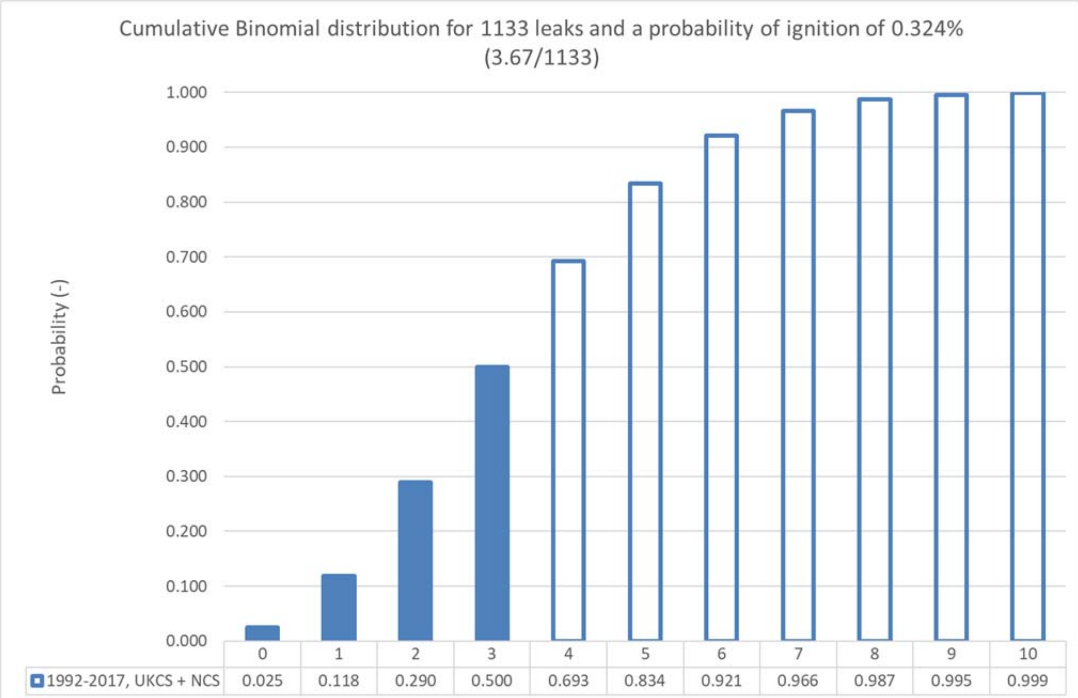


Figure 7.4 – Cumulative binomial distribution for 1133 leaks assuming a probability of ignition of 0.34%, which mathematically corresponds to 3.67 ignited leaks per 1133 leaks

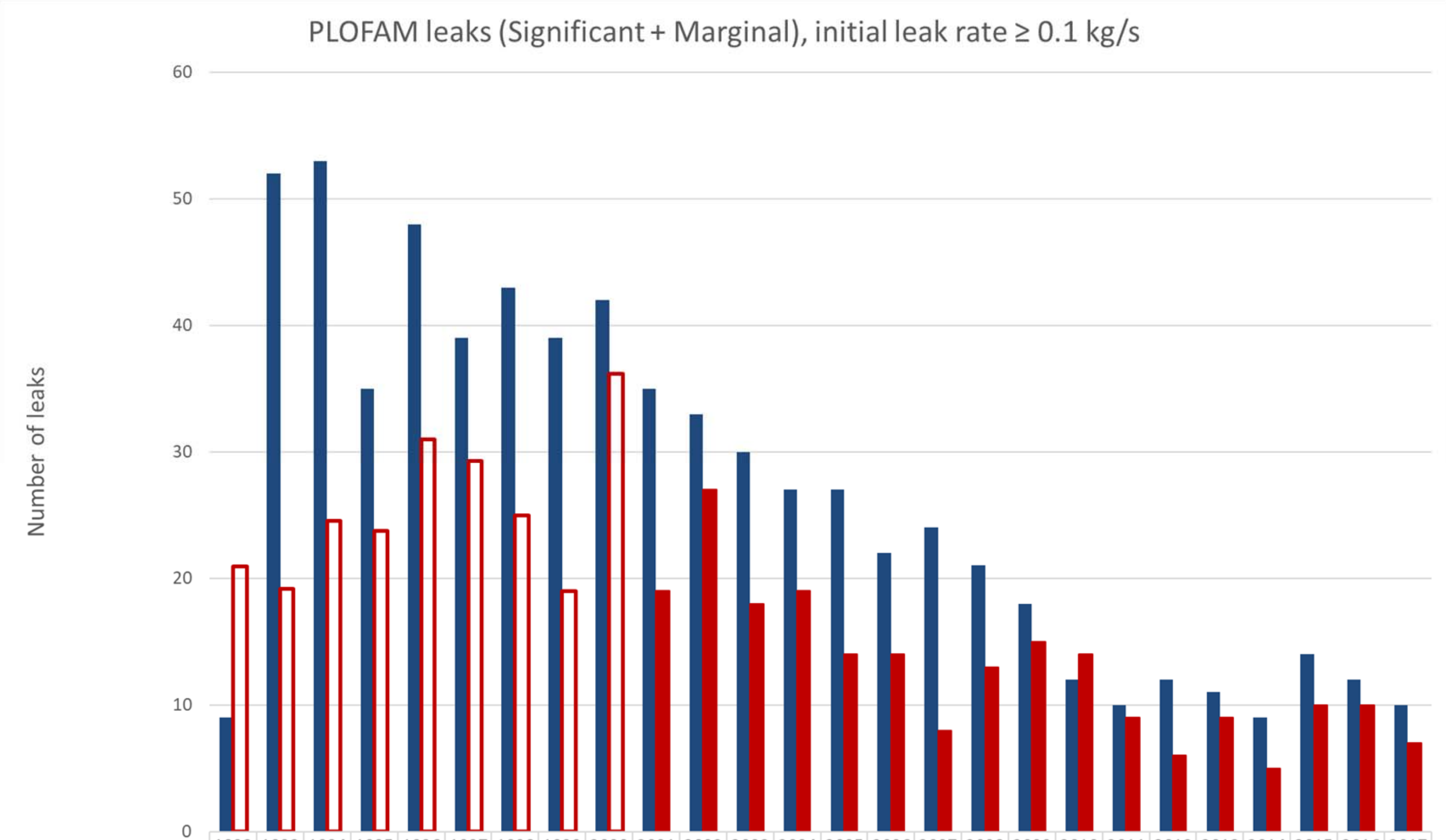
Table 7.7 – The resulting base probability and the corresponding number of ignited leaks per number of observed leaks exposing equipment in hazardous areas

	2001-2017			1992-2017		
Parameter	UKCS	NCS	UKCS + NCS	UKCS	NCS	UKCS + NCS
Base ignition probability, denoted $P_{ign,50\%}$, and the mathematically corresponding number of ignited leaks per number of observed leaks (in parenthesis)	1.12% (3.67/327)	0.32% (0.69/217)	0.67% (3.67/546)	0.53% (3.67/687)	0.15% (0.69/448)	0.32% (3.67/1,133)

The retrospective time trend for the estimation of the underlying ignition probability for the various populations can be illustrated based on the stated premise for interpretation of the data (*i.e.* using 50% percentile in binomial distribution). The result is shown in Figure 7.8 is based on the number of PLOFAM leaks per year and corresponding registered ignited leaks presented in Figure 7.5 through to Figure 7.7. Note that the ignition probability is calculated based on the 50% percentile in the binomial distribution. The figure displays the targeted estimate of the underlying ignition probability assuming an annual update of the MISOF report since recording of data started in 1992.

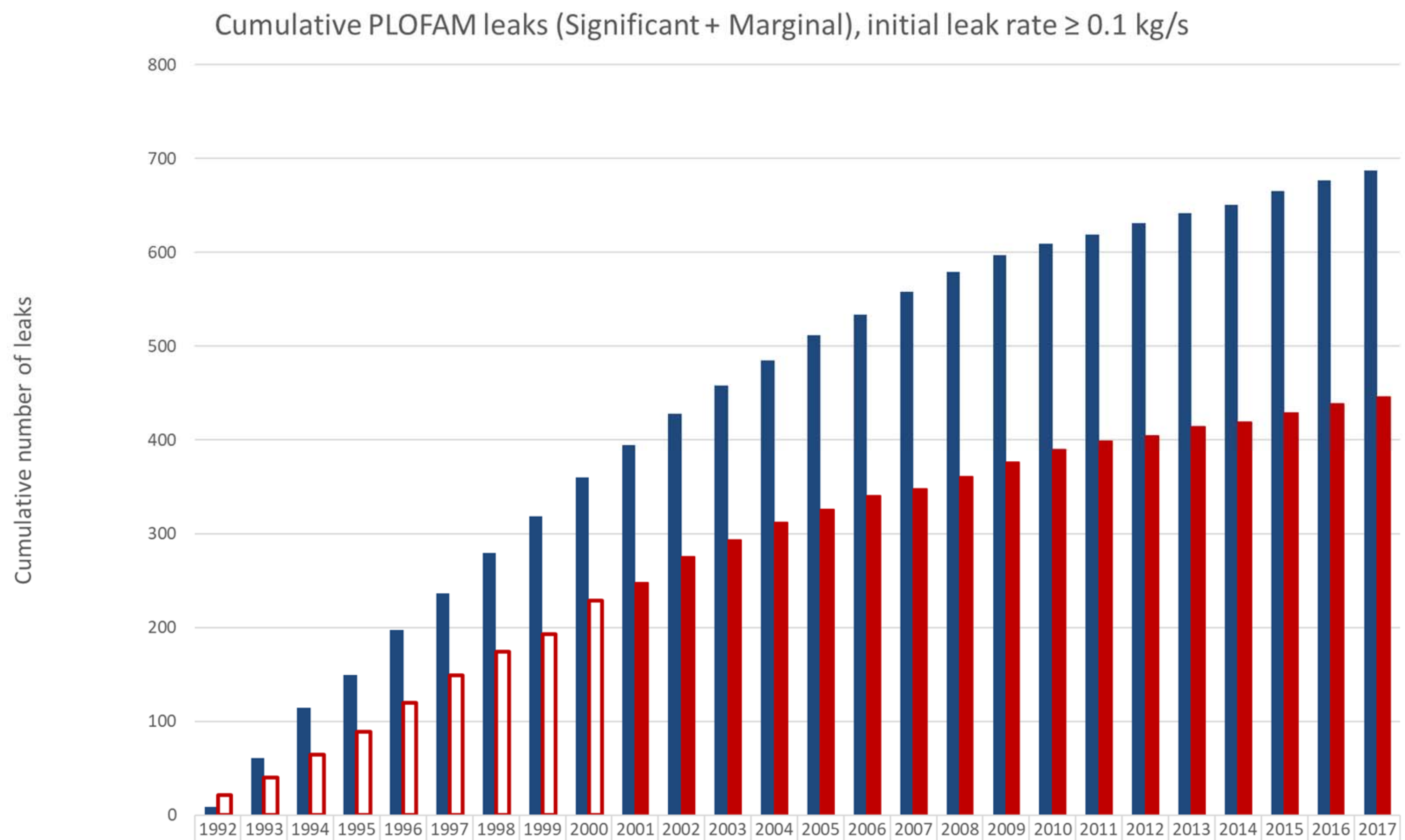
Broadly, the result shows that the estimate of the underlying ignition probability is surprisingly constant and also quite similar for the two populations (UKCS and NCS). From 1994 and onwards, the estimate of the ignition probability is fluctuating around 0.25% for the North Sea (UKCS + NCS). This result indicates that we can be quite confident that the underlying ignition probability is around 0.25%. Such a statement does rely on the quality of the data and our judgement that there is no underlying trend in the data. The time trend indicates that there is an underlying increasing trend, but that has not been supported by casual arguments (see Chapter 7.5). However, even if such a moderate time trend should be true, this would not violate the statement above, *i.e.* that the underlying ignition probability due to immediate and delayed ignition for all leaks on installations in the NCS and UKCS should be around 0.25%. In fact, disregarding any issues related to the quality of the data and assuming that there is no difference between installations in the NCS and UKCS, the best estimate is about 0.25%. The presented time trend is based on the total number of leaks per year. The number of leaks per year (partly estimated for NCS in the period 1992-2000) is judged to be reliable, and is utilised to support this statement.

In order to monitor any possible underlying time trend, it is considered important to update the MISOF model with a regular frequency. Then the MISOF model will be able to capture and incorporate any trend to ensure it is adaptable for the future. It is important to keep in mind that a fundamental basis for the validity of MISOF is that the observed data extracted from operating installations tare applicable to the future design and operational conditions.



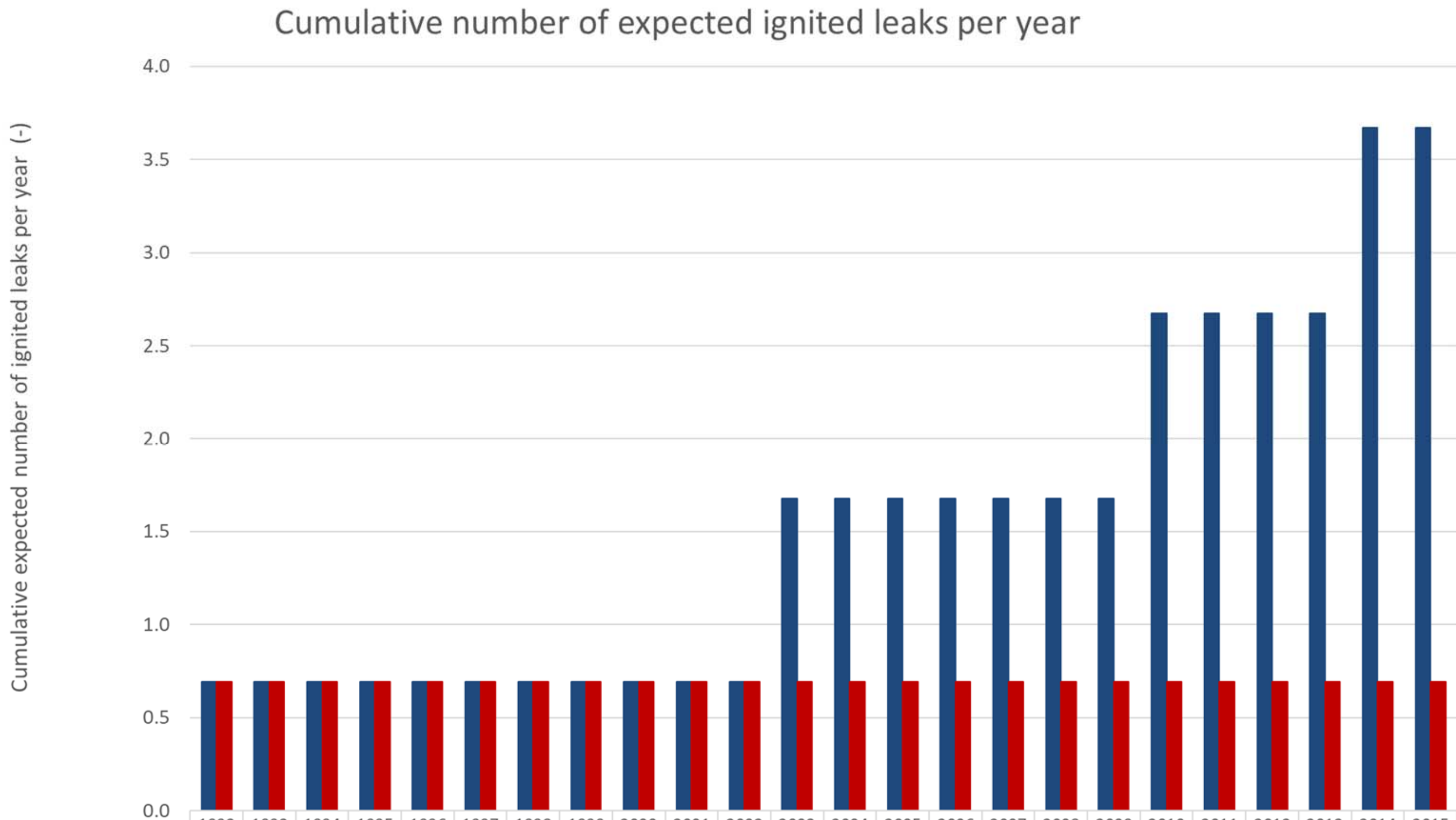
	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
PLOFAM leaks UKCS	9	52	53	35	48	39	43	39	42	35	33	30	27	27	22	24	21	18	12	10	12	11	9	14	12	10
PLOFAM leaks NCS	21	19	25	24	31	29	25	19	36	19	27	18	19	14	14	8	13	15	14	9	6	9	5	10	10	7

Figure 7.5 – Number of PLOFAM leaks per year for the period 1992 and onwards. The data for installations on the NCS before 2001 is estimated based on various data sources, and there is some uncertainty associated with these data. The data for this period is therefore marked with unfilled bars



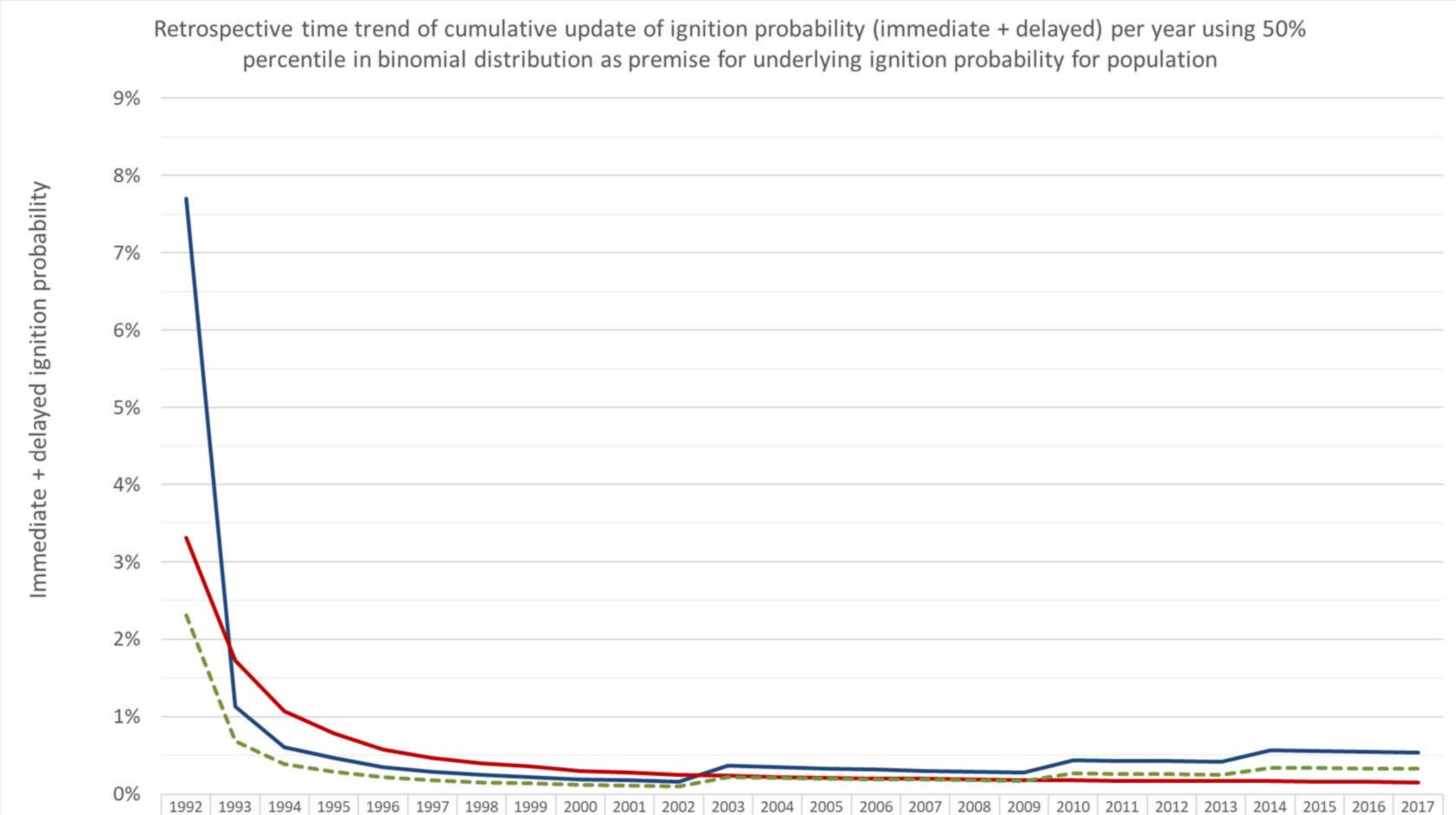
	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
PLOFAM leaks UKCS	9	61	114	149	197	236	279	318	360	395	428	458	485	512	534	558	579	597	609	619	631	642	651	665	677	687
PLOFAM leaks NCS	21	40	65	88	119	149	174	193	229	248	275	293	312	326	340	348	361	376	390	399	405	414	419	429	439	446

Figure 7.6 – Cumulative number of PLOFAM leaks per year for the period 1992 and onwards. The data for installations on the NCS before 2001 is estimated based on various data sources, and there is some uncertainty associated with this data. The data for this period is therefore marked with unfilled bars



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
50% percentile ignited leaks, UKCS	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	1.68	1.68	1.68	1.68	1.68	1.68	1.68	2.67	2.67	2.67	2.67	3.67	3.67
50% percentile ignited leaks, NCS	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69

Figure 7.7 – Cumulative number of ignited PLOFAM leaks per year for the period 1992 and onwards including the effect of randomness (using 50% percentile in binomial distribution as premise for estimation of the underlying ignition probability)



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
UKCS	7.70%	1.14%	0.61%	0.47%	0.35%	0.29%	0.25%	0.22%	0.19%	0.18%	0.16%	0.37%	0.35%	0.33%	0.31%	0.30%	0.29%	0.28%	0.44%	0.43%	0.42%	0.42%	0.56%	0.55%	0.54%	0.53%
NCS	3.31%	1.73%	1.07%	0.78%	0.58%	0.47%	0.40%	0.36%	0.30%	0.28%	0.25%	0.24%	0.22%	0.21%	0.20%	0.20%	0.19%	0.18%	0.18%	0.17%	0.17%	0.17%	0.17%	0.162%	0.158%	0.16%
NCS + UKCS	2.31%	0.69%	0.39%	0.29%	0.22%	0.18%	0.15%	0.14%	0.12%	0.11%	0.10%	0.22%	0.21%	0.20%	0.19%	0.19%	0.18%	0.17%	0.27%	0.26%	0.26%	0.25%	0.34%	0.34%	0.33%	0.32%

Figure 7.8 – Retrospective time trend of cumulative update for ignition probability per year (immediate plus delayed) using 50% percentile in binomial distribution as premise for estimation of the underlying ignition probability

8 Ignition model parameters for objects intended for use in potentially explosive atmospheres

8.1 General

Based on the updated statistical data, the ignition model parameters for objects intended for use in potentially explosive atmospheres have been updated. An illustration of the main building blocks is shown in Table 8.1.

It should be noted that the uncertainty related to the parameter values being derived is significant, which is discussed in Chapter 11.

8.2 Area of application

The model for ignition sources located inside classified areas is only valid for objects intended for use in potentially explosive atmospheres. There are in general three Ex zones:

- Zone 0: An area in which an explosive mixture is continuously present or present for long periods
- Zone 1: An area in which an explosive mixture is likely to occur in normal operation
- Zone 2: An area in which an explosive mixture is not likely to occur in normal operation and if it occurs it will exist only for a short time

The model can be used for all Ex zones. In practice, the relevant areas are in most cases classified as Zone 1 or Zone 2.

The level of protection and methods for protection vary for the different Ex classes, and critical failure rates that could cause ignition will vary accordingly. The ignition model is based on statistical data collected from facilities in the North Sea, and the established parameter values can be considered to be a result of the average industry practice in that area with respect to Ex equipment. No detailed population data on the use of Ex equipment with regard to hazardous zone classification has been available. However, a model to reflect the type of protection for electrical equipment and instruments has been established based on a detailed study for three installations in the Norwegian continental shelf (Ref. /10/) combined with engineering judgment of expected industry practice.. Consequently, the model provides a basis to reflect the type of protection method, *i.e.* whether the electrical equipment in the area complies with Zone 0, Zone 1 or Zone 2.

For the category 'Rotating machinery' no data has been found to support a model for different types of protection. If relevant, the electrical motor for such objects can be modelled in accordance with the suggested failure frequencies for electrical equipment. For the category 'Other' the ignition mechanisms are unknown and no data is found that provides a basis for a model that varies with the Ex zone classification level. Likewise, for the probability of immediate ignition (denoted "event ignition" in previous models), the given ignition probability applies to all types of process equipment typically found in any of the Ex zones. Improved knowledge of the ignition mechanisms and/or access to reliable statistical data of releases and ignited events within the different Ex zones may provide a basis to reflect these factors for equipment other than electrical units and instruments. For the 'Other' category, as stated above, the given parameter values should be considered to represent the average industry practice in the North Sea with respect to use of Ex equipment.

The model for electrical equipment suggests that the likelihood of faulty equipment causing ignition is significantly less for equipment that is rated for Zone 1 and Zone 0 atmospheres, than equipment that is rated for Zone 2 atmospheres (in general a relative factor of 10 on the failure rate is implemented). Therefore one could argue that such a correlation also exists for the other equipment categories. This argument could be used to reduce the parameter values for modules with high level of protection. In contrast, one could also argue that the basic parameter value that is established is somewhat optimistic for Zone 2 areas because the obtained values are based on the average industry practice.

All of the Ex categories except Ex n and some of Ex s are applicable to Zone 1, and many operators require Zone 1 equipment in Zone 2 areas, so there will be a considerable amount of Zone 1 equipment in any Zone 2 area. Consequently, if there is a decreasing trend in the probability of ignition with increasing levels of protection, the average parameter values could be misrepresented. For example, the probability of ignition for Zone 2 equipment/modules with only Zone 2 equipment could be estimated to be lower due to the inclusion of Zone 1 equipment, of lower ignition probabilities within the area. As the ignition mechanisms are not fully understood and there is considerable uncertainty it is therefore recommended that the parameter values for the ‘Other’ and ‘Rotating machinery’ categories, are not adjusted unless thoroughly justified with respect to type of Ex class and/or protection method.

8.3 Overview of model

On a high level, the ignition model consists of the following main groups

i) Probability for ignition before a flammable gas cloud has been formed. This is a special case where the ignition mechanism often is related to the properties of the object that the release originates from and/or the fluid that is released. The likelihood of exposure is irrelevant in this case. This group is denoted "immediate ignition"

ii) Probability of ignition due to exposure of objects that constitute a potential source of ignition if exposed to flammable atmospheres. Ignition will in this case take place after start of the release. This group is denoted "delayed ignition"

These two groups are further broken down to a few categories dependent on the type of equipment and ignition mechanism.

For the group "immediate ignition" there is two categories (see 6.14 and section 6.15 for description):

i) Immediate ignition

ii) Pump immediate ignition

The equipment categories under the delayed ignition group are as follows (see Chapter 6.19 for description):

i) Rotating machinery

ii) Electrical equipment

iii) Other

The starting point for modelling of the ignition probability given exposure to these different equipment categories is the generic parameter, "Ignition sources in the area", λ_i (see Chapter 6.17 for description).

Based on general classification of ignition mechanisms the following two types are used in the ignition model (see Chapter 6.11 for description):

i) Continuous

ii) Discrete

The modelling of the exposure probability ($P(E)$ in equation (6.1)) for these two classes is different, which has to be reflected in the transient exposure model.

For the categories 'Rotating machinery' and 'Electrical equipment', three different models are developed requiring inputs of varying resolution. The model that should be used is dependent on the available information in terms of the location and properties of the equipment. The high-level model is purely generic, *i.e.* there is no correlation between the value of the ignition parameter in the model, the equipment properties and layout. The detailed model allows for specific modelling in terms of location of the pieces of equipment for both categories. For the 'Electrical equipment' category, the level of protection and protection method can be reflected. Intermediate models are suggested for both categories in cases where some information about the equipment properties and layout is known.

In addition to the equipment categories and ignition mechanism given above, the parameters reflecting the effect of ignition source isolation, denoted P_{iso} and P_{hot}, are important building blocks of the model. These two parameters reflect the transient behaviour of $P(I\ given\ E)$ in equation (6.1). They are described in Chapter 6.21 and 6.22.

Table 8.1 - Main building blocks of the ignition model for objects in classified areas

Immediate/ delayed	Equipment category	Ignition type	Description
Immediate ignition	All equipment types except pumps	-	Generic ignition probability that applies to releases of flammable fluids from all types of equipment, except pumps
	Pumps	-	Ignition probability related to releases from pumps operating flammable fluids
Delayed ignition	Rotating machinery	Continuous	Applies to all types of rotating machinery that may be exposed to flammable fluid. In practice this is in most cases pumps and compressors
		Discrete	
	Electrical equipment	Continuous	Applies to any electrical equipment, *i.e.* both low and high voltage as well as instruments
		Discrete	
	Other	Continuous	The ignition mechanisms are unknown or irrelevant for the 'Rotating machinery' and 'Electrical equipment' categories
		Discrete	

8.4 Derivation of model parameters

8.4.1 Available data for parameterization

The observed ignited leaks at installations in the UKCS and NCS presented in Table 7.1 relevant for incorporation into MISOF parameters are summarized in Figure 8.1. One out of these ignition events is related to equipment not intended for use in explosive atmospheres, which is covered by the specific model for gas turbine air intakes (see Appendix C). The remaining three ignited events thus form the basis for setting the parameter values relevant for modelling of ignition due to exposure of objects intended for use in potentially explosive atmospheres.

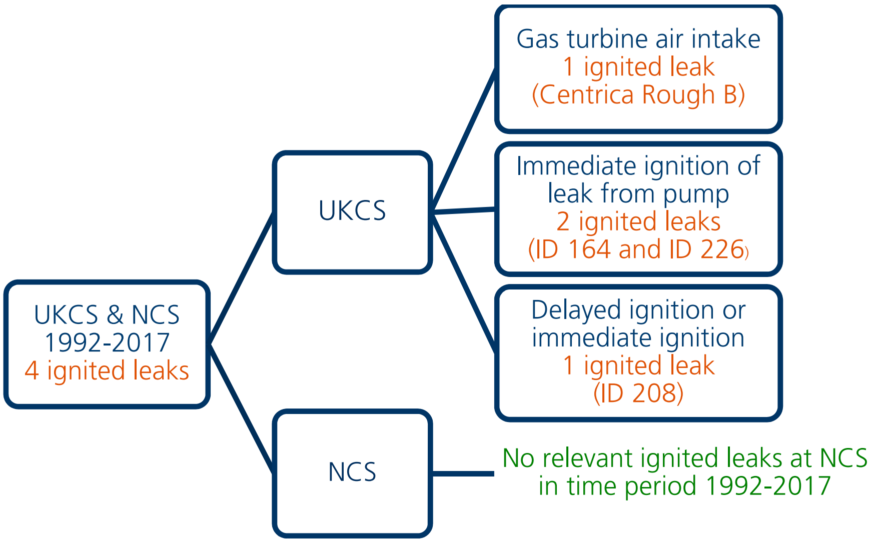


Figure 8.1 - Overview observed ignited leaks in the period 1992-2017 at UKCS& NCS relevant for modelling of ignition probability in QRA (*i.e.* corresponding to PLOFAM leaks)

In order to provide basis for distribution of the historical ignition probability on the ignition type (immediate, discrete and continuous) per equipment category, 23 additional ignited leaks have been identified in the HCR database (presented in Table A3 2-1 in Attachment A3). These 23 ignited leaks are not considered relevant for modelling of the ignition probability in QRA's (*i.e.* they do not correspond to the definition of a PLOFAM leak (see Ref /1/), but they are considered relevant for understanding of the relative distribution between the main equipment categories and ignition types.

The available description of the 26 events and the possible ignition mechanisms is limited. Therefore, engineering judgment is used to classify each event. The categorization of leaks is presented in Table 8.2 in accordance with the equipment categories defined in Chapter 6.19. Figures in brackets are the number of leaks where there is stated a delay time between onset of the leak and the point in time ignition occurs. It is expected that the delay time is not set consistently throughout the data material and it is reasonable to expect that a delay time is set when a delay time has been observed with confidence. In cases where delay is questionable, it is reasonable to expect that the delay time frequently has been set to zero. Hence, it is judged that the delay time cannot be used to categorize the events as immediate or delayed ignition in MISOF. In MISOF, immediate ignition is defined to take place exactly at the moment in time the leak starts (see Chapter 6.13).

Ten events are considered not to be related to any of the equipment categories 'Rotating machinery' or 'Electrical equipment' and are therefore categorised as 'Other'. These events are thus not related to any specific type of object and furthermore five out of those ten events are considered unknown with respect to the type of ignition. These events have HCR ign. ID 64, 144, 151, 186 and 194 (see Appendix A). An ignition delay of 900 seconds is reported for ID 151 and "Immediate" ignition is disregarded. The ignition sequence is given as "Explosion" for ID 194 and consequently "Immediate" is considered unlikely. The remaining three events are split evenly in the three categories (*i.e.* it is considered arbitrary whether they should be sorted as "Immediate", "Discrete" or "Continuous"). This implies that the 5 "Unknown" incidents are distributed as follows and the resulting distribution of these 5 incidents is shown in Table 8.3:

- two are "Continuous";
- Two are "Discrete"; and
- One is "Immediate"

Table 8.2 - Results from ignition source sorting and assessment of the 26 incidents displayed according to equipment categories and generic ignition mechanism (see Table A3 in Attachment A3 for further information). Numbers in brackets are the number of leaks where a delayed ignition time is reported. Note that the delay time set in HCRD is not judged to correspond with the definition of delayed and immediate ignition in MISOF (see more information above)

General ignition mechanism in MISOF or unknown	Rotating machinery	Electrical equipment	Other	Total
Continuous	9 (1)	4 (2)	0	13 (3)
Discrete	0	1 (1)	5 (1)	6 (2)
Immediate	2	0	0	2 (NA)
Unknown	0	0	5 (1)	5 (1)
Number of events	11 (1)	5 (3)	10 (2)	26 (6)

1) The 5 events classified as "Unknown" are split between "Immediate", "Discrete" and "Continuous". 1 is categorized as "Immediate", 2 as "Discrete" and 2 as "Continuous"

Table 8.3 – Distribution of ignition type per equipment category and general ignition mechanisms

Parameter	Rotating machinery	Electrical equipment	Other	Total
Categorization ignited leaks used to establish distribution of ignition type per equipment category				
Continuous	9	4	2	15
Discrete	0	1	7	8
Distribution of ignited leaks used to establish distribution of equipment category per general ignition mechanism				
Continuous	60.0 %	26.7 %	13.3 %	100%
Discrete	0.0 %	12.5 %	87.5 %	100%
Adjusted distribution of equipment category per general ignition mechanism				
Continuous	60 %	30 %	10 %	100%
Discrete	10 % 2)	10 %	80 %	100%
Resulting adjusted distribution of each general ignition mechanism per equipment category				
Continuous	92 %	86 %	20 %	67 %
Discrete	8 %	14 %	80 %	33 %

2) None of the events in the 'Rotating machinery' category is categorised as discrete, but 10 % is put in the discrete category to account for ignition mechanisms not observed in data set

The resulting categorisation of the events by the type of ignition (*i.e.* continuous versus discrete) is considered reasonable based on the expected ignition mechanisms. For 'Rotating machinery', the main ignition mechanism is expected to be hot surfaces, and it is found reasonable that continuous sources should be regarded as the main ignition type. This is supported by the number of ignited events reported in Table 8.3, where no discrete ignitions are registered for rotating machinery. 10% is however assigned to "Discrete" sources to account for ignition mechanisms not observed in the dataset.

Ignition mechanisms that may be considered continuous are expected to constitute the major fraction also for 'Electrical equipment', which is in accordance with the assessments in Ref. /10/. The following is quoted from that study:

> *"…different conditions for generating an arc are discussed, and it is concluded that a spark over an electrode gap is either continuous or a single event like e.g. on making or braking of a switch. Intermittent sparks are considered very unlikely given a fixed gap distance. The only realistic way of producing an intermittent spark or arc over a gap would be if the gap distance itself was intermittent due to mechanical movement of the wires."*

Another scenario considered as delayed, discrete ignition is when flammable gas requires some time to enter an enclosure containing faulty equipment causing ignition. As this type of scenario will require greater exposure than continuous sources, they are expected to be rarer than continuous ignition scenarios.

Based on the above, one out of five ignitions whereby electrical equipment has being classified as "Discrete" appears to be reasonable.

For the group 'Other' the actual ignition mechanisms are unknown and it is hard to assess the validity of the split into the three different generic ignition mechanisms. The evaluation of the 26 events resulted in more emphasis on the discrete sources (75 %) which will to some extent balance the major contribution from continuous sources resulting from the two other categories. This will place more significance on delayed ignition of large gas clouds resulting from leaks having long durations as discrete sources will tend to dominate over continuous sources for gas clouds generating a long exposure time. This will account for the uncertainty associated with the estimation of catastrophic explosions. None of the observed relevant ignited events for modelling of fires and explosions in QRA's (*i.e*. none of the 4 observed leaks at UKCS and NCS) have been categorized as delayed ignition due to exposure to a discrete source of ignition, but such types of ignition cannot be disregarded. Human activity/manual intervention could be seen as a potential scenario leading to manifestation of a discrete ignition source causing delayed ignition. Examples of this are the remote or manual operation of equipment in an area being exposed to combustible mixtures, or rescue personnel entering the scene of the event introducing an ignition source unintentionally.

Overall about 23% (6 of the 26 ignitions) of the ignitions took place after onset of the leak. This can be used to support a distribution between delayed and immediate ignition however a large amount of uncertainty remains prominent. It is reasonable to believe that the delay time is not consistently implemented in the data material, and that the actual fraction is somewhat higher.

8.4.2 Distribution of ignited events per ignition type and equipment category

Two out of the three relevant incidents (*i.e*. ID 164 and ID 226) are judged to be relevant for modelling of $P_{im,pump}$, whilst the third incident (ID 208) is considered relevant for P_{im}, $\lambda_{i,C}$ and $\lambda_{i,D}$. The $\lambda_{i,C}$ and $\lambda_{i,D}$ parameters, determine the probability for delayed ignition and are crucial for the risk contribution from explosions. Underestimation of the actual underlying probability for delayed ignition will have a negative effect on the future risk based safety design controlling explosion risk. The methodology for setting the parameters affecting delayed ignition should therefore account for the uncertainty in the data material as well as stochastic effects. It is therefore concluded that the remaining ignited event (ID 208) is to be assigned to delayed ignition. This implies a fraction delayed ignition of 33.3%. The fraction of delayed ignitions derived from the 26 ignited leaks presented in Table 8.2 is in the same region (about 23% of the 26 ignitions are classified as being delayed). Moreover, the average leak rate was > 0.1 kg/s in 7 out of the 26 ignited leaks and in 2 of those 7 leaks, the ignition was delayed.. Interestingly the correlation between all PLOFAM process leaks and the exposure to combustible atmosphere presented in Figure 7.1 (Chapter 7.6) indicates that exposure probability is not a very prominent factor for the underlying ignition probability. This result supports that the weight on delayed ignition in a QRA should be significantly less than 50%.

The split between immediate and delayed ignition is discussed in Ref. /11/, where various data sources are considered in the data review. The data material is derived from various industries and is related to different types of equipment. The review shows that the data sources generate a wide range of possible distribution between immediate and delayed ignition (ranging from 94% to 10% weight on early ignition). The report concludes with the following:

> *"It is therefore concluded that risk assessment approaches based on a 30:70 to 50:50 split in early:delayed ignition or jet/pool/ fire:flash fire/explosion are reasonable."*

None of the data sets used to establish this conclusion are directly relevant for the PLOFAM leaks, which is used as basis for the MISOF model. It is therefore judged that the distribution presented in Ref. /8/ cannot be directly used as basis for setting a distribution for parameters incorporated into the MISOF model.

In conclusion, it is determined that one in three of the events above are classified as delayed ignition, which leads to a proportion that appears to be reasonable and also accounts for uncertainty. The latter means that the estimate is expected to be somewhat on the high side, but should still be considered to be a best estimate. Rounding off 1/3 to the closest tenth results in the following distribution:

- 70% on immediate ignition
- 30% on delayed ignition

The observed incidents indicate that most emphasis should be put on immediate ignition of leaks stemming from pumps and therefore both incidents assigned to immediate ignition are leaks from pumps. Hence, it is judged to use the following distribution of the fraction related to immediate ignition (a total of 70%):

- 50% on leaks from pumps (this parameter is denoted $f_{im,pump}$)
- 20% on leaks not from pumps (this parameter is denoted f_{im})

The distribution of incidents on immediate and delayed ignition is considered to be step 1 in development of the total distribution. The next step is to establish a distribution of delayed ignition by type of ignition per equipment category.

The distribution on "Continuous" and "Discrete" sources is established based on the distribution obtained from the 26 incidents presented in Table 8.2. Eight out of 23 ignitions are assigned to "Discrete", which is about one third of the ignitions. Rounding off to the closest tenth leads to the following distribution of the fraction assigned to delayed ignition (a total of 30%):

- 10% of all ignitions are delayed, "Discrete" (this parameter is denoted $f_{if,D}$)
- 20% of all ignitions are delayed, "Continuous" (this parameter is denoted $f_{if,C}$)

The final and 3rd step is to calculate the distribution on equipment category. The adjusted distribution is presented in Table 8.3. The combination of the distribution per step to obtain the distribution per ignition type per equipment category is shown in Table 8.4. The distribution per step and the resulting ultimate distribution are illustrated in Figure 8.2.

The distribution of these events per ignition type and equipment category is crucial for the resulting parameter values in the ignition model presented in the subsequent chapters. Hence, when considering the uncertainty related to any other parameter in the model, it should be viewed in the light of the uncertainty related to the distribution. For instance, if 50% of the cause of event HCR ignition ID 208 is attributed to immediate ignition, instead of 100% to delayed ignition, the contribution from delayed ignition in the quantitative risk analysis would decrease by 50% (if the contribution from special types of ignition sources, such as gas turbine air intakes can be neglected). A reduction in contribution from delayed ignition of this magnitude would have a significant effect on conclusions generated from a quantitative explosion risk analysis. However, it may also be the case that the actual underlying contribution from delayed ignition should be higher than 30%. The number of observed events is small, and the distribution based on the statistical data is sensitive to randomness. The concluded distribution per ignition type and equipment category should be considered best estimate, *i.e.* not considered to be conservative. The uncertainty is discussed further in Chapter 11.2.1.

Table 8.4 – Fraction per ignition type and equipment category

Parameter	Rotating machinery	Electrical equipment	Other
Continuous	12% (0.3·(0.2/0.3)·0.6)	6% (0.3·(0.2/0.3)·0.3)	2% (0.3·(0.2/0.3)·0.1)
Discrete	1% (0.3·(0.1/0.3)·0.1)	1% (0.3·(0.1/0.3)·0.1)	8% (0.3·(0.1/0.3)·0.8)

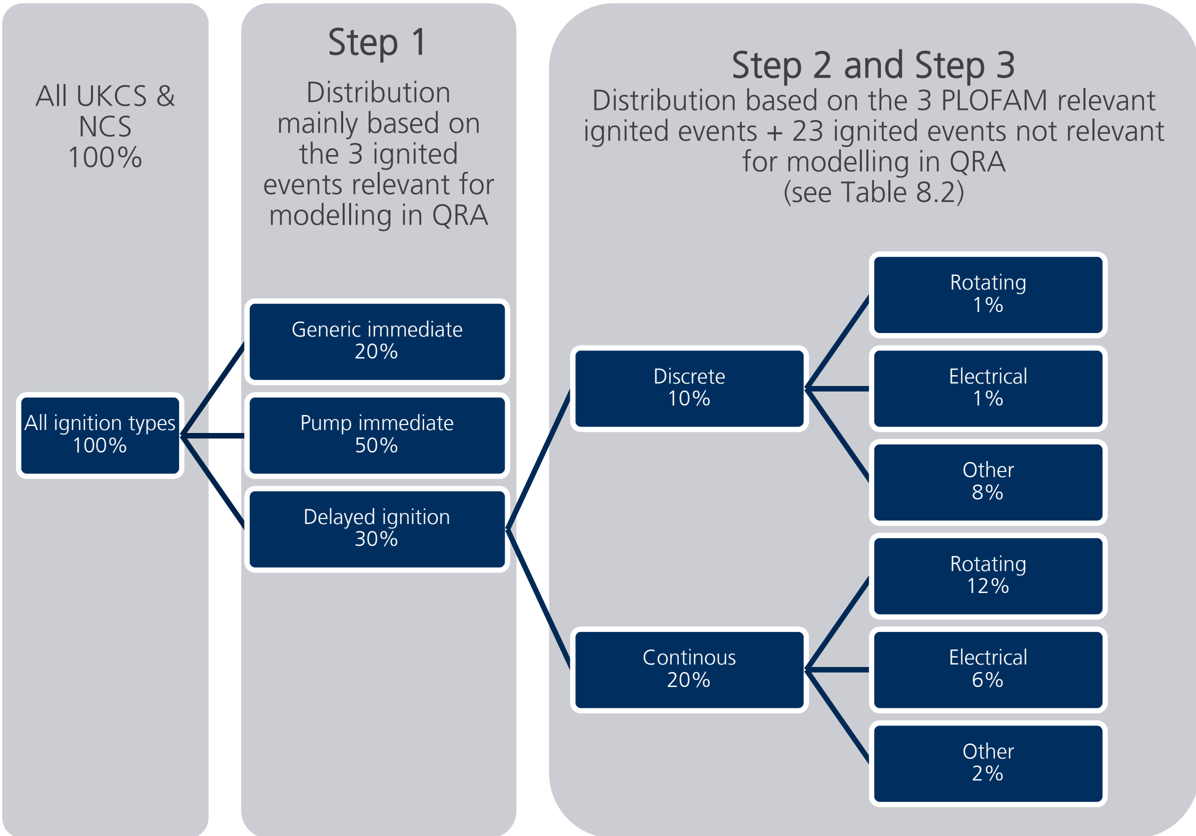


Figure 8.2 - Application of data and resulting distribution of observed ignited events for parameterisation of MISOF parameters

8.4.3 Main model parameters

8.4.3.1 General

In this chapter, the model parameters are presented based on various subsets of the established dataset presented in Chapter 7.5. The subsets are established based on two different time periods (1992-2000 and 2001-2017) and whether the data stem from installations in the UKCS or NCS. This is to illustrate the importance of the selection of which data subset to use to determine the model parameters.

The recommended MISOF model parameters are marked with **bold** font throughout the tables presenting the results for the various data subsets.

8.4.3.2 Effect of isolation of ignition sources

The ignition probability for delayed ignition sources is highly dependent on how quickly the gas is detected, the process system is shut down and ignition sources are isolated. With $V_{LEL,max}$ and $V_{LEL,max,BD}$ as the total exposed volume and exposed volume before detection respectively, and P_{iso} as fraction of ignition sources that are shut down upon isolation of ignition sources, then an average adjustment factor, denoted F_{adj}, can be calculated from the following expression

$$F_{adj} \cdot \lambda_i \cdot V_{LEL,max} = \lambda_i \cdot V_{LEL,max,BD} + (1 - P_{iso}) \cdot \lambda_i \cdot (V_{LEL,max} - V_{LEL,max,BD}) \qquad (8.1)$$

By assuming that

- one third of the exposed volume is generated prior to detection and shutdown, and the remaining two thirds of the exposed volume is exposing equipment after detection and shutdown. This is a reasonable best estimate. If the exposed volume after detection constitutes a greater fraction, the adjustment factor would decrease
- 30% of all possible ignition sources are shut down (rough assessment based on recommended values for P_{iso} presented in Table 8.19). Increasing the value would lead to a larger adjustment factor

The adjustment factor for effect of isolation and shutdown of $P_{if,C}$and $P_{if,D}$ is estimated to 80% according to the following:

$$F_{adj} \cdot \lambda_i \cdot V_{LEL,max} = \lambda_i \cdot V_{LEL,max} \cdot \left(\frac{1}{3} + \frac{2}{3} \cdot 0.7\right) \qquad (8.2)$$

$$\Updownarrow$$

$$F_{adj} = 0.8$$

In other words, the 80% adjustment factor (F_{adj}) means that the ignition control barrier (detection, ESD, BD and isolation of ignition sources) has on average reduced the number of historical ignitions by 20 % (the expected number of events reduced from 1.25 (= 1/0.8) without this safety function to 1.0 including the effect of this safety function.

The parameters set to estimate F_{adj} are based a reasonable best estimate. This means that it may be that the actual historical effect of isolation of ignition sources is somewhat higher, which would lead to increased values for the parameters in the model describing delayed ignition.

8.4.3.3 Estimation of main model parameters

The mathematical expressions used to estimate these model parameters are given in equation (8.3) – (8.6). The involved parameters are described in Table 8.5.

$$P_{im,pump} = \frac{P_{ign,50\%} \cdot M_{leak,all} \cdot f_{im,pump}}{M_{leak,pump,PLOFAM}} \qquad (8.3)$$

$$P_{im} = \frac{P_{ign,50\%} \cdot M_{leak,all} \cdot f_{im}}{(M_{leak,all} - M_{leak,pump,PLOFAM})} \qquad (8.4)$$

$$\lambda_{i,C} = \frac{P_{ign,50\%} \cdot M_{leak,all} \cdot f_{if,C}}{V_{LEL,max} \cdot F_{adj}} \qquad (8.5)$$

$$\lambda_{i,D} = \frac{P_{ign,50\%} \cdot M_{leak,all} \cdot f_{if,D}}{VT_{LEL:UEL,avg} \cdot F_{adj}} \qquad (8.6)$$

Table 8.5 – Description of parameters used in equation (8.3) through

Parameter	Description
$P_{ign,50\%}$	The MISOF base ignition probability corresponds to an underlying likelihood for the observed number of events, or fewer, of 50%. See Table 7.7.
$M_{leak,all}$	Total number of relevant leaks, including leaks from pumps (see Table 7.4)
$M_{leak,pump}$	Number of relevant leaks from pumps (denoted pump leaks). See Table 7.4.
$M_{leak,pump,PLOFAM}$	Number of relevant leaks from pumps (denoted pump leaks) adjusted for the PLOFAM leak frequency model ($M_{leak,pump,PLOFAM} = M_{leak,all} \cdot 0.0224$). See Chapter 7.3.
$f_{im,pump}$	Fraction of ignitions that are immediate ignitions on pumps. See Chapter 8.4.1
f_{im}	Fraction of ignitions that are immediate ignitions on other equipment than pumps. See Chapter 8.4.1
$f_{if,C}$	Fraction of ignitions that are ignited by continuous ignition sources. See Chapter 8.4.1
$f_{if,D}$	Fraction of ignitions that are ignited by discrete ignition sources. See Chapter 8.4.1
F_{adj}	Adjustment factor to take the effect of detection, ESD, BD and isolation into account for derivation of $P_{if,C}$ and $P_{if,D}$
$V_{LEL,max}$	Cumulative gas cloud volume for all relevant leaks [m^3], see Appendix A
$VT_{LEL:UEL,avg}$	Cumulative gas cloud volume integrated with respect to time for all relevant leaks [m^3·sec], see Appendix A
$P_{im,pump}$	Immediate ignition probability per pump leak [per pump leak]
P_{im}	Immediate ignition probability for all leak sources except pump leaks [per leak]
$P_{im,avg}$	Immediate ignition probability for all leak sources, including pump leaks [per leak]
$\lambda_{i,C}$	Expected number of ignitions due to continuous ignition mechanisms given exposure [per m^3]
$\lambda_{i,D}$	Expected number of ignitions due to discrete ignition mechanisms given exposure over time [per m^3 and second]

Note that the parameter λ_i gives the expected number of delayed ignitions per m^3 and thus is not a dimensionless ignition probability. However, unless the exposed volume is huge and/or the exposure time is very long, the expected value is an adequate approximation for the ignition probability per volume unit. The potential importance of the approximation is discussed further in Chapter 10.

The data required for the equations are as follows:

- The relevant observed leaks. They are presented in Table 7.3 and Table 7.4
- The methodology to estimate $P_{ign,50\%}$ based on the binomial distribution is presented in Chapter 7.7. The results are summarized in Table 7.7
- The cumulative exposed volumes at UKCS and NCS presented in Appendix A and summarized in Table 7.6
- The values for $f_{im,pump}$, f_{im}, $f_{if,C}$ and $f_{if,D}$ can be found in Figure 8.7 (0.5, 0.2, 0,2 and 0.1 respectively)

The calculated MISOF model parameters, (*i.e.* the probability of immediate pump ignition given pump leak etc.) are given in Table 8.6. The results are visualized in Figure 8.3 through to Figure 8.6. In conclusion, the parameter to be used in the MISOF model is rounded off and marked with black font (figures with one more significant digit can be found in Figure 8.3 through to Figure 8.6).

The ultimate distribution is also shown in Figure 8.7 according to the main model building blocks. Note that the sizes of the building blocks are not proportional to the fractions assigned to the specific part of the model.

Given the split in equipment category and ignition type presented in the previous Chapter, the distribution of $\lambda_{i,C}$and $\lambda_{i,D}$ per equipment category can be calculated, which is presented in Table 8.8.

It should be noted that the reduction in ignition probability with time for continuous sources is judged to be different for 'Rotating machinery' and 'Electrical equipment'. The time dependent behaviour of continuous sources after detection is described in Chapter 8.5.4.

The effect of ignition source isolation on ignition probability (P_{iso}) for the different equipment categories is discussed in Chapter 8.5.

Table 8.6 – Calculated ignition probabilities (model parameters). The PLOFAM parameters for the subset UKCS + NCS 1992-2017 are rounded off. Figures with one more significant digit can be found in Figure 8.3 through to Figure 8.6

	UKCS + NCS, 2001-2017			UKCS + NCS, 1992-2017		
Parameter	**UKCS**	**NCS**	**UKCS + NCS**	**UKCS**	**NCS**	**UKCS + NCS**
$P_{im,pump}$ [per pump leak]	25.04%	7.12%	15.05%	11.92%	3.47%	7.2 %
P_{im} [per leak]	0.23%	0.07%	0.14%	0.11%	0.03%	0.07 %
$\lambda_{i,C}$ [per m^3]	2.84E-05	4.37E-06	1.27E-05	1.18E-05	2.38E-06	6.1E-06
$\lambda_{i,D}$ [per m^3 and sec]	9.34E-08	8.00E-09	2.92E-08	3.31E-08	5.23E-09	1.5E-08

Table 8.7 – Relative distribution of relevant ignited leaks

Parameter	Based on assessment of available data from UKCS for 1992-2017 and engineering judgement (see Figure 8.2)
$P_{im,pump}$	50%
P_{im}	20%
$\lambda_{i,C}$	20%
$\lambda_{i,D}$	10%

The average immediate ignition probability for all leak sources is applicable to areas where the number of pumps is consistent with the North Sea average. In areas with more pumps than the North Sea average, the fire frequency stemming from immediate ignition will be underestimated. Moreover, the hole size frequency distribution for pumps is different than for the other leak sources. The average immediate ignition probability for all leak sources becomes:

$$P_{im,avg} = \frac{(50\% + 20\%) \cdot 3.67}{1133} = 0.0023 \tag{8.7}$$

Table 8.8 – Delayed ignition parameters per equipment category (rounded off)

Parameter	UKCS + NCS, 2001-2017			UKCS + NCS, 1992-2017		
	Rotating	Electrical	Other	Rotating	Electrical	Other
$\lambda_{i,C}$ [per m^3]	7.60E-06	3.80E-06	1.30E-06	3.70E-06	1.80E-06	6.00E-07
$\lambda_{i,D}$ [per m^3 and second]	2.90E-09	2.90E-09	2.30E-08	1.50E-09	1.50E-09	1.20E-08

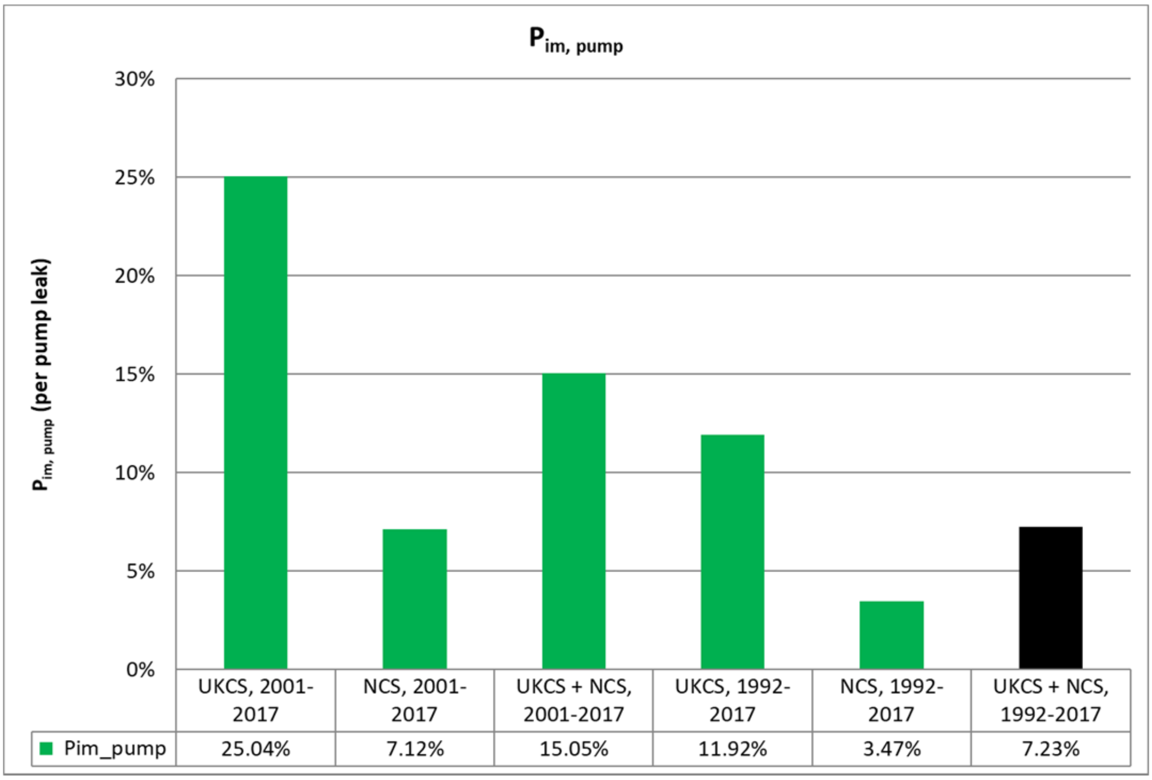


Figure 8.3 - Immediate ignition probability for pump leaks. The concluded parameter to be used in the MISOF model is shown in black colour

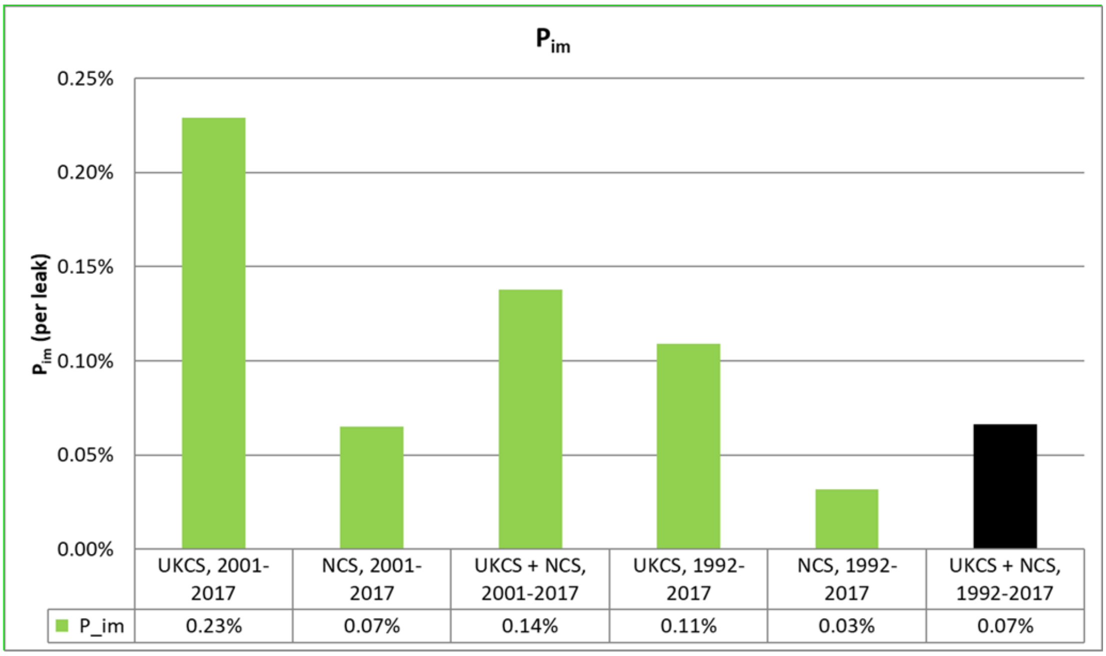


Figure 8.4 - Immediate ignition probability for equipment other than pumps. The concluded parameter to be used in the MISOF model is shown in black colour

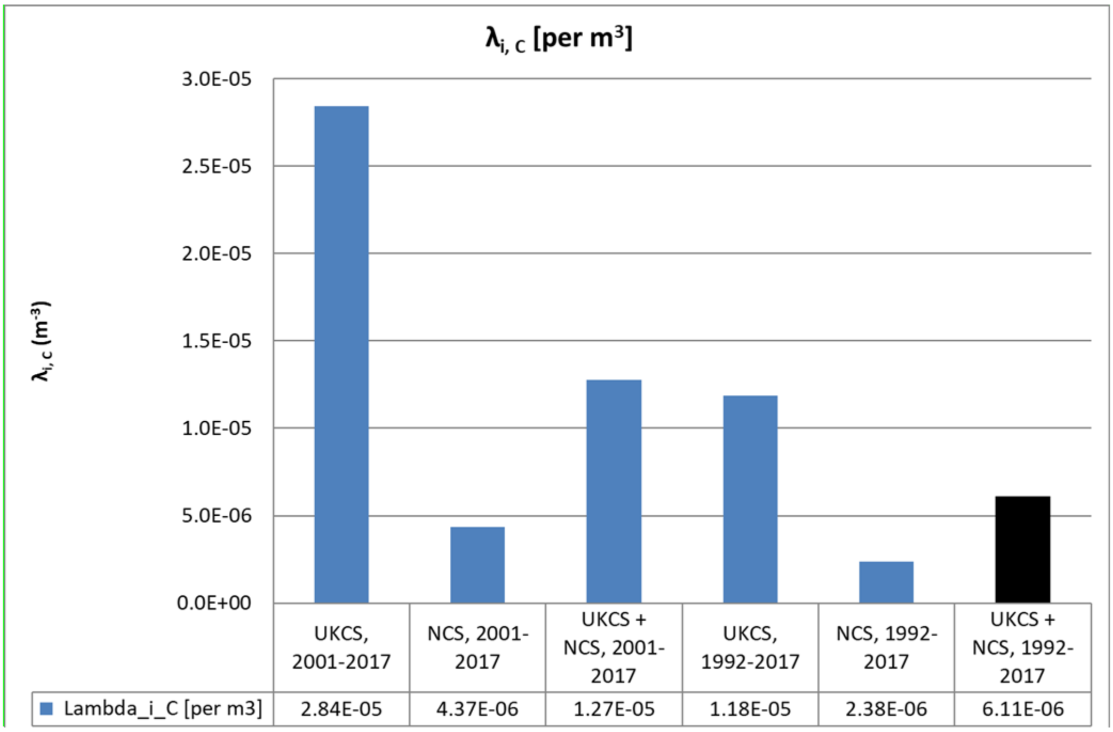


Figure 8.5 - Delayed ignition probabilities for continuous ignition sources. The concluded parameter to be used in the MISOF model is shown in black colour

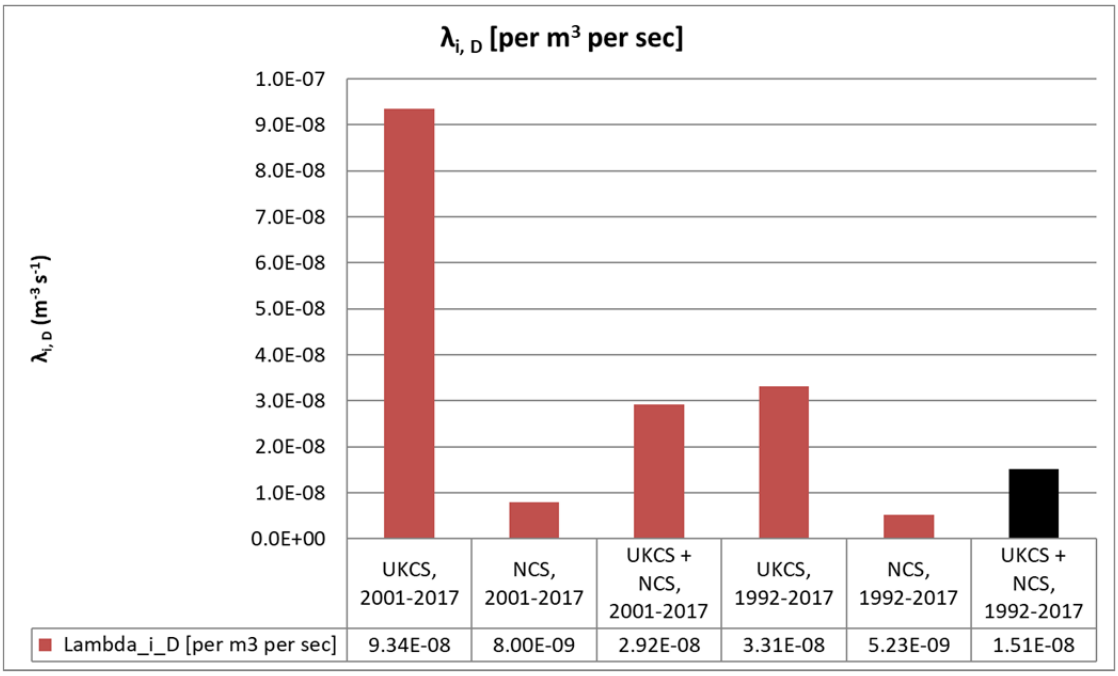


Figure 8.6 - Delayed ignition probabilities for discrete ignition sources. The concluded parameter to be used in the MISOF model is shown in black colour

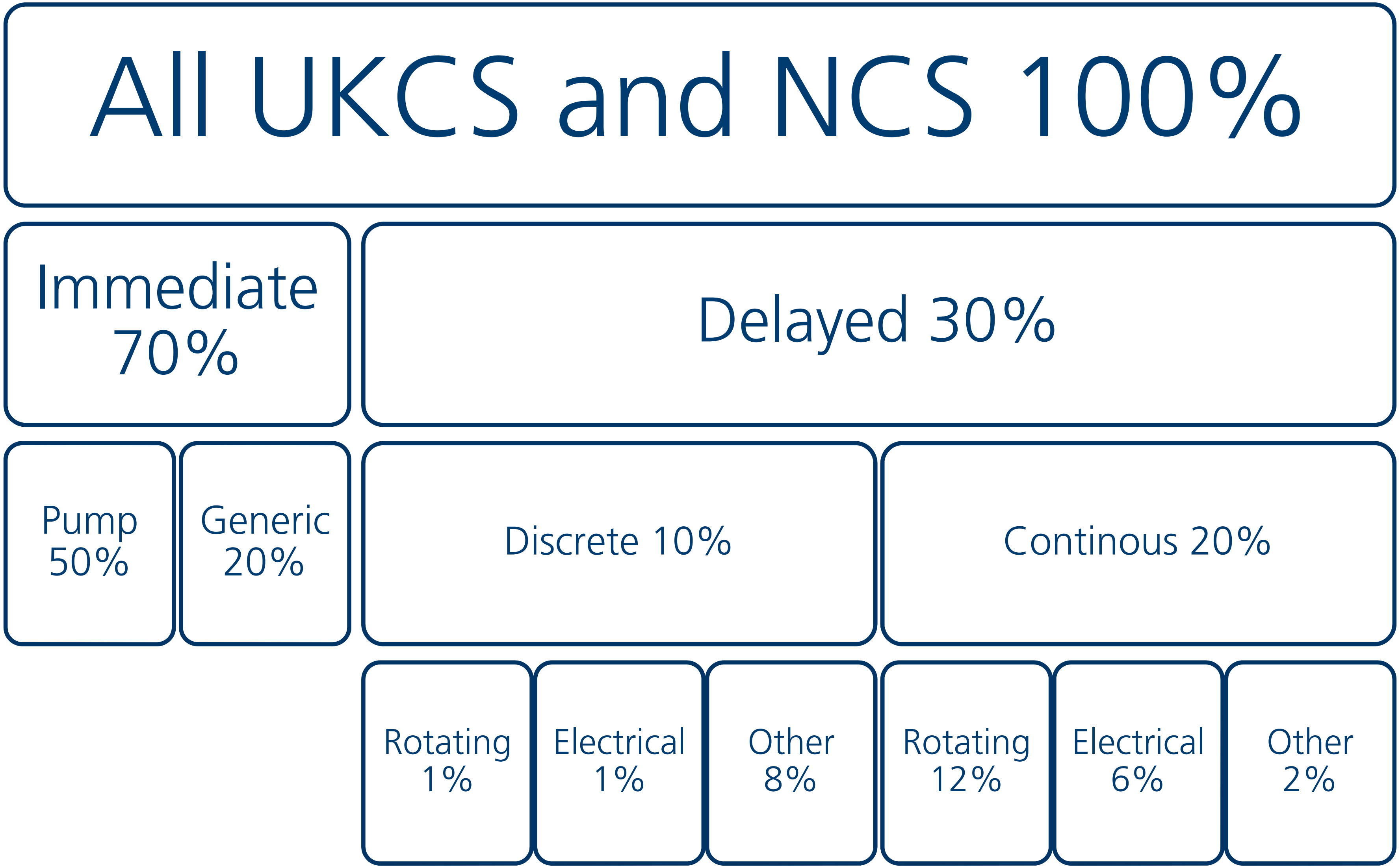


Figure 8.7 - Overview resulting distribution of relevant ignited leaks for MISOF parameters for objects intended for use in potentially explosive atmospheres

8.4.4 Model parameters per rotating machinery unit

In order to calculate the equipment specific ignition probability for a given exposure, an estimate of the average number of operating rotating machinery per m^3 is required to be consistent with the data set used for calculation of $\lambda_{i,C}$ and $\lambda_{i,D}$.

The volume per rotating equipment can be calculated based on available information in the HCR database, but the quality of the reported data is considered to be poor. Detailed equipment counts of hydrocarbon containing equipment from eight installations on the Norwegian Continental Shelf have therefore been used instead. The equipment counts were established for the calculation of leak frequency in probabilistic explosion risk studies performed by LR on behalf of Equinor. Corresponding calculation of the module volumes are available in these studies. The data set is denoted LR population data (LRP), and is presented in Table 8.9.

In addition to equipment counts of hydrocarbon containing process pumps and compressors, counts of all pumps and their corresponding operational times are available for Platform 5 in the LRP data set. The total number of pumps in process areas adjusted for operational time is 30 for Platform 5. Detailed counts of electrical equipment and instruments are also available for Platform 5, Platform 4 and Platform 10, which is presented in Table 8.13 in Chapter 8.4.5. Data on rotating equipment is not available for Platform 4 and Platform 10. The dataset is summarised in Table 8.9.

Table 8.9 - Description of installations in LRP data set for calculation of volume per rotating machinery (the anonymization of the installations is in accordance with the approach used in Ref. /1/)

Installation	Type of installation	Number of units in main process 3) 5)		Total volume[1] of relevant modules (m^3_{ff})
		Pumps	Compressors	
Platform 5	Jacket	6 [2)]	5	30,900 [4)]
Platform 4	Condeep	Not available	Not available	55,553
Platform 10	Jacket	Not available	Not available	39,444
Platform 1	Jacket	5	2	26,724
Platform 7	Floating	13	7	63,042
Platform 8	Floating	6	5	40,100
Platform 9	Floating	4	5	31,924
Platform 6	Jacket	4	3	17,082
Total	NA	38	27	209,772[6)]

2) The volume in this context is the free flow volume (V_{ff}) available for fluid flow within the boundary of the area being studied (see Chapter 6.10 for further description)
3) The total number of pumps in process areas adjusted for operational time is 30 (6 out of those are the 6 process pumps).
4) The operational time of the process units is 100 %.
5) Volume excluding wellhead module is 18,030 m^3
6) Both the pumps and the compressors include the drive powering the unit. For compressors, several compressors can be mounted on one single drive, but this is not reflected specifically.
7) Total volume excluding Platform 4 and Platform 10

The resulting equipment density, V_R, is presented in Table 8.10. The conditional ignition probability per rotating machinery, calculated from the following expressions based on the results in Table 8.8, is presented in Table 8.11:

$$\lambda_{i,C,R} = 3.66 \cdot 10^{-6} \cdot V_R \quad (8.8)$$

$$\lambda_{i,D,R} = 1.51 \cdot 10^{-9} \cdot V_R \quad (8.9)$$

The resulting conditional ignition probabilities are in line with the recommended ignition source intensities presented for pumps and compressors in the JIP-model (Ref. /2/).

The electrical drive is included in the conditional ignition probability set in the model. This model implies that the conditional ignition probability is considered to be equal for all types of pumps and compressors. The operating time of the units must be accounted for. For compressors, the provided figure applies per compressor stage. As the electrical drive is included in the basic figure, the contribution from the electrical drive is also included in the case of mechanical drive (gas turbine driving the compressor(s)). This also implies that the fraction related to the electrical drive, which is unknown, is aggregated for each stage on one shaft. Hence, the total conditional ignition probability may be somewhat conservative for cases with many stages on one shaft (*i.e.* small effect for typical cases with a few stages on one drive). In order to improve this approximation, population with increased reliability data is required (this is suggested as further work in Chapter 13).

Table 8.10 – Free flow volume (V_{ff}) per rotating machinery based on LR population

Parameter	Value
Free flow volume per rotating machinery containing hydrocarbons (m^3_{ff}/rot.eq)	3,227 m^3_{ff}
Total number of rotating machinery in process modules per total number of process rotating machinery [1]	35 / 11 ~ 3.2
Free flow volume per rotating machinery, regardless of inventory (m^3_{ff}/rot.eq), denoted V_R	1,014 m^3_{ff}

1) 35 is the sum of process compressors (5) and the 30 pumps (including process pumps) found in Table 8.9 (see also table footnote) for Platform 5. 11 is the sum of the process pumps and process compressors (5 + 6), also for Platform 5.

Table 8.11 – Conditional ignition probability per unit rotating machinery (all types of rotating machinery, regardless of inventory) given exposure to flammable fluid (calculated using equation (8.10) in section 8.4.5). The parameters to be used are given in **bold** font. Whether to use the numbers for all rotating machineries or for rotating machinery containing hydrocarbons depend on the available information about the equipment

	UKCS + NCS, 2001-2017	UKCS + NCS, 1992-2017
$P_{C,R}$ [per rotating machinery containing hydrocarbons]	2.4E-02	**1.2E-02**
$P_{D,R}$ [per rotating machinery containing hydrocarbons and sec]	9.4E-06	**5.0E-06**
$P_{C,R}$ [per rotating machinery]	7.7E-03	**3.7E-03**
$P_{D,R}$ [per rotating machinery and sec]	3.0E-06	**1.5E-06**

8.4.5 Model parameters per electrical equipment unit

In Ref. /10/ (attached as Appendix B) detailed counts for electrical equipment and instruments were carried out for the three installations (denoted Platform 5, Platform 4 and Platform 10) in the North Sea (all on the Norwegian Continental Shelf). Failure frequencies were suggested for different types of equipment based on the EU sponsored project SAFEC (Ref. /12/). The figures are presented in Table 8.12. In Ref. /10/ the absolute value of the figures was not discussed in the study as the main purpose was to establish estimates of the relative change in failure frequency for the different types of equipment with respect to level of protection and type of protection.

Table 8.12 - Failure data for electrical equipment and corresponding relative ignition potential for different types of Ex protection presented in Ref. /10/

Type of protection	Use in zone	Normal failure rate (hr^{-1})	Failure rate harsh environment	Normal ignition potential k	Extra factor to k due to harsh environment
Ex ia	0	$3.3 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	1	3
Ex ma	0	$3.3 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	1	3
Ex ib	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex mb	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex d, only sparking	1	$1 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	3	1
Ex d, sparking and hot surfaces	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex e	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex p	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex n	2	$3.3 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	100	3
Ex s*	0-2	$3.3 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	100	3

Based on the equipment counts for the different installations and the suggested failure rates, the expected ignition probability can be calculated. Table 8.13 shows the equipment counts for the process areas of the 3 installations in the LRP data set. Equipment with the same failure rate in accordance with Table 8.12 is grouped together. Zone 0 equipment is in most cases equipment inside the process system, and can be considered irrelevant with respect to exposure to flammable atmospheres due to a leak. Such equipment is therefore disregarded in the following assessments.

Table 8.13 - Equipment counts electrical equipment and instruments (Ref. /10/)

Installation	Module	Number of equipment, N_j			
		Zone 2	Zone 1	Zone 0	All
Platform 5 (Jacket)	All process modules exclusive wellhead module	26	2,823	817	3,666
Platform 4 (Condeep)	All process modules inclusive wellhead module	103	4,907	908	5,918
Platform 10 (Jacket)	All process modules inclusive wellhead module	1,252	5,999	0	7,251
5+4+10	Total	1,381	13,729	1,725	16,835

Assuming that failures are independent, the probability that there is one or more faulty pieces of equipment in the modules can be calculated. The results are presented in Table 8.14. To calculate the probability of failure on demand, it is assumed that the inspection interval is 1 year, which results in a probability of failure on demand of $1.45 \cdot 10^{-2}$ per year for Zone 2 equipment and $1.45 \cdot 10^{-3}$ per year for Zone 1 equipment. Here it is judged that the normal failure rates in Table 8.12 apply for the North Sea. The binomial probability distribution (see equation (7.1)) is used to calculate the probability of one or more objects being faulty.

The result shows that the probability of one or more objects being faulty is approximately 1 for all modules. In fact, the probability that 10 or more objects are faulty is considerable. This result can be compared with the results using $\lambda_{i,C}$ and $\lambda_{i,D}$ for electrical equipment presented in Table 8.8.

Based on the volumes of the installations (Platform 5, Platform 4 and Platform 10) presented in Table 8.9, the generic conditional ignition probability due to electrical equipment is calculated and presented in Table 8.14. The results show that the failure data are not aligned with the generic conditional ignition probability. This is also shown in Figure 8.8 where this effect is demonstrated assuming varying number of components in Platform 5. The discrepancy between the obtained data is not investigated in detail, but it is considered likely that the suggested failure rates include failure modes that do not cause ignition.

Table 8.14 - Probability of one or more faulty Zone 2 or Zone 1 equipment compared with the conditional ignition probability obtained from $\lambda_{i,C}$ and $\lambda_{i,D}$ (see Table 8.8). See also Figure 8.8 for Platform 5

Installation	Module volume [m³] (see Table 8.9)	Conditional ignition probability for platform 2)	Probability for one or more faulty Zone 2 or Zone 1 equipment
Platform 5 (Jacket)	25,800 1)	0.06	0.9885
Platform 4 (Condeep)	55,553	0.10	0.9998
Platform 10 (Jacket)	39,444	0.07	0.9999

1) Excluding the wellhead module

2) In order to calculate the contribution from discrete ignition mechanisms, the duration of exposure is set to the average duration from the data; $202\,\text{sec} = VT_{LEL:UEL,avg}/V_{LEL,max}$ (see Appendix A and Table 7.6)

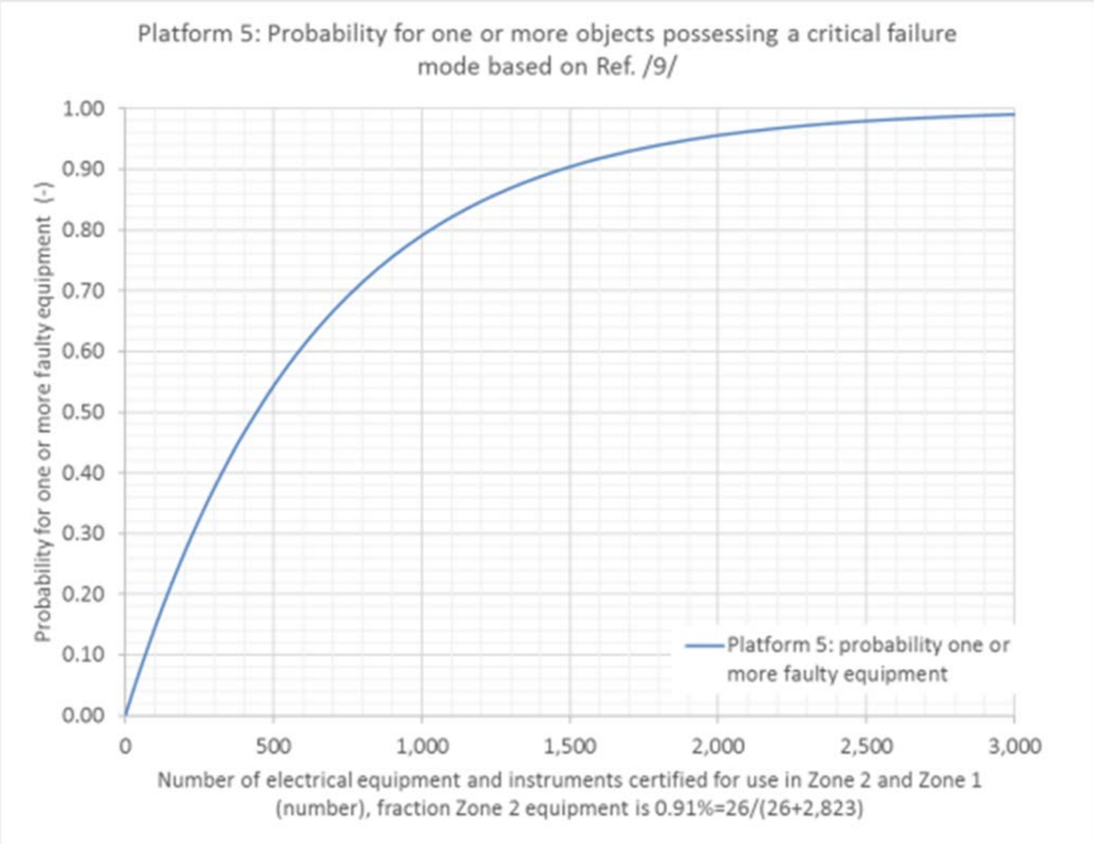


Figure 8.8 - Probability of one or more faulty Zone 2 or Zone 1 equipment for increasing number of electrical equipment for Platform 5. The fraction of Zone 2 equipment is 26/(26 + 2823) in accordance with Table 8.13

In Table 8.15, the results for decreasing number of critical failure modes (in terms of modes that potentially could cause ignition) are presented. The results are plotted in Figure 8.10. The figure displays the probability for one or more units of faulty Zone 2 or Zone 1 equipment divided by the conditional ignition probability obtained from $\lambda_{i,C}$ and $\lambda_{i,D}$ for decreasing fraction of critical failure modes (in other words increasing number of non-critical failure modes per critical failure mode). Hence increasing number of non-critical failure modes along the first axis is inversely proportional with decreasing critical failure rate.

The delayed ignition probability, which is the probability for 1 or more ignitions per time step, can be calculated from the Poisson distribution assuming that the following assumptions hold (see also Chapter 10.4.2)

- k is the number of times an event occurs in an interval and k can take values 0, 1, 2, etc.
- The ignitions are independent, which means that the occurrence of one ignition does not affect the probability that a second ignition will occur. This assumption holds because the theoretical frame work is based on that ignition is not initiated in practice
- The rate at which ignitions occur is constant at each time step and in each volume unit (m^3). The rate cannot be higher in some intervals and lower in other intervals
- Two ignitions cannot occur at exactly the same instant; instead, at each very small sub-interval exactly one ignition either occurs or does not occur

The expression for one or more ignitions becomes according to the Poisson distribution becomes

$$P_{ignition} = P(1\ or\ more\ ignitions) = 1 - P(zero\ ignitions) = \tag{8.10}$$
$$1 - e^{-\lambda_{Ign}} \frac{\lambda_{Ign}{}^{k}}{k!} = 1 - e^{-\lambda_{Ign}} \frac{\lambda_{Ign}{}^{0}}{0!} = 1 - e^{-\lambda_{Ign}}$$

where the expected value, λ_{Ign}, is given by

$$\lambda_{Ign} = 120{,}797 m^3 \cdot \left(\lambda_{i,C} + \lambda_{i,C} \cdot 202\ sec\right) = 0.2593\ expected\ number\ of\ ignitions \tag{8.11}$$

The Poisson distribute for this case is given in Figure 8.9.

The probability for one or more units of faulty Zone 2 or Zone 1 equipment for all three platforms can be expressed as:

$$P_{faulty\ Ex} = P(1\ or\ more\ faulty\ Ex\ equipment) = 1 - P(none\ faulty) = \tag{8.12}$$
$$1 - \left(\prod_{j=Ex\ type}^{ALl\ Ex\ types} (1 - PFD_j)^{N_j} \right)$$
$$= 1 - ((1 - PFD_{Zone1})^{N_{Zone1}} \cdot (1 - PFD_{Zone2})^{N_{Zone2}})$$

where N_j is the number of components of type j (see Table 8.13) and the probability of failure on demand (PFD) is given by (for 1 year inspection interval)

$$PFD_j = \lambda_{Ex,ign,j} \cdot 8760\ hrs\ per\ year \cdot \frac{1}{2} \cdot F_{PFD,i} \tag{8.13}$$

where

$$\lambda_{Ex,ign,j} = \frac{\lambda_{Ex,j}}{F_{PFD,j}} \tag{8.14}$$

$\lambda_{Ex,j}$ is the failure rate for all failure modes listed in Table 8.12, whilst $\lambda_{Ex,ign,j}$ is the critical failure rate causing ignition. $F_{PFD,j}$ is the factor representing the number of none-critical failure modes per critical failure mode, which can be calculated by solving the equations above.

$P_{ignition}$ equals $P_{faulty\ Ex}$ for $F_{PFD} = 161.4$ assuming that the fraction of critical failure modes is the same for all types of Ex equipment.

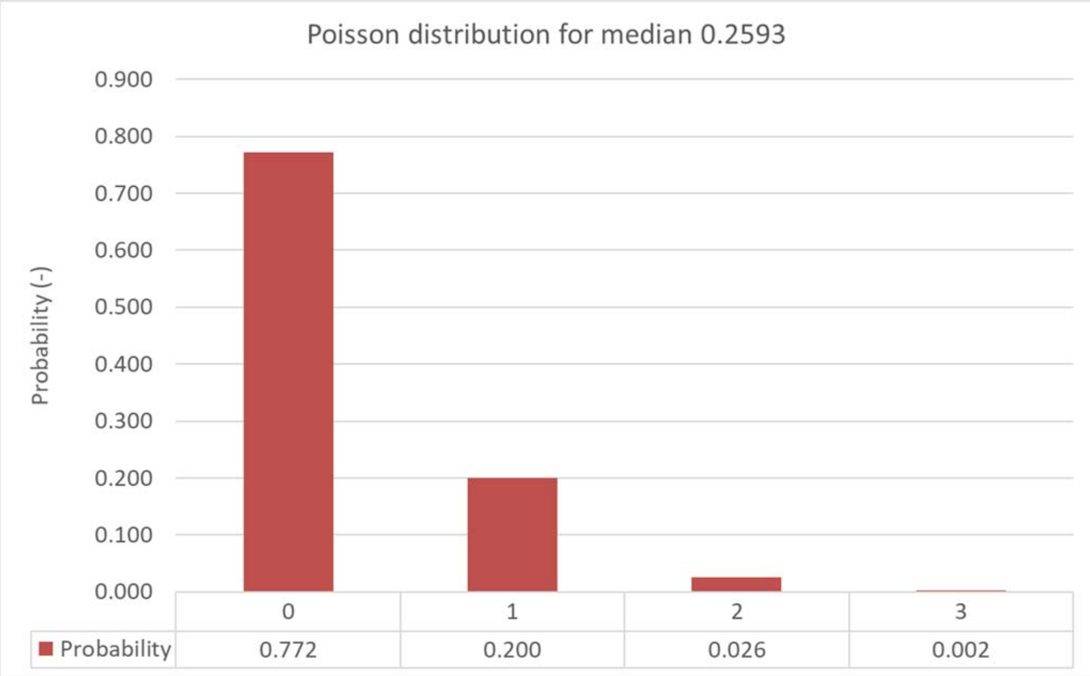


Figure 8.9 – Poisson probability distribution for number of ignitions resulting from an exposed volume of 120,797 m^3 (25,800 m^3+ 55,553 m^3+39,444 m^3) in 201 seconds based on $\lambda_{i,C}$ and $\lambda_{i,D}$ presented in Table 8.16.

Table 8.15 - Probability of one or more units of faulty Zone 2 or Zone 1 equipment for varying number of critical failure modes compared with the conditional ignition probability obtained from $P_{if,C}$ and $P_{if,D}$. The results are plotted in Figure 8.10

Installation	Total of $\lambda_{i,C}$ and $\lambda_{i,D}$ 3)	Conditional ignition probability obtained from $\lambda_{i,C}$ and $\lambda_{i,D}$ 4)	1 out of N failure modes causing ignition			
			N = 1 (see Table 8.14)	N = 75	N = 100	N = 165
			$PFD_{Zone2} = 1.45 \cdot 10^{-2}$ 2)	$PFD_{Zone2} = 1.93 \cdot 10^{-4}$ 2)	$PFD_{Zone2} = 1.45 \cdot 10^{-5}$ 2)	$PFD_{Zone2} = 9.17 \cdot 10^{-5}$ 2)
Platform 5 1) (Jacket)	0.055	0.054	~ 1	0.058	0.044	0.028
Platform 4 (Condeep)	0.119	0.112	~ 1	0.108	0.082	0.053
Platform 10 (Jacket)	0.085	0.081	~ 1	0.300	0.235	0.156
5+4+10	0.259	0.228	~ 1	0.412	0.328	0.223

1) Excluding wellhead module
2) Based on an inspection interval of 1 per year. The PFD for Zone 1 equipment is a factor 10 less.
3) In order to calculate the contribution from discrete ignition mechanisms, the duration of exposure is set to the average duration from the data; $202 \text{ sec} = VT_{LEL:UEL,avg}/V_{LEL,max}$ (see Appendix A and Table 7.6)
4) Calculated from the Poisson distribution (see Figure 8.9).

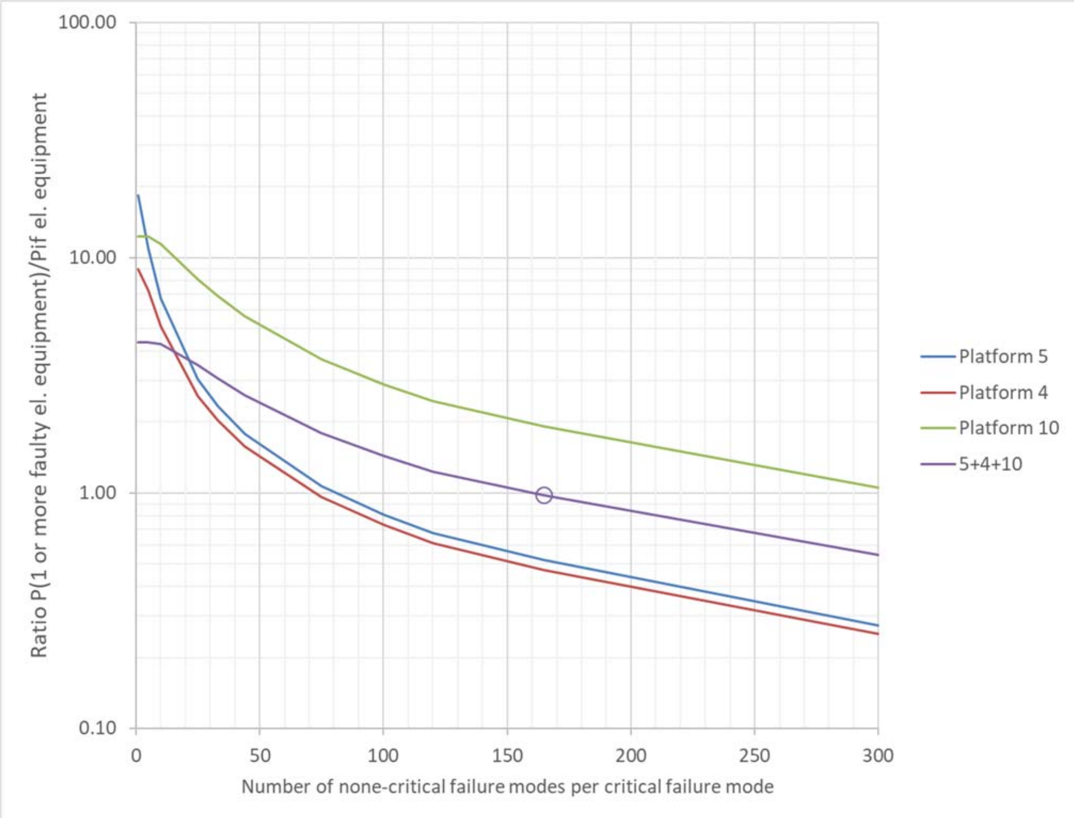


Figure 8.10 - Probability of one or more units of faulty Zone 2 or Zone 1 equipment divided by the conditional ignition probability obtained from $\lambda_{i,C}$ and $\lambda_{i,D}$, for increasing numbers of non-critical failure modes per critical failure mode. The result for all platforms altogether equals 1 for a number of non-critical failure modes per critical failure mode of about 165 (marked with a circle)

The results show that if the number of critical failure modes is in the range 1 per 75 to 1 per 300 failure modes, the result balances the contribution from $\lambda_{i,C}$ and $\lambda_{i,D}$ for the various installations. The fraction of critical modes to be used in the model depends on the properties of the average installation in the North Sea with regard to type of protection as well as the number of electrical components and instruments. An activity attempting to gather data based on an interview with subject matter experts in the industry was initiated, but the data collection was not successful. It is recommended to initiate such a task as basis for the next revision of the MISOF model (see Chapter 13).

Platform 5 is a rather new installation which commenced operation in 2000, and it can be argued that this installation is not representative for the North Sea average. Both Platform 4 and Platform 10 were set in operation in the 90's. It is judged that Platform 10 is closer the North Sea average in terms of design of electrical equipment than Platform 4, which suggests a rather considerable reduction of the number of critical failure modes (somewhat above 300). The average for all of them indicates that there are around 165 non-critical failure rates per critical failure mode.

In order to ensure that a model does not underestimate the failure rates per component, it is suggested to use a factor of 165. In this case, the generic estimate based on $\lambda_{i,C}$ and $\lambda_{i,D}$ would be higher for both Platform 5 and Platform 4. It is considered reasonable that the resulting conditional ignition probability is less if it is based on a detailed equipment count and the critical failure rate per component, than if it is based on a generic calculation from $\lambda_{i,C}$ and $\lambda_{i,D}$. Furthermore, the sensitivity with respect to different level of protection (*i.e.* Zone 2 versus Zone 1) decreases with a lower proportion of critical failure modes. It is considered important that the model produce a significant risk reducing effect of shifting from Zone 2 to Zone 1 equipment. For Platform 10, a factor of 165 would cause a higher estimate of the conditional ignition probability using failure data compared to $\lambda_{i,C}$ and $\lambda_{i,D}$. However, the effect of replacing Zone 2 equipment with Zone 1 equipment would be more prominent. The resulting failure rates using a factor of 165 are presented in Table 8.16.

The fraction related to continuous and discrete ignition mechanisms are according to Table 8.3 $I_{C,E} = 86\%$ and $I_{D,E} = 14\%$ respectively.

Table 8.16 - Failure rate for critical failure modes resulting in ignition upon exposure to flammable atmosphere, and relative ignition potential for different types of Ex protection

Type of protection	Use in zone	Normal failure rate (hr^{-1}) 1)	Failure rate harsh environment1)	Normal ignition potential k	Extra factor to k due to harsh environment
Ex ib	1	$2 \cdot 10^{-9}$	$6 \cdot 10^{-9}$	10	3
Ex mb	1	$2 \cdot 10^{-9}$	$6 \cdot 10^{-9}$	10	3
Ex d, only sparking	1	$6 \cdot 10^{-10}$	$6 \cdot 10^{-10}$	3	1
Ex d, sparking and hot surfaces	1	$20 \cdot 10^{-9}$	$6 \cdot 10^{-9}$	10	3
Ex e	1	$2 \cdot 10^{-9}$	$6 \cdot 10^{-9}$	10	3
Ex p	1	$2 \cdot 10^{-9}$	$6 \cdot 10^{-9}$	10	3
Ex n	2	$2 \cdot 10^{-8}$	$6 \cdot 10^{-8}$	100	3
Ex s*	0-2	$2 \cdot 10^{-8}$	$6 \cdot 10^{-8}$	100	3

1) The fraction related to continuous and discrete ignition mechanisms are according to Table 8.3 $I_{C,E} = 86\%$ and $I_{D,E} = 14\%$ respectively.

8.5 Isolation of ignition sources

8.5.1 General

Initiation of ignition control following detection of an on-going leak reduces the number of potential sources of ignition. This is reflected by the following models, presented in this chapter:

- Isolation of equipment upon detection, which intends to represent the technical performance of the technical system isolating equipment and the properties of the equipment themselves.
- Time dependent reduction of discrete ignition mechanisms more than 300 seconds after start of the leak. This accounts for a reduction in unknown potential ignition sources not controlled by the technical performance of the ignition control system
- Time dependent reduction in continuous ignition mechanism after isolation to account for a cooling time of hot surfaces after detection

The different models are described in separate chapters. A summary chapter describes the general total effect of the models incorporating isolation of ignition sources.

8.5.2 Isolation of equipment upon detection

The effect of ignition source isolation on ignition probability is quantified using the parameter P_{iso}. P_{iso}= 0. This means that ignition source isolation has no effect with respect to ignition probability. P_{iso}= 1 means that ignition source isolation effectively stops all ignition sources in the area. The effect on continuous ignition sources that are hot surfaces is not immediate. This is taken into account by the parameter P_{iso} described in Chapter 8.5.4.

The isolation of ignition sources on gas detection will take place in different steps at different points in time depending on the extension and location of the gas. The shutdown is governed by the ESD shutdown logics, for which the basic requirements are given in NORSOK S-001 item 10.4.3. The main items of relevance are given in Table 8.17.

Table 8.17 - Main levels of isolation of ignition sources

Cause	ESD level	Main effect on isolation
Single gas detection	Alarm only	Isolate all sockets and external non-essential consumers
Confirmed gas detection in hazardous areas	ESD 2	Stop process. Different degree of isolating consumers in hazardous areas except safety critical equipment (*e.g.* F&G equipment)
Confirmed gas detection in safe area of the installation (*e.g.* air intakes)	ESD 1	Trip main generators, start emergency generator

The different levels of electrical isolation will occur at different times depending on the dispersion of the gas. At each consecutive level of isolation more consumers are isolated, so in general there will be 3 different isolation factors F occurring at different times as illustrated in Table 8.18.

$$F = 1 - P_{iso} \tag{8.15}$$

Table 8.18 - Isolation factors and corresponding times for electrical isolation

Shutdown level	Isolation factor [1)]	Time
Single Detection (SD)	F_{SD}	t_{SD}
ESD 2	F_{ESD2}	t_{ESD2}
ESD 1	F_{ESD1}	t_{ESD1}

1) The isolation factor, F, and P_{iso} is related as follows: $P_{iso} = 1 - F$

In practice, the time difference between single gas detection and ESD 2 will be short in all scenarios except quite small leaks, where only one detector is exposed to gas above the detector set point. ESD1 will normally presuppose a large leak in combination with unfavourable wind condition exposing detectors in unclassified areas or in air intakes. The process of calculating a representative value of t_{ESD1} is more complex and should be given special consideration if ESD1 is relevant. Note also that F_{ESD1} will be the smallest F, often significantly smaller than F_{ESD2}.

In general, a detailed assessment of the isolation factors (*i.e.* P_{iso}) according to the methodology used in Ref. /10/ is preferred. This is because the specific ESD shutdown logics and type of equipment being used is important for the results (see variability in Table 8.20). However, doing this assessment in detail requires the counting of individual different pieces of equipment, which is time consuming and therefore some default values are established. As the delayed ignition probability is very sensitive to the default values being used, the validity of these default values should be considered and discussed for each study being performed. The study should present a sensitivity analysis with respect to the modelling of P_{iso}.

The default values are presented in Table 8.19 based on the following assessments:

- 'Rotating machinery' is mostly a part of the main process or utility systems related to the main process. It is therefore considered reasonable that these potential sources of ignition shut down upon initiation of ESD 2
- Ref. /10/ demonstrated that 'Electrical equipment' is very dependent on the ESD shutdown logics (see Table 8.20). It is judged that Platform 4 in the LRP data set is more representative than Platform 5 for the North Sea average platform with respect to P_{iso}. Hence the default value is set to a quite low value, *i.e.* 25 %. No effect due to single detection is included in the default model, but it can be justified based on a specific evaluation

- As 'Other' equipment is unknown, it is hard to assess P_{iso}. Based on the assessment of the 10 unknown events used as basis for the model (see Chapter 8.4.1) it is judged that 3 out of these could be isolated upon detection (HCR Ignition ID 144 and 201 (Leak ID 189 and 12) and one of the remaining 8 unknowns, (see Table A3 2-1 in Attachment A3) would result in a P_{iso} of 30 %. It is considered reasonable to include no effect on single detection for the unknowns in this category

Table 8.19 - Default P_{iso} for the different groups for varying cause according to ESD shutdown logics

Parameter	Rotating machinery	Electrical equipment	Other
Single detection	0 %	0 %	0 %
Confirmed gas detection in hazardous areas	100 %	25 %	30 %
Confirmed gas detection in safe area of the installation (*e.g.* air intakes)	100 %	40 %	30 %

Table 8.20 - Recommended values for ignition source isolation efficiency (Ref. /10/)

Ignition source control philosophy	Process		Drilling	
	F	$P_{iso} = 1 - F$	F	$P_{iso} = 1 - F$
Isolate sockets and process shutdown (typical Platform 4 [1)])	0.8	0.2	0.95	0.05
Partial isolation of other equipment (typical Platform 5 [1)])	0.4	0.6	0.8	0.2
Trip main power, ESD 1	0.25	0.75	0.5	0.5

1) Installations refer to the installations in the LRP data set (see Table 8.9).

8.5.3 Discrete ignition mechanisms more than 300 seconds after onset of the leak

Historical data (Appendix A) contains very few ignitions taking place more than 5 minutes after start of the release. This is also observed in recorded data for blowouts, which is presented below (see Figure 8.11). One explanation for this is that activities are less likely to introduce ignition sources as time goes on. Activities in this regard are:

- Personnel are often present at the scene of the event, but it is reasonable to expect that such personnel would evacuate the area after a few minutes. The personnel may be performing activities (*e.g.* operating systems or equipment) locally to the incident leading to ignition
- Remote operation of equipment as part of emergency response to control the incident (*e.g.* operation of a switch and/or equipment being shut down) may generate potential sources of ignition. Such activities will most likely occur in the initial phase of the incident
- Emergency response activities such as seek and rescue may introduce ignition sources, which is less likely after some time (*i.e.* when the actives have been executed)
- Additional shutdown (*i.e.* beyond the equipment automatically shut down by the ignition control system) of systems or equipment initiated manually after some time may reduce the number of live potential sources of ignition

- A time dependent model improves the modelling of ignition probability in the late phase of the leak scenario, due to the way the parameters for delayed ignition are set. The methodology for estimation of the exposed volume ($V_{LEL,max}$ and $VT_{LEL:UEL,avg}$) is truncated over a duration of 300 seconds (see Appendix A) for entries where the duration is unknown. This is to obtain an estimate of $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$ in line with our understanding of the typical duration of actual leaks. In a probabilistic model in a QRA based on PLOFAM, the duration of the leak scenario is based on a spontaneous leak occurring during normal operation, where only the ESD and BD valves limit the loss of containment. This approach focuses on the investigation of the loss of containment and ignition control barrier elements, rather than the estimation of the actual fire and explosion frequency observed in industry. In practice, other barriers tend to limit the loss of containment (*e.g.* human intervention, check valves or reciprocating pumps). It is therefore found reasonable to limit the ignition intensity for the late phase of the leak scenario used in a QRA
- Further to the point above, a model has been developed which limits the contribution from discrete ignition mechanisms more than 5 minutes after onset of the leak. The suggested model for the reduction of discrete ignition mechanisms is based on experience from long duration gas exposure resulting from blowouts. Table 8.21 shows experienced blowouts and ignitions based on Ref. /13/. The causes for ignition are generally unknown (see Table A3 5.6). Based on this limited knowledge of the actual ignition mechanisms, it is considered reasonable to split the contribution equally between discrete and continuous ignition mechanisms. Consequently it is assumed that 50% of the early ignitions (before 5 minutes) and all the late ignitions are caused by discrete (intermittent) ignition mechanisms. According to the blowout data presented in Table 8.22 and Figure 8.11, the ignition probability per unit of exposure time decreases rapidly with time

Table 8.21 - Ignition probability for blowouts from the period 1980-2015 (US GoM OCS, UK and Norway). Blowouts with subsea release points and cases where water / mud are the only fluids released are disregarded. Unknown and irrelevant ignition types disregarded

Period (hrs)	Number of ignitions	Assumed no. of discrete source ignitions	Number of blowouts alive, not burning, at start of interval	Exposure (duration·number of blowouts not burning) [hrs]
0-5 min	10	5	103	9
5 min-0.5 h	1	1	76	19
0.5-5	4	4	71	195
5-15	6	6	57	570
15-100	4	4	42	2415

Table 8.22 - Ignition probability reduction factors (based on blowout data)

Time (hours)	Ignition probability reduction factor
0.0833	1.00000
0.25	0.09035
2.75	0.03517
10	0.01807
57.5	0.00284
150	0.00026
300	0.00009
600	0.00008

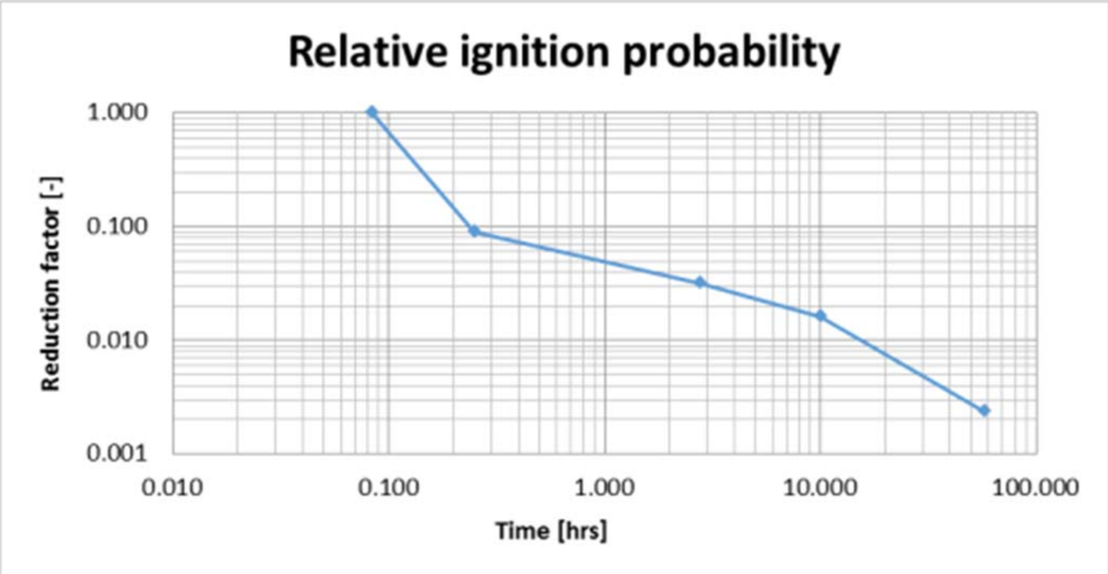


Figure 8.11 - Relative ignition probability per time unit of exposure over time for blowouts

In general, a blowout is detected within short time and shutdown of ignition sources will be initiated. It is hard to determine how effective such a shutdown will be on average for blowout scenarios. Based on Chapter 8.5, the fraction can roughly be estimated to about 50% for all equipment categories. Moreover, the relevance of the blow out data for process leaks is debatable.

To take account for the validity of the data for the purpose of the ignition model as well as the effect of isolation of ignition sources, the slope of the suggested model is slightly less than indicated by the data. The adjusted data and a fitted simple model providing a fair representation of the data are shown in Figure 8.12.

Based on above, a model is suggested to account for the expected decrease in probability for delayed ignition taking place more than 5 minutes after start of the release. For calculation of ignition probability due to the exposure of objects in classified areas more than 5 minutes after start of the release, the following function to calculate the reduction factor is recommended. The result of this is to be multiplied with the contribution from discrete ignition mechanisms:

$$K_{D,300}(t) = A \cdot t^{-b} \qquad for\, t > \frac{5}{60} hours \tag{8.16}$$

$$K_{D,300}(t) = 1 \qquad for\, t \leq \frac{5}{60} hours$$

where

$A = 0.1068\ h^{-1}$

$b = 0.9$

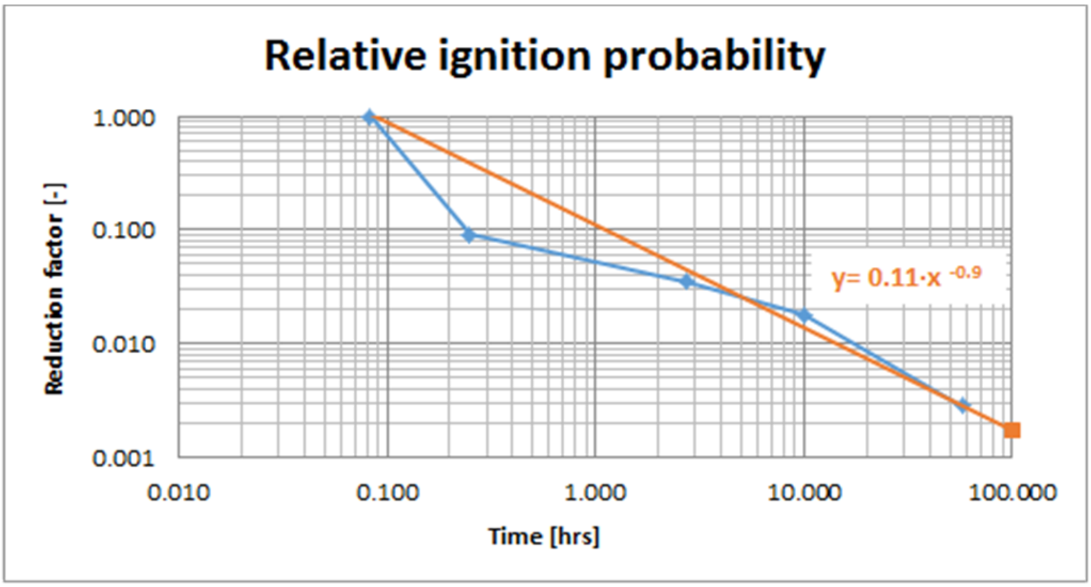


Figure 8.12 - Ignition probability reduction factor for discrete ignition sources more than 5 minutes after start of the leak

8.5.4 Ignition by continuous ignition mechanism after isolation

The continuous ignition mechanism may typically be a hot surface that requires a certain cooling time following shut down before it stops being an effective ignition source. The suggested mathematical model is a power law defined by a given half time dependent on the equipment specifics (see Chapter 6.22 for further description and Figure 8.14 for illustration of model);

$$P_{hot}(t) = 0.5^{\left(\frac{t-t_{iso}}{t_{hot}}\right)} \qquad for\, t > t_{iso} \qquad (8.17)$$

$$P_{hot}(t) = 1 \qquad for\, t \leq t_{iso}$$

where

t_{iso} is the time to isolation (the time to detection plus the response time of the system)

t_{hot} is the half time for cooling of continuous ignition mechanisms

The half times that are set for the different equipment groups are presented in Table 8.23. The half time for electrical equipment is shorter because electrical equipment is less massive than rotating machinery, and cooling will be faster with time. 'Other' is unknown and it is considered reasonable to use the same as for 'Rotating machinery'. The resulting half times are presented in Table 8.23

Table 8.23 - Half times for cooling of continuous ignition sources, denoted t_{hot}

Parameter	Rotating machinery	Electrical equipment	Other
Half time continuous sources, t_{hot}	20 seconds	5 seconds	20 seconds

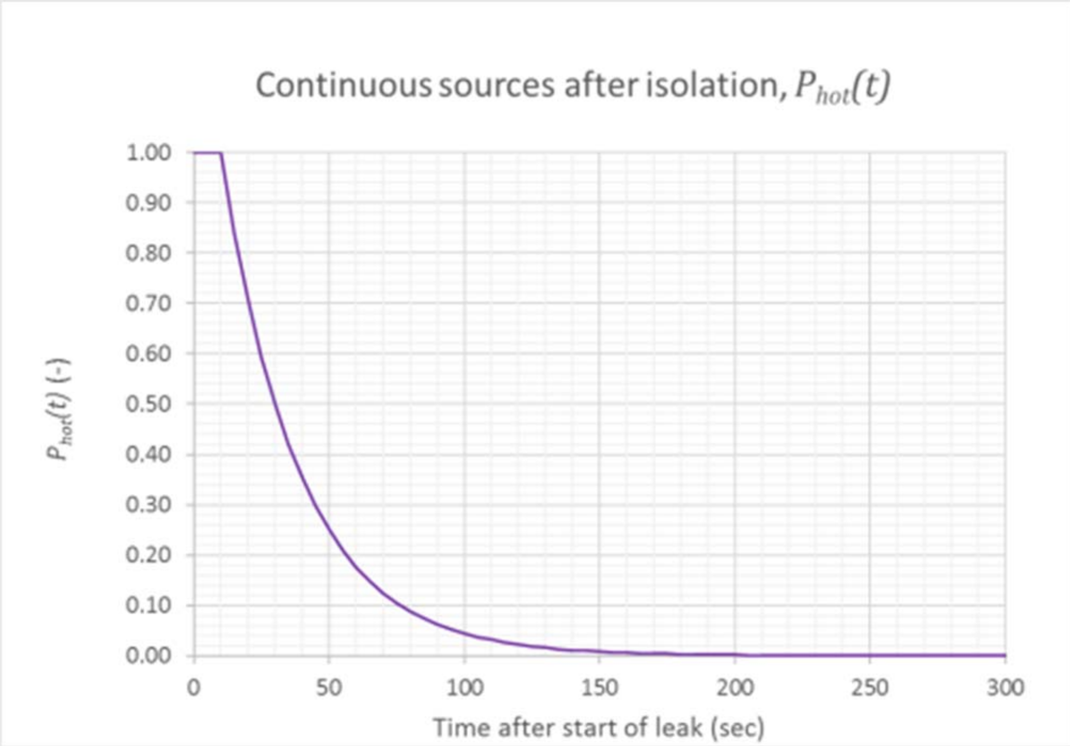


Figure 8.13 – Continuous sources after isolation to account for cooling of hot surfaces for a cooling half time of 20 sec ($t_{hot} = 20\ sec$) and isolation at 10 seconds after start of leak ($t_{iso} = 10\ sec$)

8.5.5 General time dependent characteristics of ignition sources

Based on the models for reduction of ignition intensity with time, the general time dependent effect is illustrated in Figure 8.14, where the following is assumed:

- The leak is onset at t = 0
- The leak is detected at t = 5 sec
- The delay time from detection until isolation of equipment is performed is set to 5 seconds (includes gas detector response time, signal processing time and time execute isolation of equipment)
- The cooling time, t_{hot}, is set to 20 seconds
- The effect of isolation of ignition sources is to 50%, *i.e.* P_{iso} = 0.5

The result shows that the effect of P_{iso} is immediate for discrete ignition mechanisms, but following a decay function for continuous ignition mechanisms determined by t_{hot}. After some time (*i.e.* about 100 seconds after isolation), the relative effect is the same for discrete and continuous ignition mechanisms. The relative effect (t) is constant for the remaining part of the scenario for continuous ignition mechanisms. For discrete ignition mechanisms for more than 300 seconds after start of the leak, the intensity is reduced according to the model described by equation (8.11).

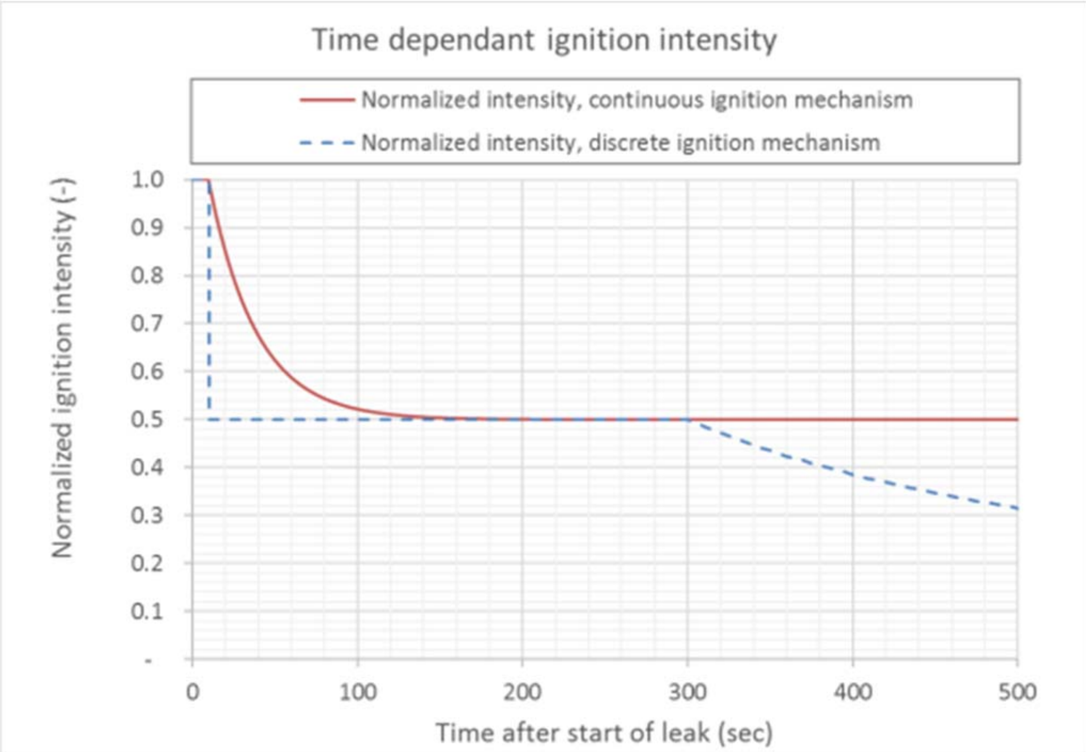


Figure 8.14 – Normalized time dependent ignition intensity for continuous and discrete ignition mechanisms for a typical scenario. This assumes detection at t = 5 sec, a system response time of 5 seconds (*i.e.* delay time from first gas exposure of detectors until isolation of ignition sources has taken place), t_{hot}= 20 sec and P_{iso} = 0.5

9 Ignition model parameters for objects not intended for use in explosive atmospheres

9.1 General

This chapter cover ignition potential related to gas exposure of objects not intended for use in explosive atmospheres. The objects that are covered are:

i) Gas turbine air intakes
ii) Combustion engines (in practice diesel engines)
iii) Equipment in enclosures protected by a mechanical ventilation system
iv) Equipment in unclassified areas
v) Supply vessels
vi) Hot work
vii) Flare

It is emphasised that other sources of ignition may be relevant for the facility in question, and such sources must be clarified as part of the risk analysis being performed (typically a part of the hazard identification process (often denoted HAZID work shop)). Hence the list above is not exhaustive.

9.2 Gas turbine air intake ignition model

Based on the current understanding of the potential ignition mechanisms, the Ignition probability of an external gas cloud entering the air intake of a gas turbine can be modelled by use of the following phases, depending on when the gas initially exposes the air intake (shutdown is considered to take place at $t = 0$ as illustrated in Figure 9.1):

- Initial gas exposure while the gas turbine is running, *i.e.* prior to $t = 0$
- Initial gas exposure during phase 1 of the gas turbine run down
- Initial gas exposure during phase 2 of the gas turbine run down
- Initial gas exposure after phase 2 of the gas turbine run down

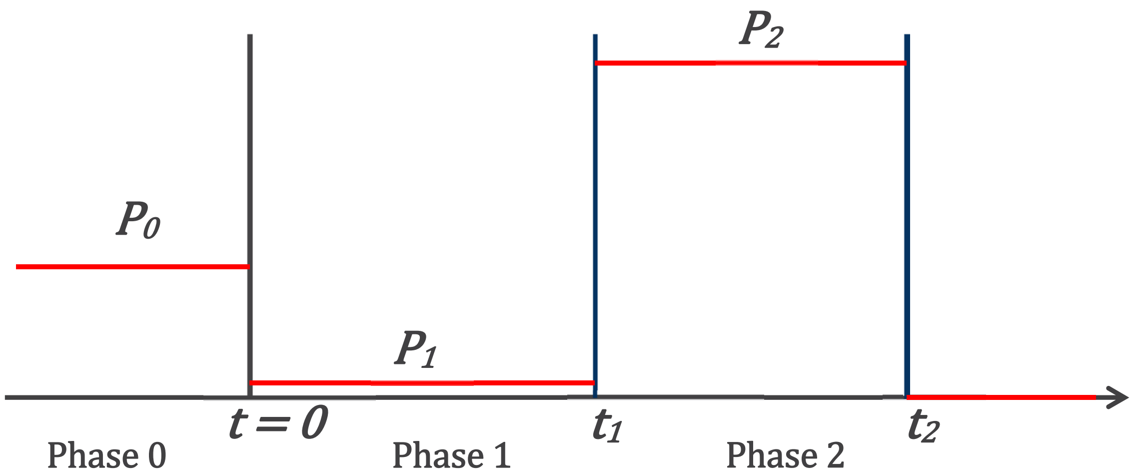


Figure 9.1 - The phases and parameters of the gas turbine ignition model

The ignition mechanisms in the three phases are considered as continuous; either the gas ignites or does not when it is exposed to the gas turbine in any of the phases, and there is no random discrete behaviour increasing the ignition probability with time of exposure. Due to this nature, the durations of the phases are less important than the probability levels; the duration only affects the probability of exposing the air intake in the first place, not the ignition probability given exposure of the air intake.

This also means that if gas initially exposes the air intake while the gas turbine is running, *i.e.* phase 0 in Figure 9.1, it will also expose the air intake during the subsequent phases (assuming the exposure duration is sufficiently long). The ignition probability p_2 then applies to the fraction of scenarios which did not ignite in phase 0. The same argument applies to those scenarios that ignited neither in phase 0 nor in phase 1. For exposure after phase 2 the ignition probability is 0.

It has been attempted to set the values for the various phases in the model. Due to a lack of information regarding the design and operation of gas turbines, the use of a simple model represented by a single probability, denoted P_{GTAI} has been concluded as the best approach. This probability covers ignition inside a gas turbine due to ingestion of combustible fluid leading to ignition of the external cloud. The probability applies to exposure within 5 minutes following shut down of the turbine. The figure also applies to exposure before shutdown. The conditional ignition probability is set to

$$P_{GTAI} = 50\%$$

for a gas turbine air intake exposed to combustible gas within 5 minutes following shut down of the gas turbine. Hence, 5 minutes equals t_2 in the model in Figure 9.1.

The assessment above is based on the results of Phase 0 of a JIP on gas turbine air intake ignition control headed by Lloyd's Register (Ref. /14/). The overall objective of the project was to investigate the behaviour of gas turbines when intake air includes combustible fluid in order to evaluate whether risk mitigating measures are required to enhance the safety levels of the ignition control systems for gas turbines.

For the likelihood of ignition of a combustible fluid mixed with air being ingested by a gas turbine through the air intake, the following hypothesis has been established:

- Combustible fluid included in gas turbine intake air is likely to be ignited inside the gas turbine if ingested prior to shutdown of the gas turbine and/or within a certain time frame after gas turbine shuts down. The exact time frame must be investigated further, but is believed to be limited to the first few minutes after shutdown

And:

- if the gas exposure of the air intake is continuous over a prolonged period of time (the exact period of time must be investigated further) ignition of the external gas cloud is believed to occur, either through propagation of the initial flame from inside the gas turbine to the external environment or through damage of the gas turbine

The hypothesis was based on observed incidents taking place at oil and gas facilities in the North Sea (see Table 7.1), assessment of the potential ignition mechanisms and discussions with one gas turbine vendor.

The uncertainty associated with the hypothesis cannot be neglected as the ignition scenarios are not fully understood. However, an overarching principle in safe design is to account for such uncertainty if the potential consequences are significant, which is the case for the scenario considered.

In order to falsify or verify the hypothesis for the likelihood of ignition, it is judged that comprehensive research including experimental work and development of numerical models will be necessary. In addition, access to detailed gas turbine data for the relevant gas turbine designs is required. The scope of work that cover these aspects have been included in the project proposal for the consecutive phase (Phase 1) of the mentioned JIP. The MISOF model for gas turbine air intakes should be updated when Phase 1 of the JIP project has been executed.

9.3 Combustion engine air intake ignition

Ignition probability for combustion (diesel) engines exposed to flammable gas is described in Appendix C. Based on experiments performed by GexCon, the following ignition mechanisms are found relevant:

- Flammable gas exposure to air intake: experience from experiments performed by GexCon suggests that:
    - When exposed to stoichiometric fuel-air concentration the gas will ignite in practically all cases
    - The ignition occurs immediately on exposure
    - For lower fuel concentrations, the flame speed is lower and hence the likelihood of the flame being capable of propagating against the air flow is reduced
    - The reliability of flame arrestors is very high, a probability of failure on demand of 0.01 is considered conservative. Note that the effect of the flame arrestor presumes that the air intake system as such is able to contain the generated overpressure
- Flammable gas exposure to exhaust pipe or engine casing: experience from experiments performed by GexCon shows that ignition probability in this case is likely to be very low.

Based on this, the recommended ignition probabilities for diesel engine air intakes are given in Table 9.2.

Table 9.1 - Recommended ignition probabilities for combustion (diesel) engine air intakes

Scenario	P_{engine}
Stoichiometric gas in air intake, no flame arrestor	$P_{CEAI} = 90\ \%$
Non- stoichiometric gas in air intake, no flame arrestor	$P_{engine} = 0.9 \cdot \frac{s(EQ)}{s(1)}$ where s = laminar flame speed EQ = Equivalence ratio
Flame arrestor in air intake The air intake system must be able to contain the explosion.	0.01

9.4 Hot work

9.4.1 General

Hot work is not reflected by the general model for ignition sources in the area, which means that $\lambda_{i,C}$ and $\lambda_{i,D}$ are based on an assumption that hot work activities are not performed in the area under consideration. Ignition due to hot work thus has to be modelled specifically.

Hot work activities as sources for ignition were emphasised in the previous revision of the offshore ignition model (Ref. /3/). A separate report in Phase 1 of that project, Ref. /15/, was published. The suggested model in MISOF is based on this work.

Hot work performed in habitats is to be regarded as an ignition source as specified in Chapter 6.23. The probability for gas exposure of the habitat needs to be estimated with an appropriate model, and combined with the recommended conditional ignition probability.

It is important that the exposure probability model is able to reflect geometrical layout. The location of the hot work activity relative to the location of the leak sources will have an important effect on the estimated ignition probability. For a limited amount of hot work activity, simplification by use of a model that assumes uniform distribution of the hot work activities relative to the location of the premixed cloud may be acceptable. For high activity periods, an advanced exposure model reflecting the geometrical situation is recommended.

If hot work takes place without habitat protection, the probability of ignition upon gas exposure shall be assessed based on the probabilities given in Table 9.2.

Table 9.2 - Ignition probabilities for hot work activities, denoted P_{HW}

Activity	P_{HW}
Open flame and welding	1.0
Grinding	0.1
Hot surfaces [1)]	0 if t < AIT
Hot work Class B	< 0.1 [2)]

1) For higher temperatures than Auto Ignition Temperature (AIT), the probability of ignition is to be taken as 1.0 if not documented otherwise.

2) Requires equipment failure or the equipment is used in a wrong way. These failure modes are unlikely to occur simultaneously with a gas leak causing exposure of the equipment. Thus, a negligible figure (*i.e.* ~ 0) can be used if adequately justified.

9.4.2 Hot Work in habitat

A welding habitat is a special case for an enclosure. The general guidelines described in Chapter 9.5 apply, but in addition, human errors have to be accounted for.

The human error (*i.e.* the habitat door is opened while the ignition source is still active and the habitat interior is exposed to gas) is considered to dominate the failure probability of the habitat.

If the habitat door is opened, the overpressure will be lost, and the potential ignition source will be exposed to the atmosphere directly outside the habitat.

A default probability for human error of 30% (denoted $P_{open\,door}$) is defined, but may be set otherwise if based on a specific study of the human reliability, for instance based on the Petro-HRA methodology.

The probability for ignition is set to 1.0 (denoted $P_{activity}$) if flammable mixture migrates into the enclosure.

The probability for ingress of flammable mixture into the habitat depends on the leak scenario and hence the gas concentration on the outside of the habitat.

The general conditional ignition probability due do hot work in habitat thus becomes

$$P_{HW,habitat} = P_{open\,door} \cdot P_{gas\,ingress} \cdot P_{activity} \tag{9.1}$$

A generic model for $P_{gas\,ingress}$ is presented in Table 9.3, which is based on knowledge provided by experts being involved in a study of the performance of habitats subjected to gas exposure. However, a specific exposure probability model is preferred that reflects the geometrical layout and the relevant leak sources that may generate exposure to the habitat. A significant benefit of using such a model is the ability to reflect leak scenarios that hit the habitat. Large leaks hitting the habitat cause a significant force acting on to the habitat, which may affect the integrity of the habitat as well as the probability for human error (*i.e.* $P_{open\,door}$).

Based on the generic model, the reliability of the habitat becomes 0.3 for large leaks (= 0.3·1.0·1.0), and about 0.06 for small leaks (= 0.3·0.17·1.0).

Table 9.3 – Suggested generic ignition probabilities for significant gas ingress into habitat given habitat door opened with flammable atmosphere on the outside

Scenario generating gas exposure outside the habitat (door is opened)	$P_{gas\,ingress}$
Very large leaks; > 30 kg/s	1.0
Large gas leak; 10-30 kg/s	0.67
Medium gas leak; 1-10 kg/s	0.33
Small gas leak; 0.1-1 kg/s	0.17

9.5 Enclosures protected by a ventilation system

There are several potential sources of ignition at an offshore installation that are safe by means of a ventilation system. This may be a crane, an engine room, an equipment room, or even a module, *e.g.* the living quarters. If gas with flammable concentration enters such areas, the probability of ignition will be high if the objects inside the enclosure are not intended for exposure to explosive atmosphere.

In general, the probability will be determined by the following:

- The probability for exposure to the air intake supplying the enclosure
- The probability for detection provided by any general detectors or detectors in the air intake itself
- The effectiveness and reliability of any gas tight damper located in the air duct system
- The effectiveness of isolation of potential sources of ignition inside the enclosure
- The amount of gas migrating into the enclosure
- The position of live ignition sources inside the enclosure relative to the gas migrating into the enclosure through ventilation system inlets

In the North Sea, generally detectors are located in the air intake that initiates closure of the gas tight damper preventing the gas from entering the enclosure. To ensure that the damper is effective, an adequate length of the air duct upstream the damper is implemented. In such a case, the ignition probability is mainly decided by the reliability of the damper. Normally, a safety integrity level of 0.01 is set for such systems. The probability for ignition given failure of the damper in a scenario where combustible mixture is exposing the air intake should be set to 1.0 unless a specific study justifies otherwise. Hence, the ignition probability for the general case will set the ignition probability equal to the failure on demand of the damper. In most cases, this will be equal to a SIL level of 2, which implies an ignition probability of 0.01.

In cases where there is no damper that stops the flammable mixture from migrating into the enclosure, a model that reflects a build-up of combustible mixture inside could be established if required. However, it is important that such a model incorporates the important aspects of the ventilation system and the geometrical situation on the inside of the enclosure. A perfect mixing model can be used, but this must be justified appropriately as otherwise this may lead to a non-conservative estimate. This is because the ignition source can be exposed to flammable gas concentration before the average concentration inside the enclosure becomes flammable.

In both cases described above, the probability for ignition due to gas ingress into an enclosure is very dependent on the capability of the exposure probability model to estimate the probability for exposure of the air intake inlet. In general, only models that is able to reflect the flow pattern between the origin of the leak and the air inlet can generate reliable results. However, coarse models can be justified in accordance with the targeted level of detail for the risk analysis.

9.6 Non-Ex equipment in unclassified areas

In general, non-Ex equipment is rarely used in the North Sea. At new fixed installations, all outdoor equipment is in most cases certified for use in explosive atmospheres. However, some special types of equipment cannot be designed according to the ATEX directive. At older installations, non-Ex equipment may be found in unclassified areas. Non-Ex equipment in outdoor areas is also found at most drilling rigs and flotels, as well as marine vessels operating inside the safety zone. A scenario where this is important is where Jack-ups are providing drilling and well intervention services through a fixed installation. In this case, leaks at the fixed installation may expose non-Ex equipment on the Jack-up. In this case, it is important that the capability of the probabilistic exposure model is adequate, *i.e.* able to reflect the geometrical layout.

It is hard to determine a general conditional ignition probability for non-Ex equipment as the potential ignition modes will be equipment specific. It is therefore recommended that a specific assessment (study) is performed to set the conditional ignition probability for the non-Ex equipment being addressed. It is expected that the conditional ignition probability for such equipment is significantly higher than the conditional ignition probabilities set for rotating machinery and electrical equipment in the MISOF model (see Chapter 8.4.4 and Chapter 8.4.5).

For outdoor areas generally equipped with non-Ex equipment, a linear model is suggested to reflect the volume of the area exposed to the combustible mixture. The ignition probability is set to 90 % if a volume of 9,000 m3 is exposed. For volumes above 9,000 m3, the ignition probability is 90 %. The model becomes (see Figure 9.2);

Exposed volume to combustible gas ≤ 9,000 m3: $P_{Non-Ex} = 0.001 \cdot V_{exposure}$ (9.2)

Exposed volume to combustible gas > 9,000 m3: $P_{Non-Ex} = 0.9$ (9.3)

where

P_{Non-Ex} is the ignition probability given exposure of the unclassified area containing non-Ex equipment to flammable mixture

$V_{exposure}$ is the free flow volume in the unclassified area exposed to flammable mixture (see Chapter 6.10)

It is suggested that the ignition probability is independent of the exposure time.

The ignition mechanisms causing the ignitions in such areas are not discussed in detail, but it is judged that electrical equipment (including instruments), like switches and lighting fixtures, and personnel activity (*e.g.* operation of tools) are important potential ignition sources.

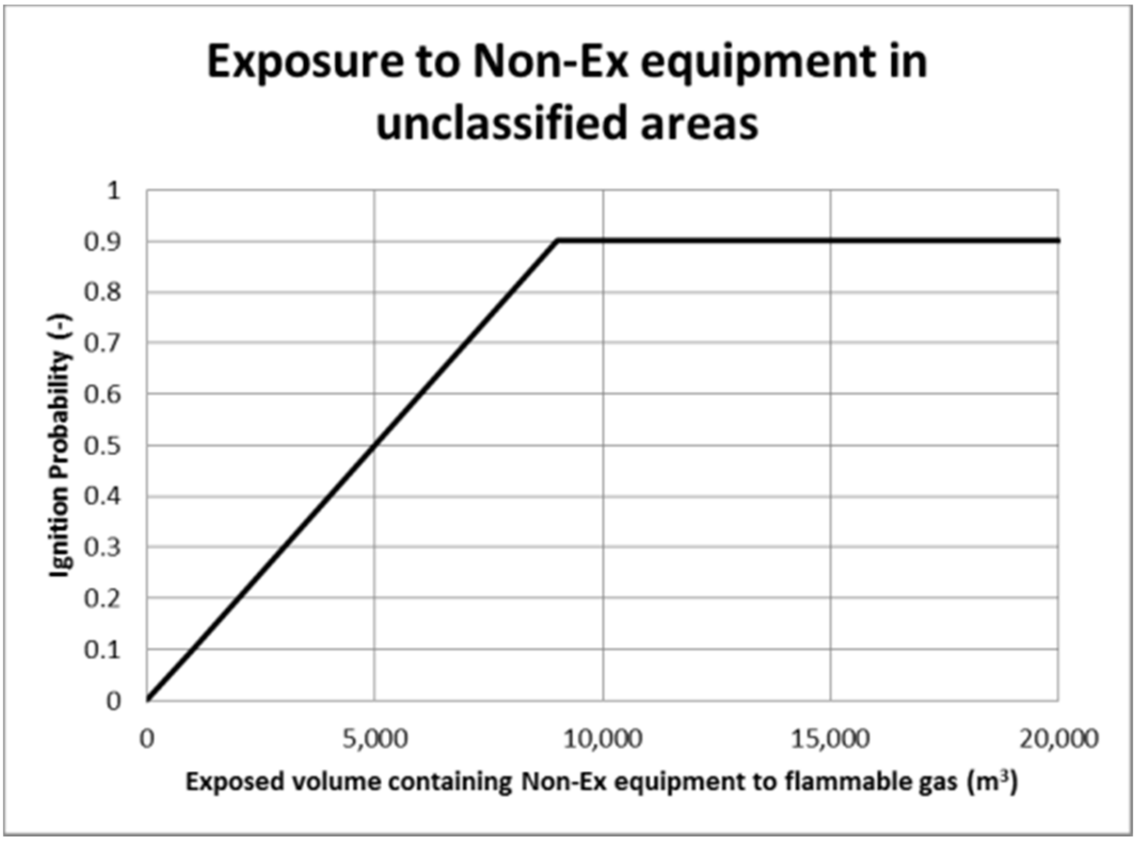


Figure 9.2 - Exposure to non-Ex equipment in unclassified areas. This is applicable to areas where non-Ex equipment is generally used. For specific non-Ex equipment, (believed to be the regular case in the North Sea) a special study defining the conditional ignition probability associated with the equipment is recommended

9.7 Supply vessels

Subsea gas releases and splash zone gas releases can be ignited by supply vessels. Potential ignition sources are outdoor non-Ex equipment, such as lighting fixtures, and the air intake to the engine. An ignition probability of 50% is suggested for substantial gas exposure of a supply vessel. However, as stated in Chapter 9.6, a specific study can be performed to justify a specific conditional ignition probability for the supply vessel being considered.

9.8 Flare

The ignition probability given exposure of flammable mixture to a flare is 100 %.

10 Guidelines for use of the model

10.1 Introduction

Guidelines for application of the model are presented in this chapter. In addition, the ignition model parameters and corresponding default values are summarized for efficient look up of parameter values.

It is considered beyond the scope of this report to describe the detailed algorithms required to calculate the exposure probability, *i.e.* $P(E)$ ·in equation (5.1). The focus of the guidelines is to describe the most important aspects related to use of the conditional ignition probabilities (*i.e.* $P(I\ given\ E)$) and highlight important requirements to the probabilistic exposure model. The capability of the probabilistic exposure model is critical for the accuracy of the ignition probability estimate in many cases, and must be tailored for the objective of the risk analysis being performed. A suggested algorithm for transient calculation of the ignition probability based on an idealized model where the objects are uniformly distributed is included, as this is a common approach used in industry.

10.2 Validity of model

The model is based on releases of hydrocarbons from process equipment on North Sea offshore facilities. It is found reasonable to argue that the model is applicable to platforms and land based facilities where the properties of the objects in question can be considered equivalent with what are found generally on North Sea installations. However, a specific assessment must be carried out in each case, and conclusions must be documented properly.

If appropriate, correction factors should be used to adjust for particular equipment properties and/or the fluid type in question. In such cases the validity of the model should be assessed and presented as part of the documentation the basis for the risk analysis being performed.

10.3 Identification of ignition sources

Other sources of ignition than covered by MISOF may be relevant for the facility in question, and must be clarified as part of the risk analysis being performed. It is recommended that this is covered in the hazard identification analysis, for instance through use of appropriate guide words in a HAZID workshop.

10.4 Guidelines exposure probability model

10.4.1 General

In order to quantify the ignition probability according to equation (5.1), a transient cloud model must be established. In principle, this can be performed by any tool ranging from CFD simulation of the transient leak scenarios to engineering judgment. However, it is very important to understand that the methodology implemented to combine the conditional ignition probabilities with a probabilistic exposure model is crucial for the accuracy of the estimated ignition probability. But more importantly, implementation of a simplistic method, still in compliance with MISOF, will not enable the full potential of the model to investigate the importance of the various barrier elements affecting the fire and explosion risk picture. A key element is the representation of the location of rotating equipment and special sources of ignition such as gas turbine air intakes and hot work activities. If the probabilistic exposure model is based on that the conditional ignition probability related to these units are uniformly distributed in space, the effects of the location of the leak sources and the ignition sources are not reflected. On the other hand, to fully capture the effects of location of leak- and ignition sources as well as other parameters such as wind speed, wind direction, release rate and release direction, a sufficient number of simulations will be required. If such an approach is used, convergence of the model, which is dependent on the number of simulations, must be demonstrated.

General requirements how to build a probabilistic exposure model can be found in NORSOK Z-013 Annex F. Compliance with the requirements in NORSOK does not necessarily mean that the properties of the probabilistic exposure model are adequate. The key issue is the importance of the geometry to fulfil the objective of the QRA. The overall geometrical layout, which determines the behaviour of the released fluid, the location of the leak sources relative to the potential ignition sources as well as the location of the gas detectors affects the resulting estimate.

However, sound simplifications that ensure compliance with the objective of the QRA can be established. A common approach is to assume that the leak sources, ignition sources and gas detectors are uniformly distributed. This may be a reasonable approach for calculation of the delayed ignition probability in typical semi-confined offshore modules, and especially for modelling of the contribution from electrical equipment. It is in general considered reasonable to assume that the electrical equipment is uniformly distributed in the module, which is the basis for derivation of $\lambda_{i,C}$ and $\lambda_{i,D}$. For large process areas, typically found at FPSO's and semi-submersibles, the location of the ignition source, such as rotating machinery and hot work activity, increases in importance. Furthermore, in case of special ignition sources located outside the hazardous zone are relevant, the flow pattern between the leak sources and the source of ignition is decisive for the resulting ignition probability. The geometrical layout also affects the detection probability (exposure to gas detectors inside the hazardous zone, in air intakes and in unclassified area), and thus couples back to the effect of the safety functions being initiated (*i.e.* emergency shutdown, blow down and isolation of ignition sources).

Based on the above, the exposure model should possess the following features

- the ignition probability calculation should be performed as an integration in time for each of the leak scenarios considered, in order to reflect the effect of detection, ESD, BD and isolation of ignition sources properly. The algorithm for such a model assuming uniform distribution of ignition sources is presented in the following chapter
- the gas exposure model should reflect the exact location of the most prominent sources of ignition relative to the location of the release sources. This applies in particular to rotating machinery, hot work activity, gas turbine air intakes and diesel engines, but this list should not be considered exhaustive

A simple exposure model can be used if appropriately justified in the analysis. Uniform distribution of the ignition sources in area, enabling use of a simple exposure model, can be used if appropriately justified in analysis (see algorithm described in the following chapter).

10.4.2 Algorithm in simplified probabilistic model

In this chapter, the algorithm for the calculation of the transient ignition probability is presuming that the ignition sources are distributed uniformly in the area described. The example case used to illustrate application of the algorithm is a gas leak with an initial leak rate of 15 kg/s from a valve (see Figure 10.1) in a typical offshore module.

It assumed that the scenario is detected after 5 seconds and that isolation of ESD valves and initiation of blow down (opening of blow down valves) occurs 15 seconds after detection (*i.e.* 20 seconds after onset of the leak).

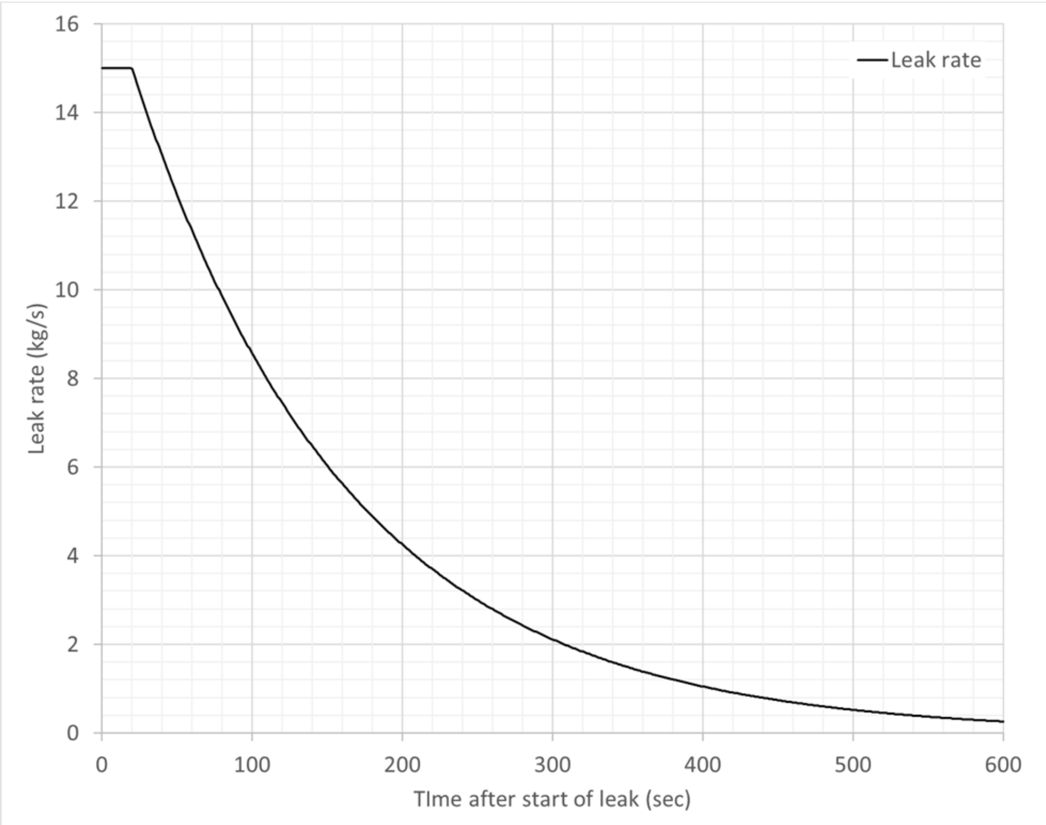


Figure 10.1 - Time dependent leak rate used as basis for an example to illustrate use of algorithm for uniform distribution of ignition sources in area

Step 1: Immediate ignition

Immediate ignition is ignition resulting from a mechanism that is related to the cause of the loss of containment. Immediate ignition occurs before a combustible cloud has formed, and will therefore not generate an explosion, only a fire (a premixed cloud is a prerequisite for a vapour cloud explosion to take place). For the same reason, immediate ignition is not dependent on the ventilation conditions.

The immediate ignition probability (P_{im}), denoted $P_I(I)$ in our case, is 0.07% as the leak is stemming from a valve. The effect of assuming that the leak is stemming from a pump is discussed in
Step 9.

Step 2: Gas exposure

In order to quantify the delayed ignition probability, the transient development of the gas cloud must be estimated. As stated in 10.4.1, the estimate of the cloud size may be provided by tools ranging from simulation with CFD software to simple empirical models. The estimation of the gas cloud characteristics in the example case is generated based on scaling of the beta distribution with the following parameters: alpha=2, beta=8, lower limit=0, upper limit=800 seconds. The mode of the distribution is scaled with a factor to obtain a combustible peak volume ($V_{LFL:UFL}$) at 10,000 m^3. V_{new} is set to the derivative of the beta distribution approaching zero at the mode of the distribution. Knowing the time dependent gas cloud, the presented case example can be recalculated quite easily implementing the algorithm in a spread sheet or similar.

The volume of the flammable cloud and the volume detectable by detectors (*i.e.* volume above set point of the detectors) are required to calculate the ignition probability. Only the volumes where potential ignition sources are present are to be considered (see Chapter 10.6).

The ignition probability calculation is performed as integration in time. The calculation of ignition probability for one time step is considered to describe the methodology. A high-resolution discretisation scheme can be used to improve accuracy. This means that the resolution in the time domain affects the results.

The algorithm described below applies for a model that does not reflect the location of the potential sources of ignition. For large modules and open areas (*e.g.* FPSOs), it is suggested that the exposure model should reflect the location of the ignition sources. Then the equations below cannot be applied directly as they are based on that the ignition sources are uniformly distributed throughout the volume. However, the algorithm will be the same also in this case. The following volumetric and time variables are used:

- The volume exposed to flammable gas at the considered time step is $V_{LFL:UFL}$
- The new volume exposed to flammable gas over the considered time step is V_{new}
- The time step is Δt

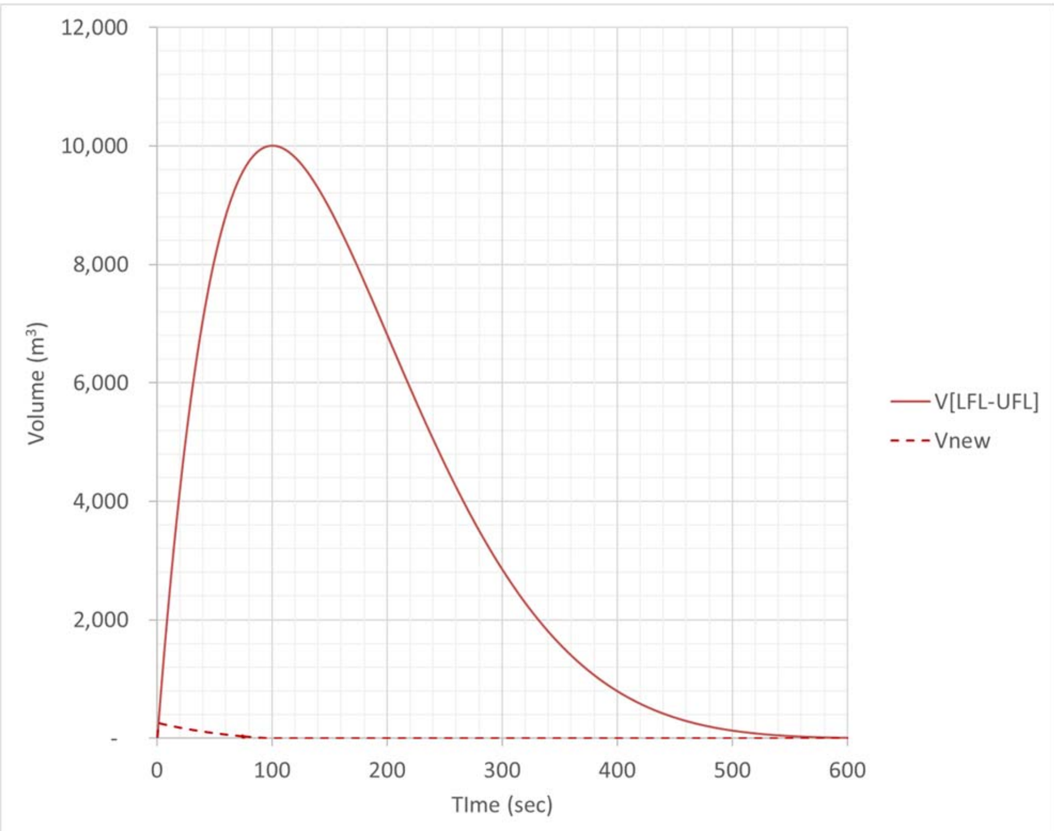


Figure 10.2 - Time dependent gas cloud parameters for a case example required to use an algorithm for uniform distribution of ignition sources in a given area

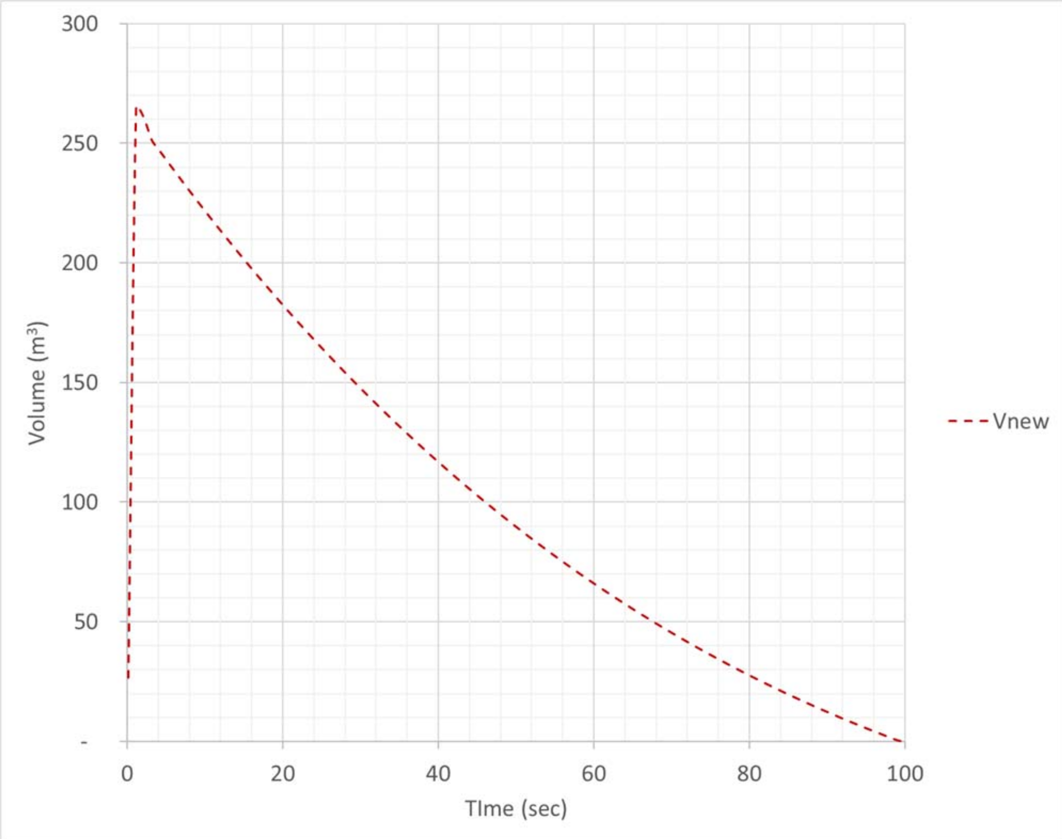


Figure 10.3 - Time dependent V_{new} for a case example required to use an algorithm for uniform distribution of ignition sources in a given area

Step 3: Determine the delayed ignition modelling parameters

The parameters $\lambda_{i,C}$ and $\lambda_{i,D}$ describe the likelihood of ignition for exposure of a unit of 1 m^3 process module (free flow volume inside a hazardous zone on an offshore installation) to combustible vapour for a defined time interval without any effect of isolation of ignition sources. The parameter values reflect the average North Sea industry standard of the ignition control barrier.

If specific ignition sources, such as rotating machinery or electrical equipment, are modelled explicitly in terms of location of the equipment, the $\lambda_{i,C}$ and $\lambda_{i,D}$ in the algorithm below can only be used to estimate the contribution form the category denoted 'Other'.

Note that the parameter λ_i has the unit 'expected number of ignitions per m^3' and thus is not a dimensionless ignition probability.

Table 10.1 - Basic ignition model parameters used in algorithm

Parameter	Description
$\lambda_{i,C}$	Expected number of ignitions per 1 m^3 due to continuous ignition mechanisms
$\lambda_{i,D}$	Expected number of ignitions per 1 m^3 and second due to discrete ignition mechanisms
P_{iso}	The fraction of ignition sources that is shut down upon isolation of ignition sources

Step 4: Detection and ignition source isolation

At the considered time, a fraction of ignition sources is isolated. The probability that isolation has been performed is denoted P_{det}. The delay from exposure of gas detectors until isolation in the process area is initiated and should be taken into account when quantifying P_{det}.

The parameter P_{iso} describes the fraction of ignition sources that is shut down upon isolation of ignition sources, and hence the effect of ignition source isolation on ignition probability. With $P_{iso} = 0$, isolation has no effect, while $P_{iso} = 1$ means that isolation effectively removes all ignition sources. However, for continuous sources, the effect is not immediate.

The fraction of continuous ignition sources that is active at time t is:

$$F_C(\text{t}) = (1 - P_{det}) + P_{det} \cdot \{P_{iso} \cdot P_{hot}(\text{t}) + (1 - P_{iso})\} \tag{10.1}$$

The fraction of discrete ignition sources that is active at time t can be described by

$$F_D(\text{t}) = \{(1 - P_{det}) + P_{det} \cdot (1 - P_{iso})\} \cdot K_{D,300}(t) \tag{10.2}$$

The quantification of $K_{D,300}(t)$ and $P_{hot}(t)$ is based on decay in ignition intensity for discrete and continuous sources described by equation (8.11) and (8.12). P_{det} is a stochastic variable (*i.e.* not switching from 0 to 1 at the time when detection occurs) and the algorithm for modelling of P_{det} must be documented as part of the basis of the QRA as it is very important for the result.

Step 5: Ignition from continuous sources

Ignition probability due to continuous ignition mechanisms is calculated on the basis of the new flammable volume, denoted V_{new}, over the time step Δt. Given that ignition has not occurred before, the expected number of ignitions due to continuous sources equals

$$E_C(I) = \lambda_{i,C} \cdot V_{new} \cdot F_C \tag{10.3}$$

The delayed ignition probability, which is the probability for 1 or more ignitions at the time step, can be calculated from the Poisson distribution assuming that the following assumptions hold

- k is the number of times an event occurs in an interval and k can take values 0, 1, 2, etc.
- The ignitions are independent, which means that the occurrence of one ignition does not affect the probability that a second ignition will occur[1]. This assumption holds because the theoretical frame work is based on that ignition is not onset in practice. Conceptually, this is unphysical, but this assumption holds because the theoretical frame work is based on that ignition is not onset in practice. Conceptually, the Poisson distribution can rather be thought of as the probability for the number of flashes throughout the time-dependent gas exposure (120,797 m^3 of combustible atmosphere in a hazardous area for 201 seconds).
- The rate at which ignitions occur is constant at each time step and in each volume unit (m^3). The rate cannot be higher in some intervals and lower in other intervals. $\lambda_{i,C}$ (and $\lambda_{i,C}$) varies through the time domain, but is constant within the volume of the combustible atmosphere at each time step.
- Two ignitions cannot occur at exactly the same instant; instead, at each very small sub-interval exactly one ignition either occurs or does not occur[1].

[1] There have been incidents where it is known that the leak was ignited by two different ignition sources at different times (*e.g.* Macondo fire in the Gulf of Mexico). This would be captured by the parameterisation of λ_i if the two ignitions are recorded in the statistics. On the other hand, since the majority of the ignited events only will ignite once, there is a possibility that the first ignition camouflages a later ignition. This could for instance have been the case in the Centrica Rough B incident at UKCS in 2006, where ignition at the gas turbine air intake eliminated a potential delayed ignition in the hazardous area. This we will never now

The expression for one or more ignitions becomes according to the Poisson distribution becomes

$$P_C(I) = P(1\ or\ more\ ignitions) = 1 - P(zero\ ignitions) = 1 - e^{-E_C(I)}\frac{E_C(I)^k}{k!} = 1 - e^{-E_C(I)}\frac{E_C(I)^0}{0!} = 1 - e^{-E_C(I)} = 1 - e^{-E_C(I)} \quad (10.4)$$

Combining 10.3 and 10.4, the total expression for the ignition probability per time step becomes

$$P_C(I) = 1 - e^{-\lambda_{i,C} \cdot V_{new} \cdot F_C} \quad (10.5)$$

The expected number of ignitions will approximately equal the ignition probability if the value is low. 0.05 expected number of ignitions per time step is suggested as a rule of thumb for the upper limit for the validity of the approximation.

The resulting time dependent ignition probability for our case example is shown in Figure 10.4 given the following parameter values:

- $\lambda_{i,C} = 6.1 \cdot 10^{-6} m^{-3}$
- $P_{det} = 1\ for\ t\ > 10\ seconds$ and $P_{det} = 0\ for\ t\ \leq 10\ seconds$ (detection occurs at $t = 5$, but 5 seconds delay time included)
- $P_{iso} = 0.25$
- $t_{hot} = 20\ seconds$
- $t_{iso} = 10\ seconds$
- $\Delta t = 1\ second$, which is required to set the discrete resolution of V_{new} versus time

  The time dependent ignition probability is calculated using the overall algorithm presented in Step 9 including the model for discrete ignition sources described in Step 6.

Note the effect of detection at $t\ = 10\ seconds$ where an exponential decrease is initiated following the cooling half time of continuous sources.

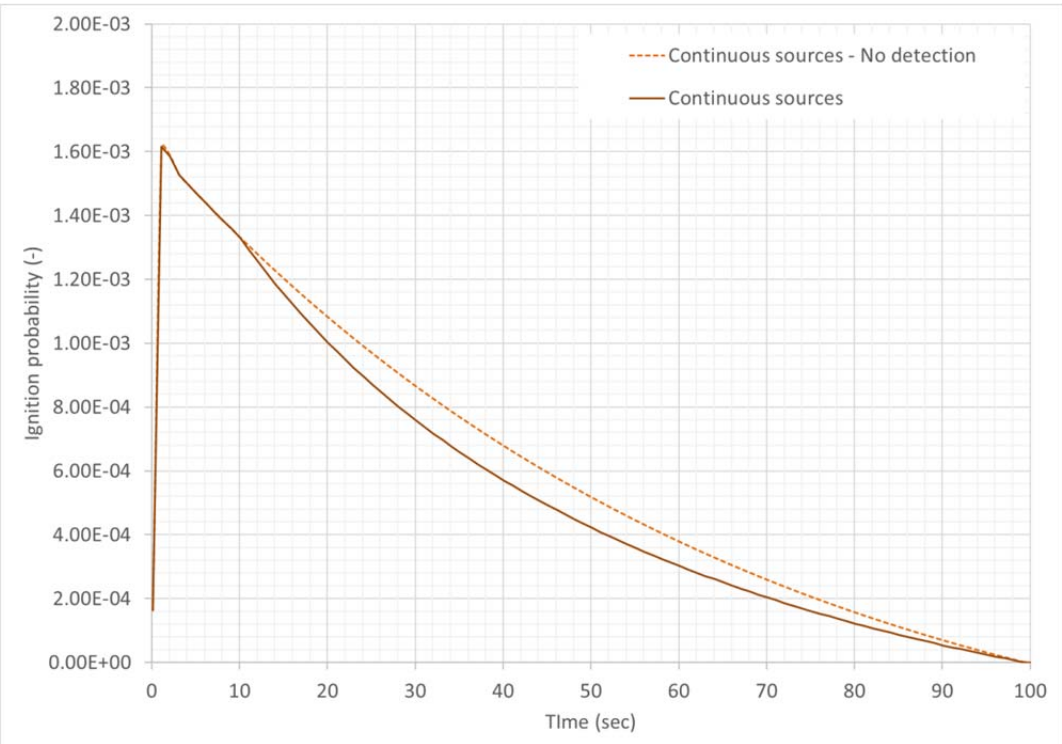


Figure 10.4 – Time dependent ignition probability calculated from equation (10.3) and using the total $\lambda_{i,C}$ for all equipment categories found in Table 10.2. Gas detection take effect at $t\ = 10\ seconds$

Step 6: Ignition from discrete sources

Ignition probability due to discrete ignition mechanisms is calculated on the basis of the flammable volume at the time considered. Given that ignition has not occurred before, ignition probability due to discrete sources equals

$$P_D(I) = 1 - e^{-\lambda_{i,D} \cdot V_{LFL:UFL} \cdot \Delta t \cdot F_D} \qquad (10.6)$$

The resulting time dependent ignition probability for our case example is shown in Figure 10.5 given the following parameter values:

- $\lambda_{i,D} = 1.5 \cdot 10^{-8} m^{-3} s^{-1}$
- $P_{det} = 1\ for\ t\ > 10\ seconds$ and $P_{det} = 0\ for\ t\ \leq 10\ seconds$ (detection occurs at $t = 5$, but 5 seconds delay time included)
- $P_{iso} = 0.25$
- $\Delta t = 1\ second$

Note the effect of detection at $t\ = 10\ seconds$ (a small dip in the probability) and the effect of $K_{D,300}$ (equation (8.11)) more than 300 seconds after start of the leak.

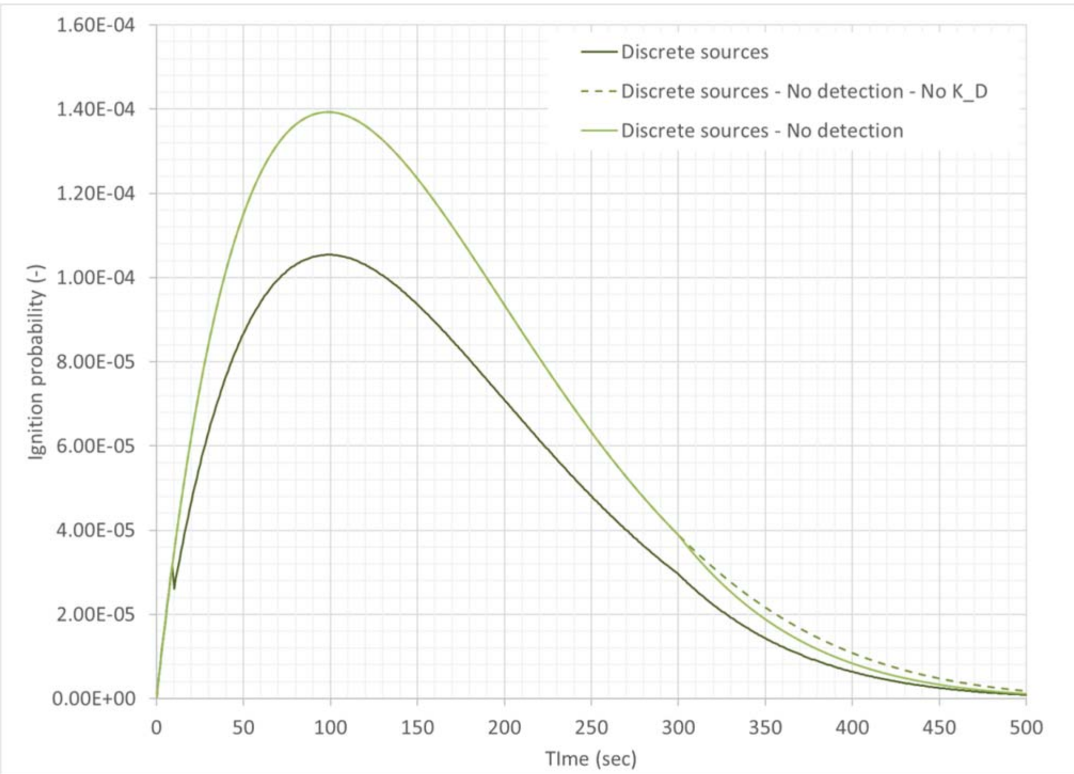


Figure 10.5 – Time dependent ignition probability calculated from equation (10.4) and using the total $\lambda_{i,D}$ for all equipment categories found in Table 10.2. Note the effect of $K_{D,300}$ more than 300 seconds after start of the leak. The time step used is 1 second. Note also the effect of detection and immediate isolation of dis crete ignition sources at 10 seconds after start of the leak

Step 7: Ignition due to hot work

Ignition probability from hot work is not reflected in $\lambda_{i,C}$ and $\lambda_{i,D}$

Specific conditional probabilities for ignition in case of exposure to hot work class A and B are defined in Chapter 9.4. The hot work ignition probability, denoted $P_{HW}(I)$, can be calculated in the same way as continuous sources described above (*i.e.* distributing the hot work conditional ignition probability uniformly in the area), but this approach will not reflect the location of the hot work relative to the leak sources in the area.

The probability for isolation, P_{iso}, may differ from the value applied for equipment in the module. For large modules and open areas (*e.g.* FPSOs), it is suggested that the exposure model reflects the location of the hot work activity.

Step 8: Ignition from external sources

The conditional ignition probability related to equipment not certified for use in explosive atmospheres (e.g. gas turbines, cranes, supply vessels, etc.) is not covered by $P_{if,C}$ and $P_{if,D}$. Normally, such equipment is located outside of the hazardous zone. Therefore, ignition due to gas exposure to such ignition sources is often denoted external ignition sources.

Exposure of external ignition sources should be calculated at each time step. The ignition probability due to external sources is denoted $P_E(I)$. The accrued $P_E(I)$ must be adjusted for the ignition probability resulting from discrete and continuous sources (per time step) to ensure that the total ignition probability represents the probability for ignition exactly once. It is important that the exposure model reflects the locations of the ignition sources, and also the transient properties of the ignition sources if it possesses a time dependent behaviour. The importance of reflecting the location of the source of ignition calls for a CFD model to be used to estimate the exposure probability (*i.e.* $P(E)$ in equation (5.1)). The test of MISOF presented in Chapter 11.3 demonstrates the importance of capturing the contribution from external sources.

Step 9: Calculate ignition probability over all time steps

The contribution from continuous and discrete sources at the considered time step is added. The expression for calculating the total ignition probability, $P_{T,i}(I)$, for time step i is:

$$P_{T,i}(I) = \left(1 - \sum_{i=1}^{N} P_{T,i-1}(I)\right) \cdot \left(P_{C,i}(I) + P_{D,i}(I) + P_{HW,i}(I) + P_{E,i}(I) - P_{cor,i}\right) \tag{10.7}$$

The expression for calculating the total ignition probability, $P_T(I)$, up to and including time step i is:

$$P_T(I) = \sum_{i=1}^{N} P_{T,i}(I) \tag{10.8}$$

The last term in Equation (10.6), $P_{cor,i}$, is included in order to ensure that the addition of probabilities is performed correctly at each time step (ensure that the calculated total probability represents the probability for ignition exactly once at time step i). One solution for addition of two ignition probabilities is using the simple calculation rule $P_{1+2} = P_1 + P_2 - P_1 \cdot P_2$. However this may be cumbersome if the number of contributions is large. Another solution is to calculate the probabilities of no ignition in each step of the algorithm, *i.e.* use the formula $P_{1+2} = 1 - (1 - P_1) \cdot (1 - P_2)$. As ignition probability is in general small over a time step, the correction is normally very small. The correction typically becomes significant when the contribution from external sources or hot work (*i.e.* $P_E(I)$ or $P_{HW}(I)$) are prominent. A general example is a gas turbine air intake located in the vicinity of the process area when the gas turbine is used for mechanical drive of the compressors.

The first term in (10.5), $\left(1 - \sum_{i=1}^{N} P_{T,i-1}(I)\right)$, adjusts for the probability for ignitions taking place at previous time steps. For leaks stemming from pumps, the effect may be significant due to high pump immediate ignition probability.

The effect of $\left(1 - \sum_{i=1}^{N} P_{T,i-1}(I)\right)$ is demonstrated in Figure 10.6 in our case example for discrete ignition mechanisms only, where it is assumed that the 15 kg/s leak originates from a pump instead of a valve. In this case, the immediate ignition probability is prominent (7.1%), and the importance of $\left(1 - \sum_{i=1}^{N} P_{T,i-1}(I)\right)$ becomes prominent as there is a significant probability for more than one ignition taking place throughout the scenario (7.1% materializes at t=0).

The resulting total cumulative time dependent ignition probability for all equipment categories ('Rotating machinery', 'Electrical equipment' and 'Other'), assuming that the ignition sources are distributed uniformly in area, and for all ignition mechanisms is shown in Figure 10.7.

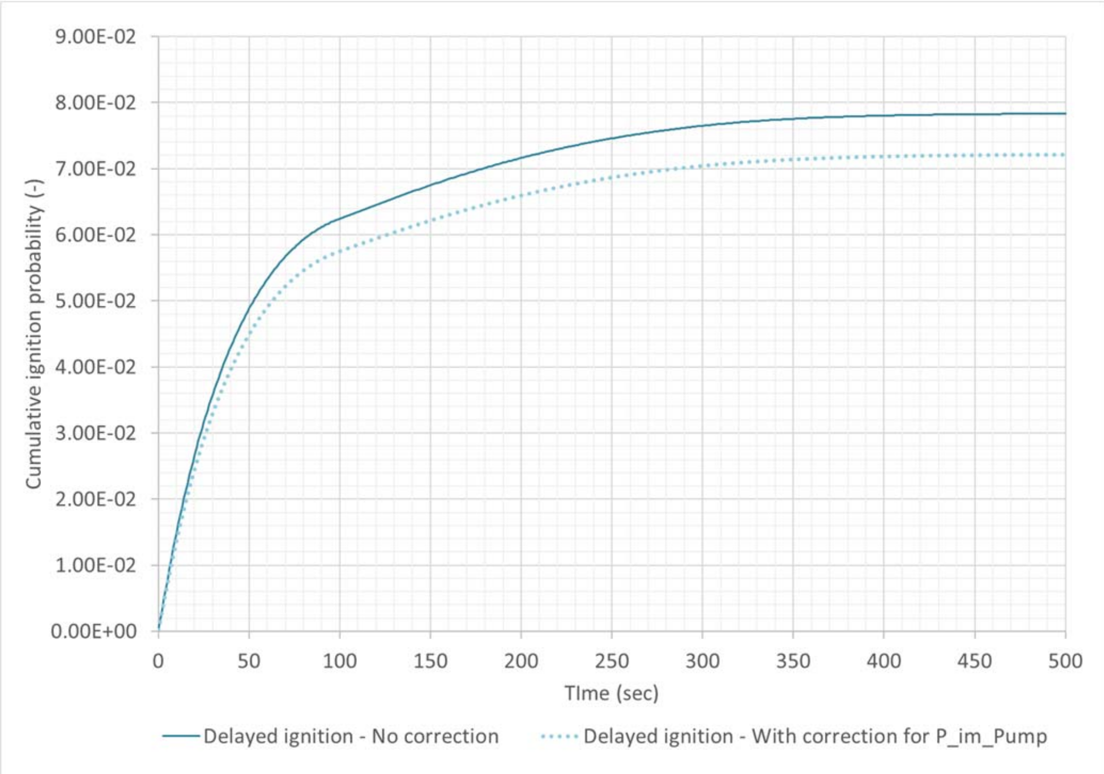


Figure 10.6 – Cumulative time dependent delayed ignition probability assuming that the leak is stemming from a pump (immediate ignition probability is 7.9%). The different curves display the effect of the term $\left(1 - \sum_{i=1}^{N} P_{T,i-1}(I)\right)$ in equation (10.6) assuming that the only contributions are $\lambda_{i,C}$, $\lambda_{i,D}$ and $P_{im,pump}$. The time step, Δt, used was 1 second

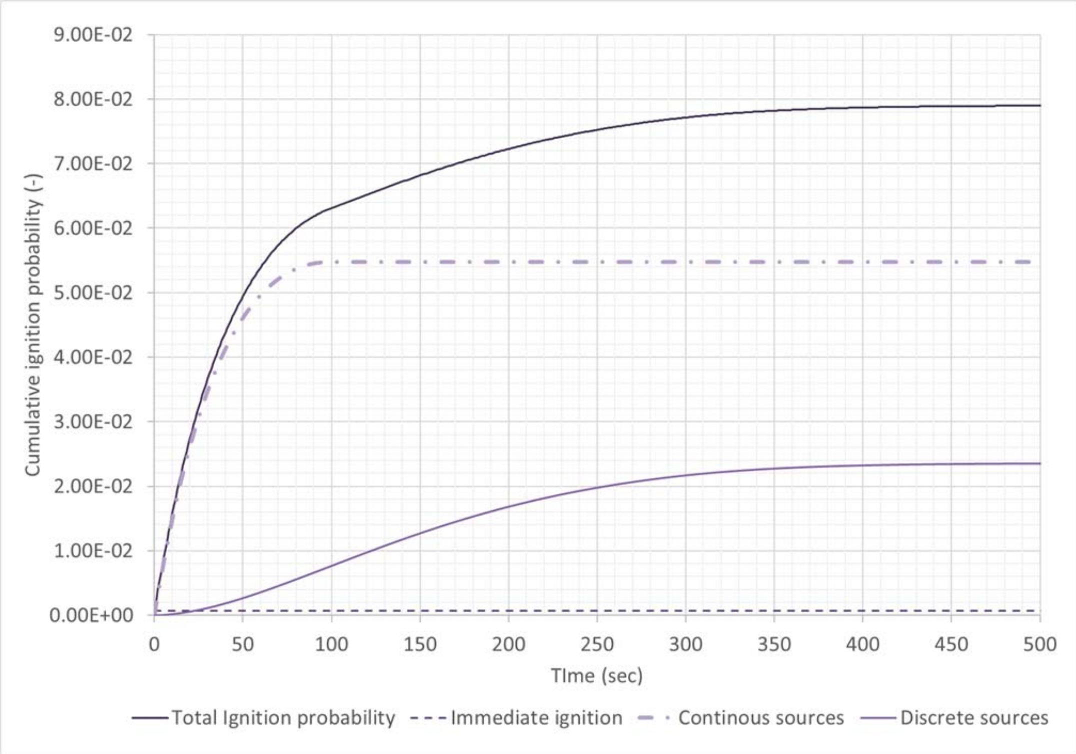


Figure 10.7 – Total cumulative time dependent ignition probability for all equipment categories and for all ignition mechanisms (using the generic probability for immediate ignition; i.e. 0.07%)

10.5 Isolation of ignition sources

If the default values of P_{iso} are used, the validity of the values used ought to be discussed as the resulting delayed ignition probability is very sensitive to the values being used. A sensitivity study should be presented in the analysis report. In general, a detailed assessment of the isolation factors (*i.e.* P_{iso}) equivalent with the methodology used in Ref. /10/ is preferred as the specific ESD shutdown logics and type of equipment being used is important for the result (ref. variability in Table 8.19). However, doing this assessment in detail requires the counting of the different pieces of equipment which is time consuming and the information required to do the equipment count may not be available. P_{iso} upon single detection for 'electrical equipment' can be implemented if adequately justified.

10.6 Free flow volume

Only the volume where potential ignition sources are present should be considered. The volume in this context is the free flow volume within the boundary of the area being studied, which is denoted V_{ff}.

For open wall boundaries, which is normally the case for one or more of the walls of wellhead and process modules on offshore installations, it is recommended to use the deck or the deck above (ceiling) as the boundary in the vertical directions.

For weather decks where there is no deck above that defines the upper boundary towards the atmosphere it is recommended to:

- use the deck (below) to define the periphery in the vertical directions
- use the periphery of the equipment plus 1 meter to define the boundary in the horizontal direction. An average elevation/height of the area could be established based on a simplified approach if appropriately justified. A too simple model may lead to underestimation or overestimation of the generic contribution

The volume occupied by objects inside the volume must be subtracted.

If there are large open areas inside the area being studied, those could be extracted from the calculation if it may be considered unlikely that ignition sources will be located in such an area. In general, open spaces normally found in an offshore module, for instance access ways, escape ways and minor storage areas, should not be excluded.

The report should clearly state how V_{ff} has been calculated.

10.7 Guideline for modelling of rotating machinery and electrical equipment

10.7.1 General

For the equipment categories 'Rotating machinery' and 'Electrical equipment' there are alternative methods developed dependent on the information available regarding the location and properties of the equipment. The resulting estimate of the ignition probability will be sensitive to the model being used, in particular for 'Rotating machinery'. Therefore, it is important to establish a solid basis for the equipment data being used, and that uncertainty related to the layout and operational time of rotating machinery should be considered at early project phases when design information is limited. Sensitivity calculations should be run in order to investigate how to account for the uncertainty when specifying the design of the safety functions at an early project stage.

10.7.2 Rotating machinery

The model allows for different approaches to calculate the contribution from rotating machinery. The full model requires that the location and corresponding operational time of all rotating machinery are known or assumed to establish a credible assumption. At an early design phase the maturity of the design of the facility in question may not allow for establishment of such an assumption. In particular, often only scarce data is available on the rotating machinery if it is not a part of the main process. Therefore, two different models for estimation of the contribution from rotating machinery are suggested. The models are defined as follows according to the information available:

I. Generic. The conditional ignition probability is calculated from the fraction related to rotating machinery per unit volume. Hence there is no correlation between the properties or the number of the actual rotating machinery and the resulting conditional ignition probability for the area in question. This model should only be used in coarse studies where there is no information of the layout with respect to rotating machinery

II. Detailed. The contribution is calculated based on the location and operational time of all hydrocarbon containing equipment (both pumps and compressors), non-hydrocarbon containing equipment (e.g. such as hydraulic pumps, produced water pumps, chemical injection pumps)) and rotating machinery. This is the recommended approach and requires the highest level of detail about the installation. In an area rooming the 1st stage compressor, one oil export pump being in operation 100% of time and two produced water pumps, of which one is always in stand-by mode, the total number of rotating machinery to be used as basis for the model becomes 3. Note that with regards to pump immediate ignition, only the oil export pump would be relevant. Only pumps resulting in a process leak according to the definition in PLOFAM are relevant for pump immediate ignition

10.8 Electrical equipment

Three different models for calculation of the contribution from 'Electrical equipment' are established. Which model to use depends upon the information that is available regarding the number and type of electrical equipment present in the area of interest. In order to calculate the ignition probability from the critical failure rate, the location as well as number and type of all electrical equipment (*i.e.* both electrical equipment and instruments) has to be known or assumed. At an early design phase, the maturity of the design of the facility in question may not allow for establishment of a credible assumption. As for platforms in operation, it is not straight forward to perform a detailed count of equipment to establish the basis for a detailed model. In such a case, a generic model using the fraction of $\lambda_{i,C}$ and $\lambda_{i,D}$ associated with 'Electrical equip-ment' should be used (denoted $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$). The three models (denoted I, II and III) are as follows:

I. Generic. The conditional ignition probability is calculated from $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$ related to 'Electrical equipment' per unit volume. Hence there is no correlation between the properties or the number of actual 'Electrical equipment' in the area and the resulting conditional ignition probability in this case
II. Combined. The contribution is calculated based on an assumed number and type of all electrical equipment per module (*i.e.* both electrical equipment and instruments). There is a model established for the calculation of the number of electrical equipment and instruments in a process module
III. Detailed. The contribution is calculated based on the actual location as well as the number and type of all electrical equipment (*i.e.* both electrical equipment and instruments)

The motivation for establishing the model based on an assumed equipment layout (*i.e*. model II), is that it allows for a more detailed risk based assessment of the design of the ignition control barrier. It is recommended to use this model instead of the purely generic model (model I) if an assumption about the design could be established with adequate precision. If the actual fraction of Zone 1 equipment is high, model I will give a somewhat high estimate of the conditional ignition probability, which consequently would lead to a conservative estimate of the fire and explosion frequency due to 'Electrical equipment'. The advantage of using model II may be more prominent if the actual fraction of Zone 2 equipment is high. In this case, $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$ may produce too lower estimate of the conditional ignition probability. In both cases, it is important that the assumption of the relative proportion of Zone 1 and Zone 2 equipment is verified along with the total number of equipment. When using model II it is also recommended to calculate the conditional probability resulting from the purely generic model (*i.e.* $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$) and evaluate the possible effect of the established assumption of the electrical equipment properties.

Based on the results for the LRP data set (see Table 8.9), the following generic parameter for calculation of number of electrical equipment and instruments per module is defined (N_{El} denotes the density of electrical equipment and instruments per unit free flow volume (see Chapter 10.6)).

$$N_{El} = 0.15\ number\ of\ Zone\ 2\ or\ Zone\ 1\ electical\ equipment\ or\ instruments\ per\ m^3_{ff}$$

On average, 0.15 should generate a somewhat too high estimate of the number of components. The number of units in the area is estimated by multiplication with V_{ff}. The fraction of Zone 2 equipment has to be assumed and appropriately justified.

The failure rates for electrical equipment are presented in Table 8.16. The generic figures for $\lambda_{i,C,E}$ and $\lambda_{i,D,E}$ relevant for 'electrical equipment' applicable to discrete and continuous ignition mechanisms respectively are presented in Table 8.8.

10.9 Gas turbine air intake

The following aspects should be adhered to when estimating the probability for ignition due to gas ingestion by a gas turbine air inlet:

- As the compressor part of the turbine will be a perfect mixer of any concentration variations in the inlet air flow, the average concentration over the entire air inlet cross section should be used when assessing the exposure probability
- The turbine will ingest a considerable amount of air, hence it is recommended to include the suction from the inlet flow in the CFD simulations if the exposure probability is based on such simulations. As a minimum, the effect of the suction should be discussed
- When gas reaches the air inlet, the turbine is shut down, normally at confirmed detection of 20 % LEL in the air inlet (2 out of 3 IR point gas detectors is a typical layout and voting philosophy). From the air inlet to the compressor air intake there is a transport time given by the distance divided by the average flow velocity in the channel. The shutdown will occur several seconds later than the time of first exposure of the air intake due to the response time of the detector and signal processing time in F&G and ESD system. The response time of gas detectors is strongly dependent on the exposed gas concentration relative to the alarm set point as well as on the detector type. If the transport time of gas from the air inlet to the turbine is shorter than the shutdown time, the turbine will be running upon initial exposed to gas, otherwise it has been shut down prior to exposure
- Exposure to gas detectors in the area prior to exposure of the gas detectors located at the air intake may have resulted in initiation of turbine shut down prior to gas exposure of the turbine air intake. With regard to the previous bullet point, this effect should be assessed specifically
- The transient behaviour of the release itself may affect the duration of the exposure, and should be reflected. For large releases, which tend to dominate the exposure frequency, the release rate may start to drop immediately after start of the release
- The consequences being generated from ignition at the specified location of the air intake should be assessed specifically. In particular, it may be the case that the explosion loads being generated are different from the loads arising on average by ignition at an arbitrary point in the area

10.10 Summary recommended model parameter values

The ignition model parameters and corresponding default values are summarized in Table 10.2.

Table 10.2 – Summary of main ignition model parameters and corresponding values

Parameter name	Parameter	Explanation	Value
Generic immediate ignition	P_{im}	Ignition that occurs immediately when leak starts and are related to the cause of the leak in some way. The value is applicable to all other equipment types than pumps	0.07%
Pump immediate ignition	$P_{im,pump}$	Immediate ignition related to pump leaks	7.2%
Ignition sources in the area	$\lambda_{i,C}$and $\lambda_{i,D}$	Ignition probability per m^3 (C) and per m^3 and seconds (D) given exposure to flammable fluid representing ignition sources that are distributed in volume of the area (described by the free flow volume, V_{ff}, see Chapter 6.10). The parameter accounts for the ignition sources found in a typical offshore process module expect those specifically modelled (such as hot work class A or a gas turbine air intake). Specific parameter values are derived for three equipment categories; 'Rotating machinery', 'Electrical equipment' and 'Other'. The values are to be used when it is assumed that the equipment is uniformly distributed in the area. For 'Rotating machinery' and 'Electrical equipment' also equipment specific conditional ignition probabilities are established (also presented below), which enable reflection of the location of the ignition sources relative to the leak sources	See below for equipment specific values
Continuous and discrete ignition probability for 'Rotating equipment' in the area, given exposure of one cubic meter free flow volume. Applies to all types of rotating equipment that may be exposed to flammable fluid. In practice this is pumps and compressors in most cases	$\lambda_{i,C,R}$	Continuous ignition mechanism	$3.7 \cdot 10^{-6}\ m_{ff}^{-3}$
	$\lambda_{i,D,R}$	Discrete ignition mechanisms	$1.5 \cdot 10^{-9}\ m_{ff}^{-3} \cdot sec^{-1}$

Parameter name	Parameter	Explanation	Value
Continuous and discrete ignition probability for 'Electrical equipment' in the area, given exposure of one cubic meter free flow volume. Applies to any electrical equipment, *i.e.* both low and high voltage as well as instruments	$\lambda_{i,C,E}$	Continuous ignition mechanisms	$1.8 \cdot 10^{-6}\ m_{ff}^{-3}$
	$\lambda_{i,D,E}$	Discrete ignition mechanisms	$1.5 \cdot 10^{-9}\ m_{ff}^{-3} \cdot sec^{-1}$
Continuous and discrete ignition probability for 'Other' equipment in the area, given exposure of one cubic meter free flow volume. Category to account for ignition mechanisms that are unknown or irrelevant for the "Rotating " and "Electrical " categories	$\lambda_{i,C,O}$	Continuous ignition mechanisms	$6.0 \cdot 10^{-7}\ m_{ff}^{-3}$
	$\lambda_{i,D,O}$	Discrete ignition mechanisms	$1.2 \cdot 10^{-8}\ m_{ff}^{-3} \cdot sec^{-1}$
Continuous and discrete ignition probability for 'Rotating equipment' in the area, given exposure of one piece of equipment. Applies to all types of rotating equipment that may be exposed to flammable fluid. In practice this is pumps and compressors in most cases	$P_{C,R}$	Continuous ignition mechanism	$3.7 \cdot 10^{-3}\ per\ unit$
	$P_{D,R}$	Discrete ignition mechanisms	$1.5 \cdot 10^{-6}\ per\ unit$
Continuous and discrete ignition probability for 'Electrical equipment' in the area, given exposure of one piece of electrical equipment. Specific values for different types of equipment denoted j.	$P_{C,E,j}$	Continuous ignition mechanism	See Table 8.16. Fraction continuous is 86%
	$P_{D,E,j}$	Discrete ignition mechanisms	See Table 8.16. Fraction discrete is 14%
Probability that isolation of ignition sources has been performed	P_{det}	Parameter to account for detection of a gas leak and initiation of ignition source control	Value calculated based on detector density in probabilistic exposure model
Effect of ignition source isolation, *i.e.* the fraction of ignition sources that is shut down upon isolation of ignition sources	P_{iso}	Fraction of ignition sources in the area that shuts down when initiation of ignition source control is initiated. Default figures upon confirmed gas detection in hazardous areas and confirmed gas detection in safe area of the installation is given, but a specific assessment/study is recommended.	See Table 8.19 for default equipment specific value

Parameter name	Parameter	Explanation	Value
Discrete sources more than 300 seconds after onset of the leak	$K_{D,300}$	Based on blow out data it is expected that probability of ignition due to exposure of discrete ignition sources decrease after more than 5 minutes after start of the release	$K_{D,300}(t) = 0.1068 \cdot t^{-0.9}$ $for\ t > \frac{5}{60} hour$
Ignition probability for hot surfaces after isolation	P_{hot}	The continuous ignition mechanism typically represents a hot surface that requires a certain cooling time from shut down until it stop being an effective ignition source.	According to half time (see (8.12)). See below for equipment specific values
Rotating machinery	$t_{hot,R}$	Half time for continuous ignition mechanisms, 'Rotating machinery'	$20\ seconds$
Electrical equipment	$t_{hot,E}$	Half time for continuous ignition mechanisms, 'Electrical equipment'	$5\ seconds$
Other	$t_{hot,O}$	Half time for continuous ignition mechanisms, 'Other'	$20\ seconds$
Free flow volume	V_{ff}	Only the volume where potential ignition sources are present should be considered. The volume in this context is the free flow volume within the boundary of the area being studied. The dimension of the free flow volume is m_{ff}^{-3}.	Value calculated based on the geometry of the area studied according to guidelines in Chapter 10.6.
Density of electrical equipment and instruments	N_{El}	Generic estimate of the number of electrical equipment and instruments per unit free flow volume	$N_{El} = 0.15\ m_{ff}^{-3}$
Conditional ignition probability for ignition upon exposure to a gas turbine air intake	P_{GTAI}	Conditional probability for ignition inside a gas turbine due to ingestion of combustible fluid leading to ignition of the external gas cloud. The probability applies to exposure at any point in time before 5 minutes after shut down of the turbine. The figure also applies to exposure before shutdown.	50%
Conditional ignition probability for ignition on diesel engine air intake	P_{CEAI}	Figure applies to stoichiometric gas without flame arrestor in the air intake. A model for adjustment according to gas concentration is provided. The suggested reduction factor associated with flame arrestor in the air intake is 0.01. See Appendix C for description of model	90%
Conditional ignition probability related to hot work	P_{HW}	The ignition probability given exposure to a hot work activity.	See Table 9.2

Parameter name	Parameter	Explanation	Value
Conditional ignition probability related exposure to enclosure air intake	P_{AI}	Ignition due to gas migration through an enclosure air intake	Specific assessment required. Typically governed by SIL rating of gas tight damper. See Chapter 9.5.
Generic conditional ignition probability for non-Ex equipment in unclassified areas	$P_{G,non-Ex}$	Generic conditional ignition probability given exposure of an unclassified area in general containing non-Ex equipment to flammable gas	Exposed volume to combustible gas ($V_{exposure}$) less than or equal to 9,000 m^3: $P_{Non-Ex} = 0.001 \cdot V_{exposure}$ Exposed volume to combustible gas ($V_{exposure}$) larger than 9,000 m^3: $P_{Non-Ex} = 0.9$
Conditional ignition probability Non-Ex equipment	P_{non-Ex}	Specific assessment required.	Not applicable.
Generic conditional ignition probability for massive exposure of supply vessels	P_{vessel}	Subsea gas releases and splash zone gas releases can be ignited by supply vessels. Potential ignition sources are outdoor non-Ex equipment, such as lighting fixtures, and the air intake to the engine.	50%
Generic conditional ignition probability for exposure to flare	P_{flare}	Exposure to flare (open flame)	100%

11 Evaluation of uncertainty and model testing

11.1 Introduction

This chapter discusses the uncertainty associated with the model prediction. It is important that the uncertainty is communicated effectively to decision makers when describing the analysis based on the MISOF report.

11.2 Total ignition probability in hazardous area

As described in Chapter 7.7, it is hard to exactly determine the underlying ignition probability for the population. We can only estimate the likelihood that the underlying ignition probability is within a certain range based on observed unignited and ignited leaks combined with our corresponding interpretation of these incidents.

The basic premise for parameterisation of the model is that the likelihood for observing the observed number of ignited leaks, or fewer, is 50% (see Chapter 7.7). We do not know the underlying ignition probability, but we assume that the underlying probability result in equal probability for observing fewer or more ignited events than the number of expected ignited events corresponding to the underlying ignition probability. This is considered to be a reasonable prediction of the best estimate considering the single observation we have at our disposal (3 ignited events out of 1133 leaks). Moreover, this approach will result in a model aiming at the best estimate slightly from the conservative side (*i.e.* the distribution is skewed). Obviously, a different confidence level could have been chosen that could have added conservatism to the model.

For instance, one could judge that the number of observed ignited leaks is an extreme observation, either unfortunate or fortunate, relative to the underlying ignition probability. Figure 11.1 shows the binomial distribution for the ignition probability generating 10% probability for observing more than 3 ignited leaks out of 1,133 leaks. In this case, it is assumed that the number of ignited events is unfortunate relative to the actual underlying probability. The ignition probability becomes 0.15%, which is about 50% of the base probability of 0.32% used for parameterisation of the model. The corresponding distribution for an equivalent fortunate scenario is shown in Figure 11.2. This is the binomial distribution for the ignition probability generating 10% probability for observing 3, or fewer, ignited leaks out of 1,133 leaks. Here it is assumed that the observed number of ignited leaks is fortunate relative to the actual underlying probability. The resulting estimate of the underlying ignition probability becomes 0.59%, which is roughly a factor of 2 larger than the base ignition probability (0.32%).

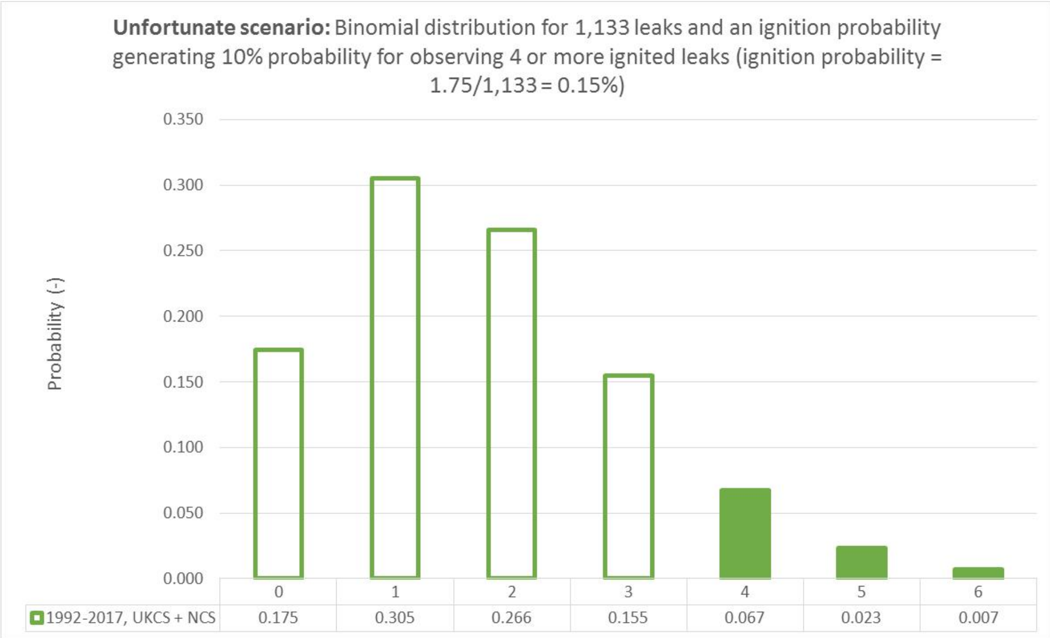


Figure 11.1 – Binomial distribution for the ignition probability (immediate plus delayed) generating 10% probability for observing more than 3 ignited leaks out of 1,133 leaks occurring at installations located on UKCS and NCS in the period 2001-2017 (ignition probability becomes 0.15%)

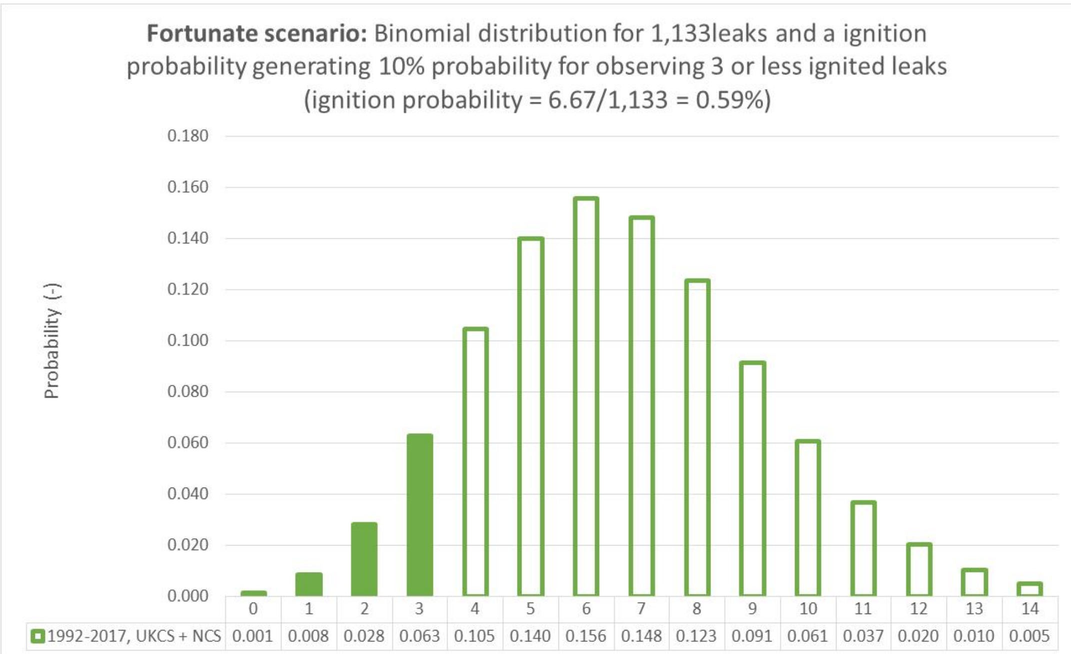


Figure 11.2 – Binomial distribution for the ignition probability (immediate plus delayed) generating 10% probability for observing 3, or fewer, ignited leaks out of 1,133 leaks occurring at installations located on UKCS and NCS in the period 2001-2017 (ignition probability becomes 0.59%)

By varying the probability for observing the number of ignited leaks, a continuous distribution displaying the variability in p (underlying ignition probability) can be calculated. The results for 3 ignited leaks in 1133 leaks are shown in Figure 11.3, which is hereafter denoted the ignition probability distribution for p given that 3 ignitions are observed. The results reveal that it is more likely that the underlying ignition probability is less than the base ignition probability (0.32%), *i.e.* the highest probabilities are found for underlying ignition probabilities less than 0.32%.

Figure 11.4 shows the same curve as in Figure 11.3 together with the corresponding curve for 0, 1 and 2 ignited leaks out of 1133 leaks, and in addition the probability of observing n leak or less (1,2 and 3 leaks or less) are included as dotted curves. The black, blue and red dots show the underlying ignition probability corresponding to a 90%, 50% and 10% probability of observing n leaks or less. The ignition probability corresponding to 50% probability of observing 3 ignitions or less corresponds to the base assumption (0.32% ignition probability) while the extreme scenarios presented in Figure 11.1 and Figure 11.2 are also marked (respectively: ignition probability of 0.15% corresponding to 90% probability for 3 or fewer leaks in the period and ignition probability of 0.59% corresponding to 10% probability for 3 or fewer leaks in the period). The result shows that the likelihood for observing 3 or less ignited leaks is remote assuming that the ignition probability is less than 0.05%. Likewise, the likelihood for observing more than 4 ignited leaks is remote given an ignition probability beyond 1%. The results are summarized in Figure 11.5 where the underlying ignition probability corresponding to 90%, 50% and 10% probability of observing n (n=0, 1, 2 and 3) ignitions or less out of 1133 leaks are given.
Figure 11.6 shows the ratios 50%/90% and 10%/90%, i.e. the underlying ignition probability corresponding to 50% relative to 90% probability of observing n or fewer ignitions out of 1133 leaks and the underlying ignition probability corresponding to 10% relative to 50% probability of observing n or fewer ignitions out of 1133 leaks.

The results for 1 and two ignitions in the below figure can be used to assess the underlying ignition probability also for delayed ignitions where only 1 ignition is observed and immediate ignitions where 2 ignitions have occurred.

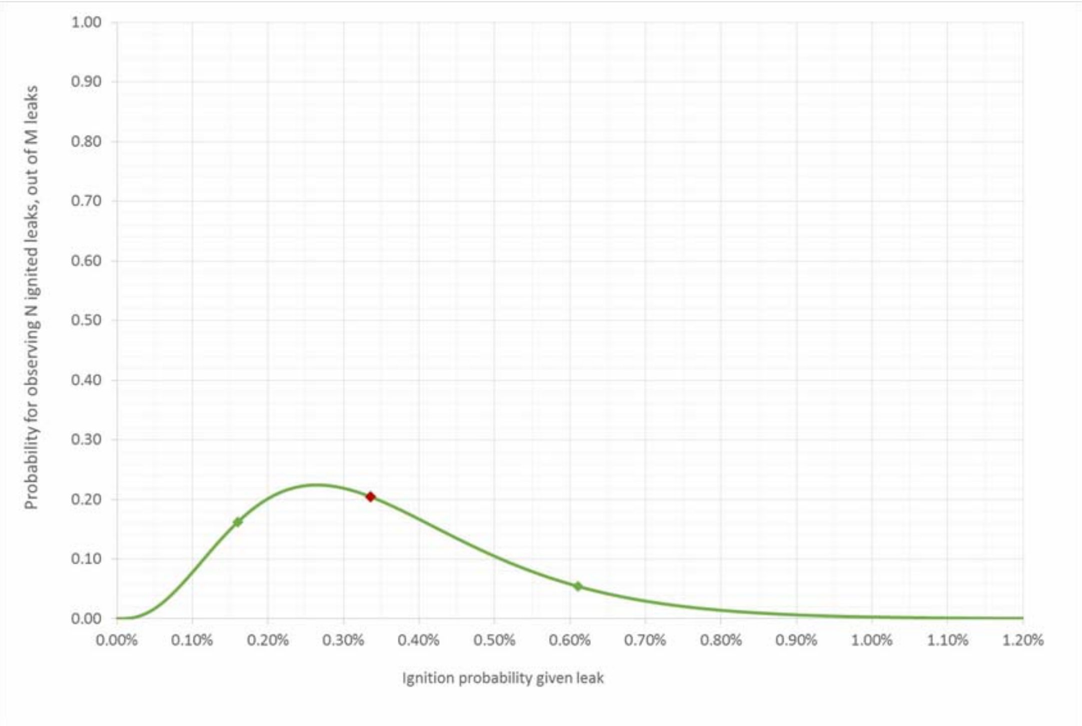


Figure 11.3 – The probability for observing the number of observed ignited leaks (3) out of 1,133 leaks as function of p (estimate of the underlying ignition probability due to immediate and delayed ignition) based on the binomial distribution. The ignition probabilities corresponding to a probability of 90%, 50% and 10% for observing 3, or fewer, ignited leaks are marked with tile type marker

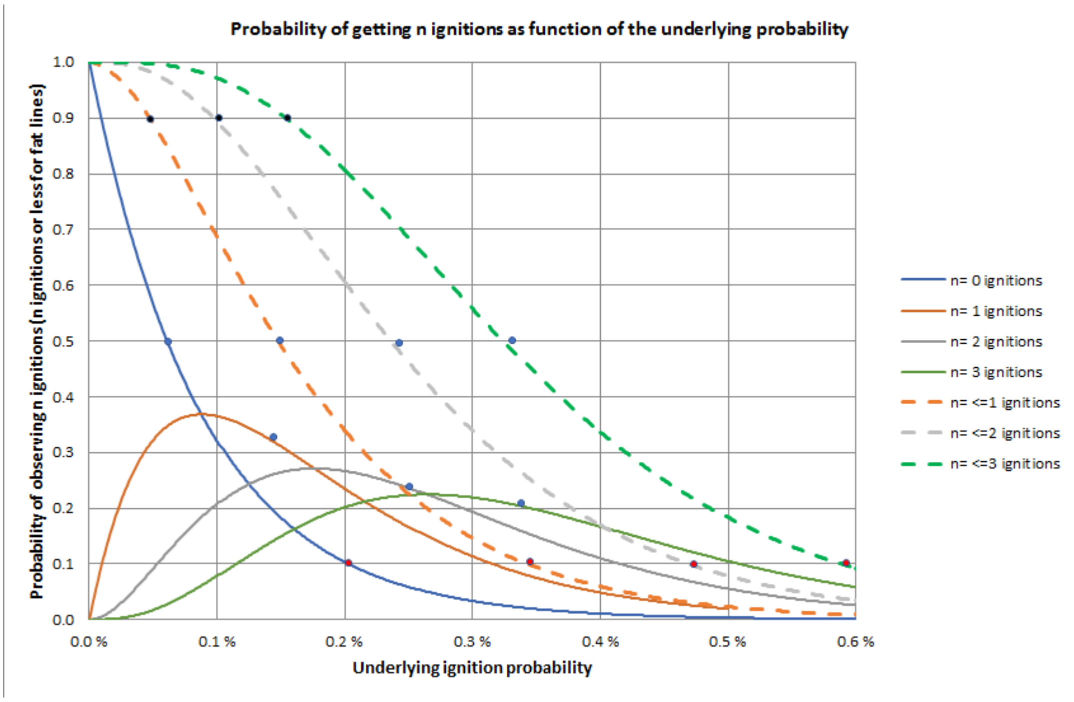


Figure 11.4 – The probability for observing 0, 1, 2 and 3 ignitions out of 1133 (full line), and the probability of observing 1, 2 and 3 leaks or fewer, out of 1,133 leaks as function of p (estimate of the underlying ignition probability due to immediate and delayed ignition) based on the binomial distribution. The underlying ignition probabilities marked with black, blue and red dots correspond to the underlying ignition probabilities giving 90%, 50% and 10% probability of observing n (n=1, 2 or 3) leaks or less

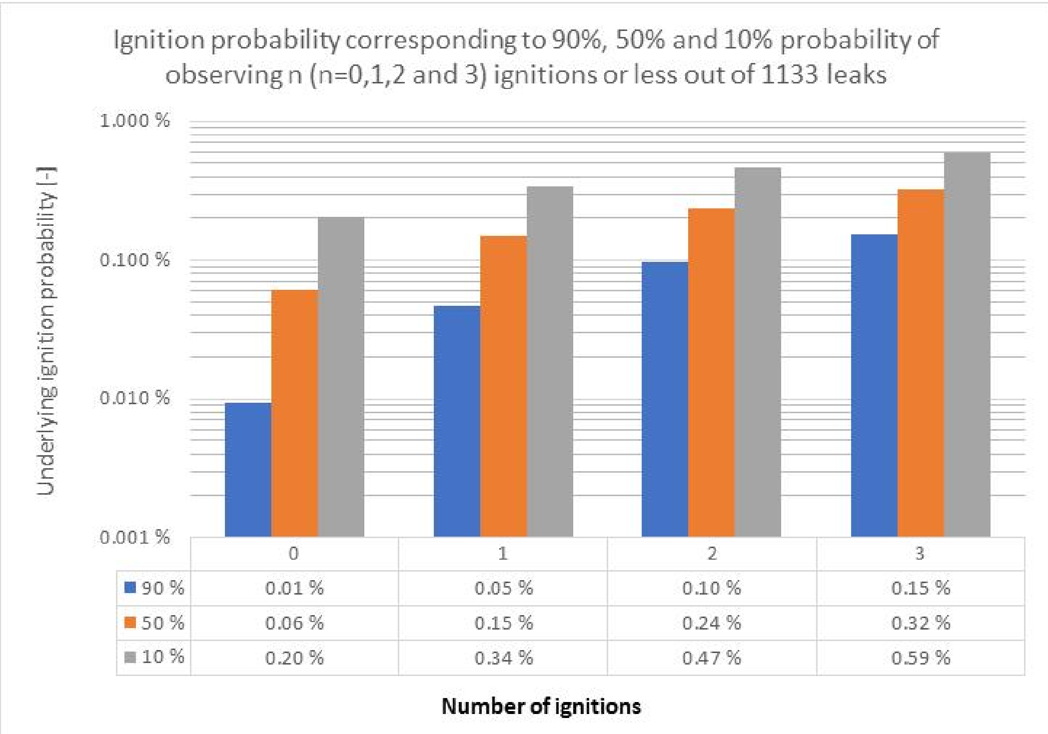


Figure 11.5 – Underlying ignition probability corresponding to 90%, 50% and 10% probability of observing n (n=0, 1, 2 and 3) ignitions or less out of 1133 leaks

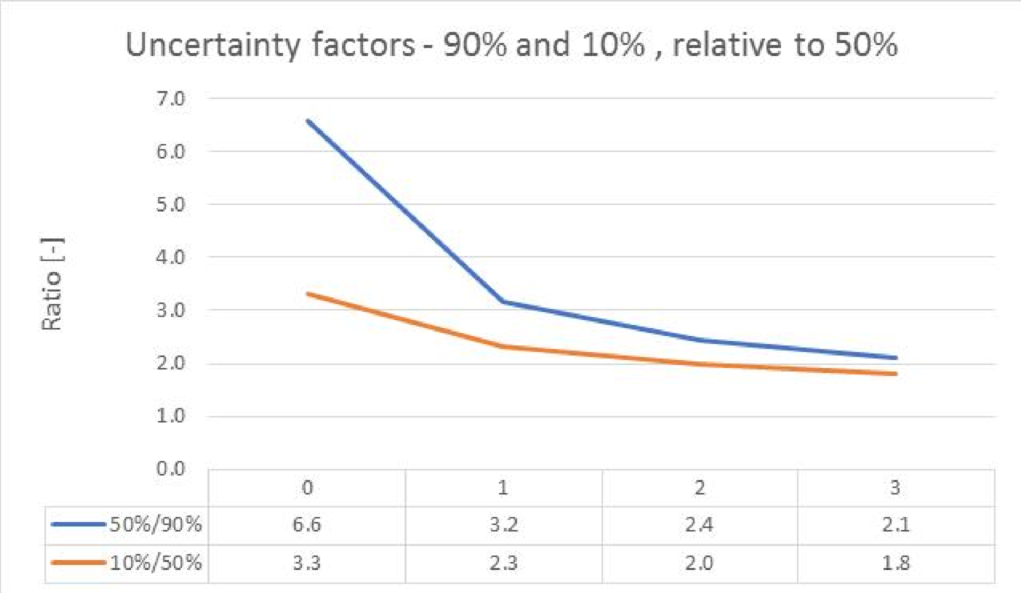


Figure 11.6 – Underlying ignition probability corresponding to 50% relative to 90% probability of observing n or fewer ignitions out of 1133 leaks, and the underlying ignition probability corresponding to 10% relative to 50% probability of observing n or fewer ignitions out of 1133 leaks

The ignition probability distribution for the base dataset along with two extreme subsets, in terms of number of leaks per ignited leak, is shown in Figure 11.7. The distribution for the base ignition probability (derived for the period 1992 – 2017 for installations on UKCS and NCS) shows that the underlying probability can be expected to be (approximately) limited by the interval 0.05 – 0.8%. The most likely ignition probability is around 0.3%, which is the average for the population (0.265% = 3/1,133).

The number of observed ignited leaks per leak after the year 2000 on UKCS installations also demonstrates a comparable underlying probability of 0.32% (observing 3 ignited leaks out of 327 leaks given an ignition probability of 0.32%). The fact that we have observed 3 ignitions at UKCS installations after 2000 can be explained by stochastic effects only. Moreover, no casual arguments have been found which point towards a drift in the performance of the ignition control barrier in the UKCS (or NCS installations) supporting a time trend in the underlying ignition probability. In fact, there is an important argument for a decreasing trend. The ATEX directives were introduced in 2003 to protect employees from explosion risk in areas with an explosive atmosphere.

For the NCS data sets (0 observed ignited leaks in the entire period starting 1992), the distribution indicates that the underlying ignition probability is zero for installations at NCS but this is not in accordance with what we would expect in practice. Obviously, the interpretation of these results is tied to our assessment of the quality of the various data sets and the phenomena being observed. Hence, any conclusion established using the data must be accompanied with sound engineering judgement.

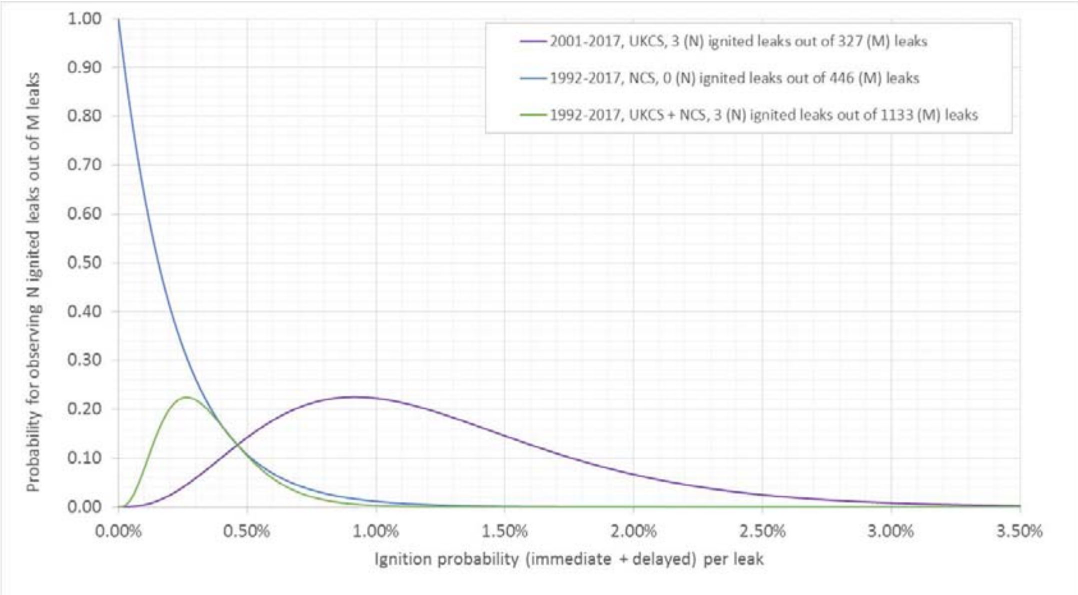


Figure 11.7 – The probability for observing N number of observed ignited leaks out of M total leaks as function of p (estimate of the underlying ignition probability due to immediate and delayed ignition) based on the binomial distribution. The results are shown for the base dataset (UKCS and NCS for the period 1992-2017) and for two extreme subsets in terms of number of leaks per ignited leak

Based on the above discussion and results, the ignition probability distribution for the entire observation period (1992 and onwards) for all installations (the green curve in Figure 11.7) can be considered to be the best representation of the variability related to the underlying ignition probability due to immediate and delayed ignition. It is important to note that is it assumed that there is no underlying time trend in the data and that there is no difference between UKCS and NCS installations. Therefore the most likely ignition probability is around 0.3%.

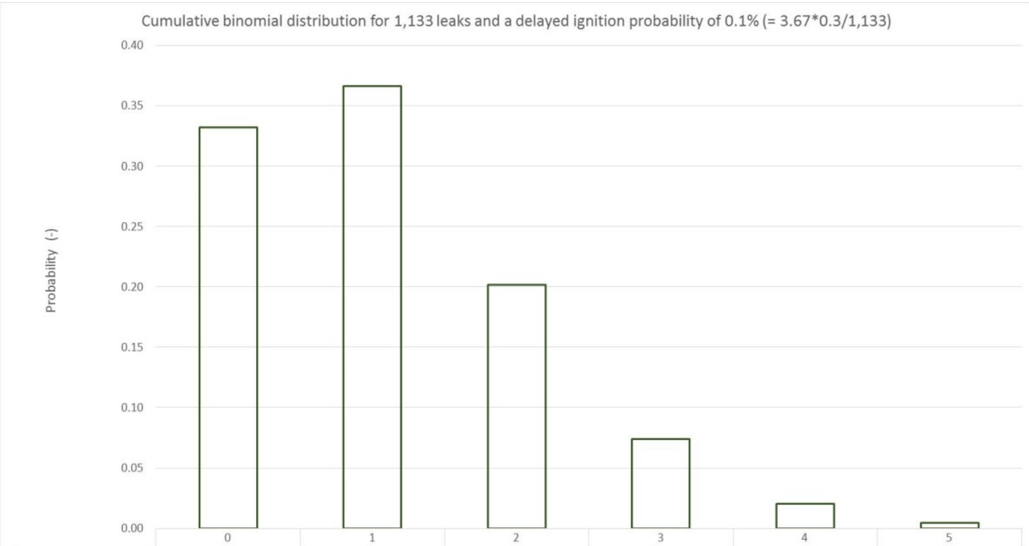
It is considered reasonable to use a probability level of 10% to determine the likely interval for the underlying ignition probability. Applying the ignition probability distribution for observing 3 ignited leaks, or fewer, out of 1,133 (see Figure 11.4), it is concluded that the total underlying ignition probability due to immediate and delayed ignition on installations is expected to be in the interval 0.15% to 0.6 % (see Figure 11.5) corresponding to a factor 2 higher and lower than the ignition probability but as basis for MISOF (see Figure 11.6). Note that the given interval applies for the average underlying ignition probability for all installations located in the NCS and UKCS. Considering the individual installations, the variability will be greater than the stated interval. However, the relative variability per installation is expected to be proportional with the variability around the expected value for the average underlying ignition probability.

This uncertainty should be communicated in a quantitative risk analyses based on PLOFAM and MISOF models to ensure that well informed risk based decisions are made. This is to ensure that cost driving measures based on the QRA are implemented acknowledging that the actual underlying fire and explosion frequency may be a factor of higher or lower than estimated in the QRA (presumed that the guidelines, see Chapter 10, for use of the MISOF are followed).

It is interesting to consider events at land based facilities. Leaks at land based facilities in Norway processing oil and gas have been reported systematically in the period 2006 onwards (Ref. /16/). The total number of relevant leaks with an initial leak rate above 0.1 kg/s is somewhat above 50 leaks. As far as we understand, based on Ref. /16/, none of the leaks relevant in the context of MISOF (*i.e.* PLOFAM leaks from process systems in hazardous area) did ignite. This provides additional confidence to our statement that the total ignition probability used to parameterise the MISOF model is most likely less than 0.32%.

11.2.1 Delayed ignition in hazardous area

An interval for the delayed ignition probability corresponding to the stated interval for the total ignition probability cannot be established with the same accuracy. Obviously, the interval for the delayed ignition probability is a subset of the interval for the total ignition probability, but the uncertainty associated with the factors deciding the subset is hard to assess. Figure 11.8 displays the binomial distribution using the 30% fraction (see Chapter 8.4.2) to determine the delayed ignition probability. The results show that the likelihood for observing more than 1 delayed ignition is low (about 30%) given the model. One of the observed leaks (HCR ignition ID 208 in Table 7.1) may have been ignited due to delayed ignition mechanisms. Hence, the model parameters are based on that 0 or 1 of the ignited leaks were due to delayed ignition mechanisms, which is consistent with the results using the binomial distribution. The binomial distribution also demonstrates that within the model (*i.e.* a delayed ignition probability of 0.10%), also 2 ignitions would be quite likely. This means that one leak being ignited due to a delayed ignition mechanism in the near future would not imply that the MISOF model parameters should be discarded.



	0	1	2	3	4	5
2001-2017, UKCS + NCS	0.33	0.37	0.20	0.07	0.02	0.00

Figure 11.8 – Binomial distribution for a delayed ignition probability of 0.1% and 1133 leaks occurring at installations located in the UKCS and NCS during the period 1992-2017

Despite the uncertainty of the methodology, a best estimate approach has been used to set the factors required to derive the parameters for the modelling of delayed ignition in MISOF. The motivation is to avoid any bias that may reduce the accuracy in the representation of the ignition control barrier elements affecting the explosion risk picture. The important factors adding uncertainty in this regard include:

- The 30% fraction of observed ignited leaks allocated to delayed ignition mechanisms. The recorded incidents indicate a fraction of 30% (see Chapter 8.4.2), but the fraction could both be higher and considerably lower. An interval of 15% to 50% enveloping the fraction of ignited leaks categorised as delayed is a reasonable representation of the uncertainty. Data presented in Chapter 7.6 indicates that 30% may be an overestimation of the contribution from delayed ignitions
- The distribution of the fraction of delayed ignition with respect to equipment type and general ignition mechanisms (*i.e.* continuous vs. discrete)

- The estimate of the exposed volumes, denoted $V_{LEL,max}$ and $VT_{LEL:UEL,avg}$ (see Chapter 7.4 and Appendix A). This is a key factor adding uncertainty to the estimation of the model parameters. A quite coarse model is used to estimate the aggregated volume parameters for all leaks, except for a few cases where CFD simulations of the leaks were available. A study investigating the vapour cloud arising in each of the recorded leaks, by use of an appropriate CFD tool (*e.g.* Kameleon FireEx KFX® or FLACS®), would reduce the uncertainty significantly. Such a project suggestion is included in Chapter 13 for future work to enhance the accuracy of the model
- The adjustment factor of exposed volume to account for isolation of ignition sources, *i.e.* F_{adj} (see equation (8.1))
- The free flow volume per rotating machinery (see Table 8.10)
- The ramp down model for discrete ignition mechanisms (see Chapter 8.5.3)
- The definition of immediate ignition is vague. In a CFD based explosion risk assessment, explosion scenarios will often be evaluated for very early ignition when the cloud size is marginal. Scenarios within the first 1-5 seconds from start of the release would likely be defined as immediate ignition in the statistics; however, they would be classified as delayed ignition frequency in the explosion study. For this reason, the assumed delayed ignition probability should preferably be somewhat higher than, not lower than, the best estimate from statistics. Taking this into account the chosen fraction of 30% is judged to be reasonable
- The idealisation of the actual ignition mechanisms (discrete and continuous) in the model (see section 6.11)

The uncertainty associated with all of these factors is an important argument for implementation of some conservatism in the base ignition probability. The delayed ignition probability is crucial for the explosion frequency pressure exceedance curve within a explosion risk analysis. Underestimation of this explosion load distribution could lead to insufficient design of the barriers controlling explosion risk.

It is judged that the MISOF parameters for the modelling of delayed ignition probability ensure that the model estimate is somewhat above or close to the underlying probability for delayed ignition. This is providing the quality of the exposure probability model is in accordance with the guidelines and it is tailored for the objective of the particular study. It is crucial that the exposure model captures the physics of the phenomena, the geometrical layout with adequate precision and that the model reflects the ignition control barrier elements appropriately (see Chapter 10.4).

It is important to note that the delayed ignition parameters in MISOF are derived from actual leaks occurring at installations in the North Sea. The duration of a large fraction of actual leaks tends to be shorter than the standard leak scenario modelled in a QRA, as other barriers than the ESD/PSD and BD valves limits the inventory being released. Other barriers in this context are physical barriers such as control valves, check valves or reciprocating pumps, but in many cases, the shorter duration results from operator intervention. Here it must be noted that for entries in the database (both leaks in the UKCS and NCS) where the duration is unknown, a cut off aligned with what is observed for the actual leaks has been implemented (typically 300 seconds, see Appendix A). The estimate of $VT_{LEL:UEL,avg}$ does therefore result in an estimate of $\lambda_{i,D}$ that corresponds to leaks having shorter duration than normally modelled in a QRA. Hence, in order to perform a consistent validation of the delayed ignition probability towards the historical ignition probability, the probabilistic exposure model should be based on leaks with a shorter duration than leak scenarios only controlled by the ESD/PSD and BD valves.

This means that a leak scenario modelled as in QRAs, where the full inventory is emptied (but taking ESD and blow down into account) will generally add a contribution to the delayed ignition probability in the late phase of the leak scenario. This is however not representative for a large fraction of actual leak scenarios. In a probabilistic model in a QRA based on PLOFAM, the duration of the leak scenario is based on a spontaneous leak occurring during normal operation, where only the ESD/PSD and BD valves limits the loss of containment. The motivation for this approach is to rather focus on investigation of the performance of the loss of containment and ignition control barrier elements, and not on the estimation of the actual fire and explosion frequency observed in industry. The effect of leaks with longer duration in QRA's is hard to quantify, and will be also be very dependent on the exposure probability model used. A ramp down model (see Chapter 8.5.3) for discrete ignition mechanisms has been implemented to partly account for this effect. The justification for the ramp down model is mainly to account for the effect of reduction in ignition sources versus time. Note that the additional delayed ignition probability generated by the longer leak duration ultimately will affect the explosion loads through increased probability for ignition of large vapour clouds.

Overall, the properties of the exposure probability model are considered to be more important for the uncertainty related to the estimate of the delayed ignition probability than the uncertainty related to the parameters set in MISOF. If an exposure probability model is used in accordance with the guidelines, it can be argued that the explosion frequency generated by the MISOF and PLOFAM models represents a best estimate.

11.2.2 Objects not intended for use in explosive atmosphere

The available data cannot be used to perform a quantitative assessment of the accuracy of the MISOF conditional ignition probabilities for equipment not intended for use in explosive atmospheres, such as gas turbine air intakes and supply vessels. The conditional ignition probabilities for these items have been set based on a best estimate approach. Thus, no conservatism is implemented. The uncertainty associated with the estimated ignition probability related to such objects generated in QRA, is very much dependent on the quality of the exposure probability model. Many of these types of objects are located outside the hazardous area where the leak takes place. In most cases, only models that can represent the flow pattern between the leak source and the ignition source, in a probabilistic context, are available to generate reasonable estimates of the exposure probability. This also applies to such objects located inside the hazardous zone (*e.g.* hot work), where the geographic location of the objects becomes important. The contribution from objects not intended for use in explosive atmospheres constitutes in many cases the dominant contribution. Hence, it is crucial that any study based on MISOF carefully evaluates the required precision of the exposure probability model. Simple exposure probability models (based on integral dispersion models, or inadequate interpolation/extrapolation of results extracted from CFD simulations) may both overestimate or underestimate the total ignition probability but more importantly, simple models may not be able to generate the appropriate understanding of how to improve the barriers affecting the risk picture. This statement also applies with respect to the exposure probability model for estimation of the delayed ignition probability in hazardous areas.

11.2.3 Overall evaluation of robustness

The assessment of the uncertainty has demonstrated that the MISOF model parameters are, on average, expected to generate a best estimate of the total ignition probability resulting from immediate and delayed ignition in hazardous areas. This is based on a statistical analysis of the available recorded data used as basis for the model. The model for the conditional ignition probabilities related to objects not intended for use in explosive atmospheres is also set based on a best estimate approach. Hence, there is no built in conservatism in the conditional probabilities in MISOF.

The robustness of the estimate of the total ignition probability is demonstrated in Figure 11.9 based on the MISOF and PLOFAM models. Considering the total observation period for both leaks in the UKCS and NCS (*i.e.* 1992-2017), the MISOF default parameters combined with the PLOFAM leak frequency model generates an expected number of 3.7 ignited leaks. The number of observed ignited leaks in the same period is 3. Looking at leaks in the NCS, the model predicts 1.4 ignited leaks (1.4 = 228.8 leaks·0.32%), which means that the models account for more than one ignited leak occurring in the near future at an installation located in the NCS. However, such a perspective is only relevant if one considers installations in the UKCS and NCS to be different in terms of ignition control.

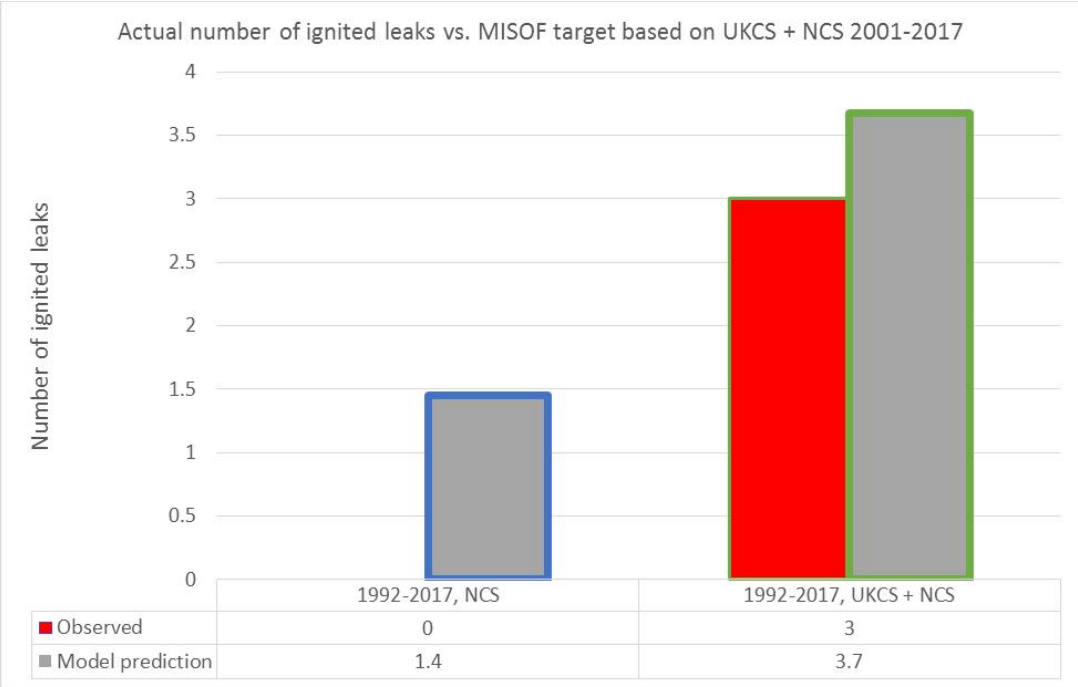


Figure 11.9 – Ignition in hazardous areas: comparison of observed number of ignited leaks vs. MISOF model prediction for the various data subsets

The uncertainty associated with the estimation of the delayed ignition probability (both due exposure to objects intended for use in explosive atmospheres and objects not designed for use in explosive atmospheres) is dominated by the quality of the exposure probability model. It is therefore paramount that the exposure probability model used is aligned with the objective of the study being performed. The uncertainty associated with the derivation of the MISOF delayed ignition parameters can be significantly reduced by running a project improving the estimate of the factors used to parameterise the delayed ignition conditional probabilities. The scope of work for such a project is described in Chapter13.

In general, the uncertainty associated with ignition probability modelling based on MISOF can be considered to be quite limited if the guidelines are adhered to. The likely interval for the underlying ignition probability is quite limited (*i.e.* 0.15 – 0.6% for ignition in hazardous areas, but somewhat wider for objects not intended for use in explosive atmosphere). Continued efforts to record leaks in the future will provide a basis for an even lower uncertainty in estimation of the model parameters. This is demonstrated in Figure 11.10 where the shift in variability is shown assuming properties of future entries (6 ignited leaks in 2,186 leaks, and 3 ignited leaks in 2,186 leaks). The variability around the most likely underlying ignition probability is considerably less for 2,186 leaks opposed to 1,133 leaks. The effect is the same if the number of future ignited leaks changes. Therefore future updates of MISOF will provide a basis for establishing risk models with reduced uncertainty.

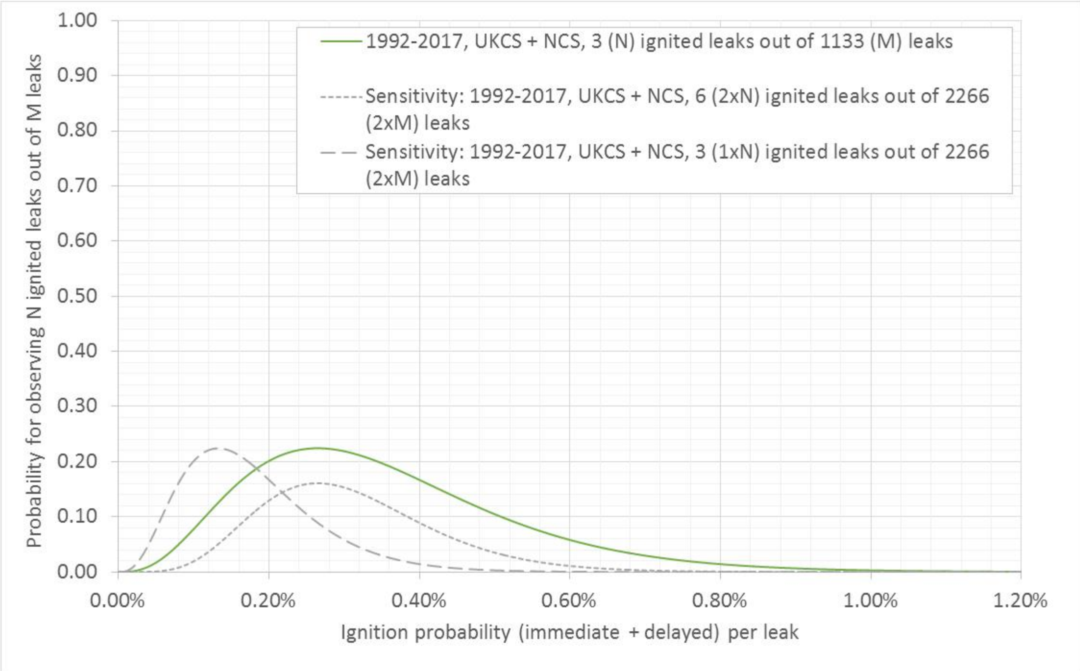


Figure 11.10 – The probability for observing N number of observed ignited leaks out of M leaks as function of p (estimate of the underlying ignition probability due to immediate and delayed ignition) based on the binomial distribution. The results are shown for the main dataset used for parameterisation and assumed outcomes in the future based on this dataset

11.3 Testing of model

11.3.1 Introduction

The MISOF model has been tested for a set of generic offshore modules in order to investigate the performance with respect to the observed historical fire and explosion frequency in the North Sea applying the model in combination with the PLOFAM leak frequency model described in Ref. /1/. The caption 'PLOFAM2' is used in the figures below to denote that rev. 2 of the PLOFAM model issued in December 2018 has been applied.

In addition, the tests were rerun based on the previous probabilistic leak frequency and ignition models used in the industry in Norway, *i.e.* the model described in the report "Offshore QRA – Standardised Hydrocarbon Leak Frequencies" (SHLFM) and the ignition model described in "Ignition modelling in risk analysis" (denoted OLF model). Testing of these models was included for comparison with the superseding models (PLOFAM and MISOF). It must be emphasized that the SHLFM and OLF are not recommended to be used for estimation of the fire and explosion risk at offshore installations. Both models deviate much from the observed historical data and our understanding of the performance of the barriers affecting the risk. Hence, the SHLFM and OLF models are to be considered obsolete.

In order to calculate the ignition probability, a dispersion model that estimates the probability for exposure to live ignition sources is required. In this study, the fully coupled ignition model in the CFD simulator Kameleon FireEx KFX® has been used. The model is a part of the risk modelling feature denoted Kameleon FireEx KFX® Risk & Barrier Management (KFX-RBM) developed by ComputIT.

3 generic offshore modules were established to study the importance of the geometrical layout for the estimated fire and explosion risk. The generic modules envelope the typical size of offshore modules located at the NCS, ranging from 4,000 to 40,000 gross m^3. The ventilation conditions in terms of openness of peripheral walls represent typical layout found at offshore installations. The modules are described in Table 11.1.

It should be noted that the modules studied are considered to on average represent rather unfavourable designs in terms of explosion risk, i.e. due to quite poor global ventilation conditions and gas turbine air intakes located in the vicinity of the edge of the process modules. The estimated explosion risk using PLOFAM and MISOF is therefore expected to be less for many equally sized modules in the North Sea.

The tests are presented in detail in Appendix D.

Table 11.1 – Description generic modules used in study

Module	Size	Open walls	Equipment
CM42EW	30 m x 15.9 m x 8.25 m	Two shortest walls open. Solid deck and roof.	One separation train Anticipated equipment 4 pumps
CM132EW	52 m x 24.9 m x 10.25 m	Two shortest walls open. Solid deck and roof.	Two separation trains including 1st stage scrubber Anticipated equipment 12 pumps
CM402EW	74.7 m x 52 m x 10.25 m	Two longest walls open. Solid deck and roof.	Six separation trains including 1st stage scrubber Anticipated equipment 36 pumps

11.3.2 Summary results

The following summarize important findings in the study:

- The generated total fire frequency will be considerably lower using the upgraded models. The leak frequency generated by the PLOFAM model is considerably lower than the leak frequency estimate generated by the SHLFM model, especially for large leaks. The large reduction in leak frequency moving from SHFLM to PLOFAM outweighs the significant increase in ignition probability generated by MISOF. Based on these results, it is expected that the new models will generate lower fire frequencies in most cases. Hence, PLOFAM-MISOF will produce lower risk figures in terms of risk metrics measuring consequences due to fires, for example impairment of escape ways due to smoke and escalation to pressurized equipment or structures. This is illustrated in Figure 11.11
- The dominant contribution is expected to result from large leaks generating a rapidly expanding gas cloud materialising ignition due to continuous sources within short time after start of the leak (within 1 minute after start of the leak). This is illustrated in Figure 11.12. This is because the continuous ignition mechanisms are the dominant contribution in the idealised ignition mechanisms modelled in MISOF. Large leaks that generate big gas clouds within a few seconds drive the explosion risk according to the model. The continuous ignition mechanism is materialized upon first time exposure, and the effect of the safety functions is relatively small within the initial half a minute or so. This general effect of MISOF does also imply that the modelling of large leaks is in many situations critical for the accuracy of a QRA
- A sensitivity study varying the weight on discrete vs. continuous sources in MISOF demonstrates the underlying uncertainty in the modelling approach. The discrete and continuous ignition mechanisms implemented in the model are imperfect idealisations of what is taking place in practice. More effort should therefore be put in understanding actual failure modes to improve the basis for the applied idealisation in the model. Acquired knowledge on this issue in the future will hopefully provide basis for reducing the uncertainty with respect to how to idealise the actual ignition mechanisms in the ignition model

- P_{iso}, reflecting isolation of equipment upon gas detection, has a profound effect on the result. Hence, it is crucial that applied value for P_{iso} is representative for the installation being studied. This is illustrated in Figure 11.13 for the intermediate module in terms of size (CM132EW), where the fraction isolated is increased with a factor of two relative to the base case ('CM132EW PLOFAM-MISOF' vs. 'CM132EW PLOFAM-MISOF-Piso*0.5'). A similar effect is observed for the smaller and bigger modules
- Specific modelling of the location of special ignition sources, such as pumps, compressors and gas turbine air intakes, may have a significant effect on the resulting distribution of ignited gas clouds.
- In unfavourable cases, the contribution from gas turbine air intakes may constitute the major contributor to fire and explosion risk. This is illustrated Figure 11.14. The location of the gas turbine air intakes is very unfavourable in this example, but there are a few installations in industry where such layouts have been implemented. Furthermore, it should be noted that (1) such solutions do not violate the safety requirements as long as the air intake itself is located outside the hazardous zone, (2) potential ignition mechanisms causing ignition when combustible gas is ingested by a gas turbine is not fully understood (Ref. /14/) and (3) the risk could be mitigated by implementation of measures (Ref. /14/)
- The resulting total and delayed ignition probability (see Figure 11.16 and Figure 11.17) as well as the dimensioning pressure (*e.g.* based on tolerance criterion of 10^{-4} per year) increase with increasing module size. In addition to the increased leak frequency in bigger modules (more process equipment in a bigger module), the driving effect is that a gas cloud is allowed to expand more freely in a large module. This is however only the case for leak rates where the expansion of the gas cloud is hampered in the smaller module. A larger gas cloud will expose more potential ignition sources (*e.g.* additional electrical units and/or running pumps), which lead to a higher accumulated ignition probability in the MISOF model (and also the OLF model)
- The effect that a bigger module is expected to result in higher explosion risk than a smaller module is not a general argument for dividing a big module in smaller modules. Such a design will in many cases reduce the ventilation rate in the smaller modules relative to the big module generating larger gas clouds for smaller leaks. A larger cloud generates higher exposure probability to potential ignition sources. Combined with that the leak frequency increase steeply with decreasing initial leak rate, the resulting exposure probability may increase. Moreover, the explosion load generated from an equally sized cloud is significantly larger in smaller module. In total these effects may outweigh the benefit from isolating leak sources from the potential ignition sources in a large area
- The generated total and delayed ignition probability (see Figure 11.16 and Figure 11.17) are within the expected range based on the data forming the basis for the parameterisation of the MISOF model. The total and delayed ignition probability is expected to be around 0.1% and 0.3% respectively for the average module in the North Sea. The two largest modules are judged to be larger than the average module in the North Sea. Based on this it is expected that MISOF and PLOFAM will generate an ignition probability and fire & explosion frequency aligned with the historical data gathered from the installations in the North Sea

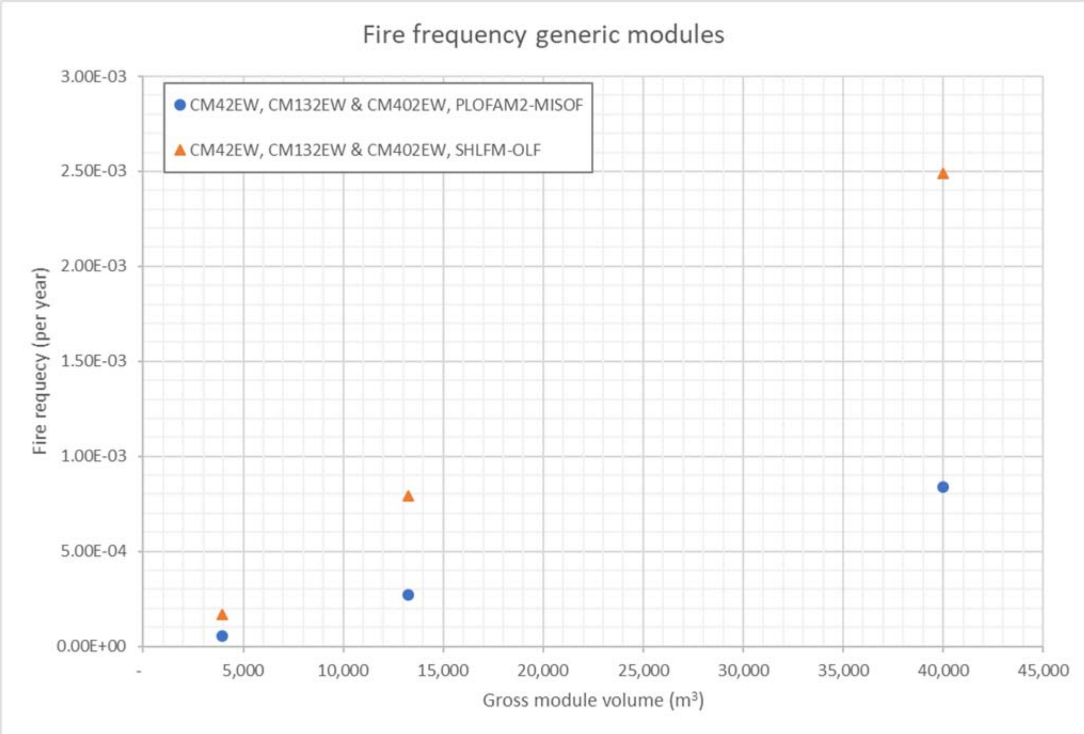


Figure 11.11 – Fire frequency vs. module volume for the various modules and probabilistic models

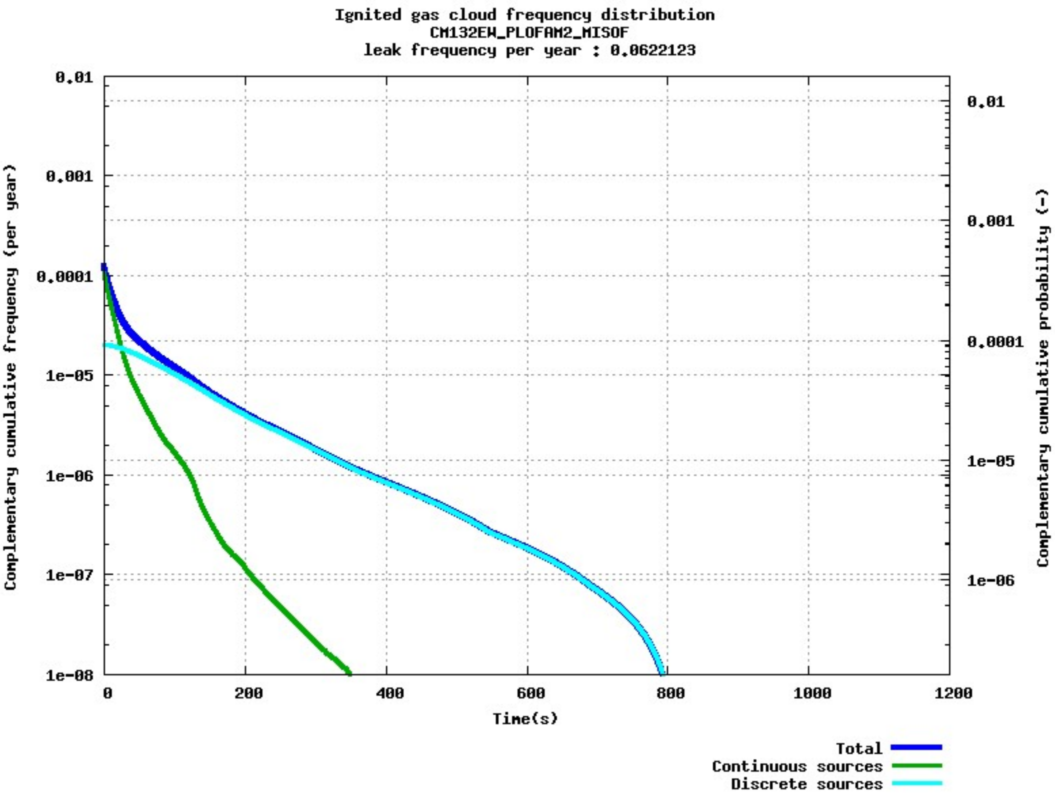


Figure 11.12 – PLOFAM-MISOF: Complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud

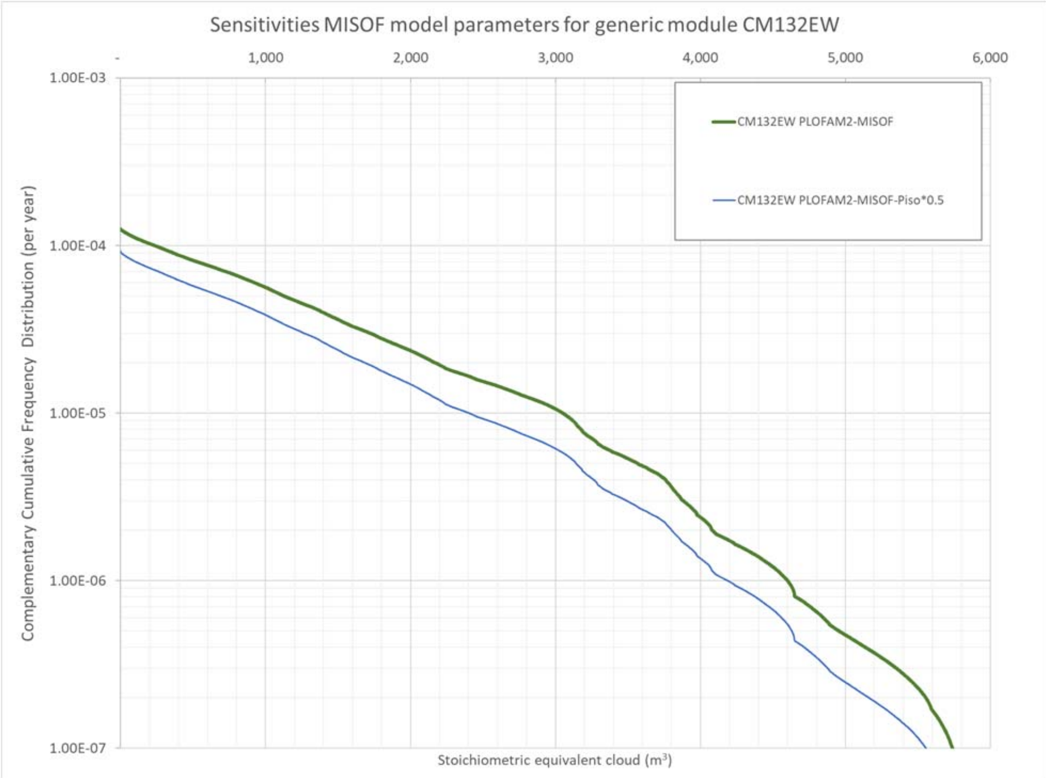


Figure 11.13 – Sensitivity P_{iso} in MISOF; default values (see Table 8.20) vs. increasing the isolated fraction with a factor of two. The figure shows the complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM132EW

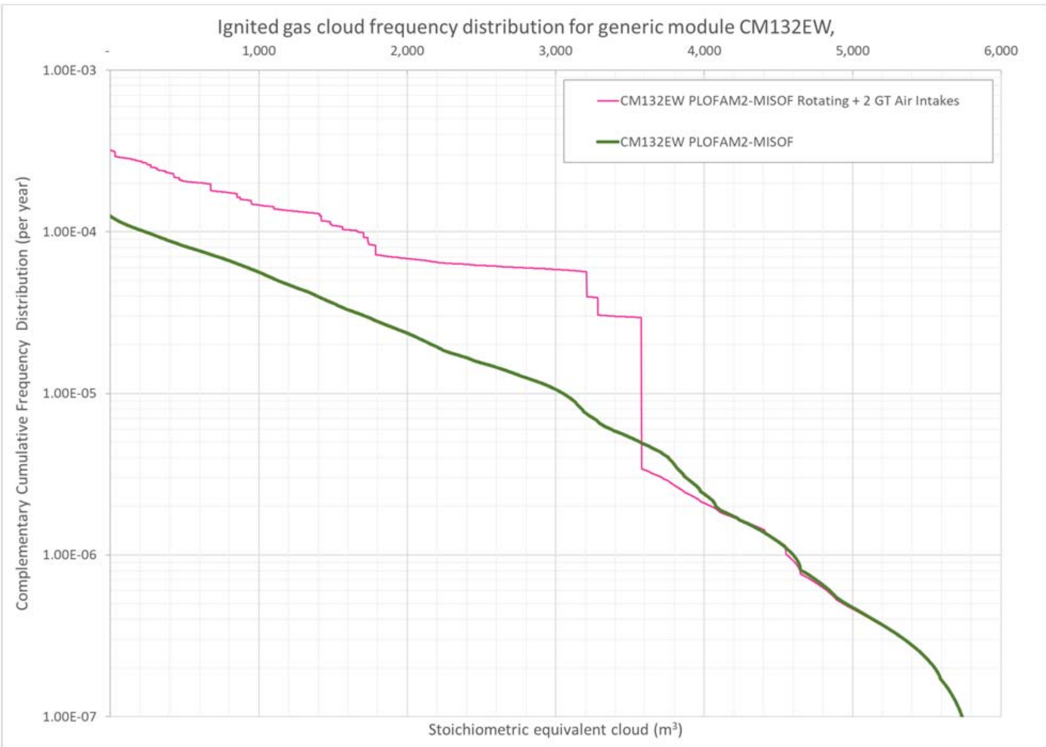


Figure 11.14 – CM132EW PLOFAM-MISOF with specific modelling of 12 pumps instead of generic volumetric modelling of rotating machinery + two gas turbine air intakes located directly above the module (see Figure 11.15); complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud

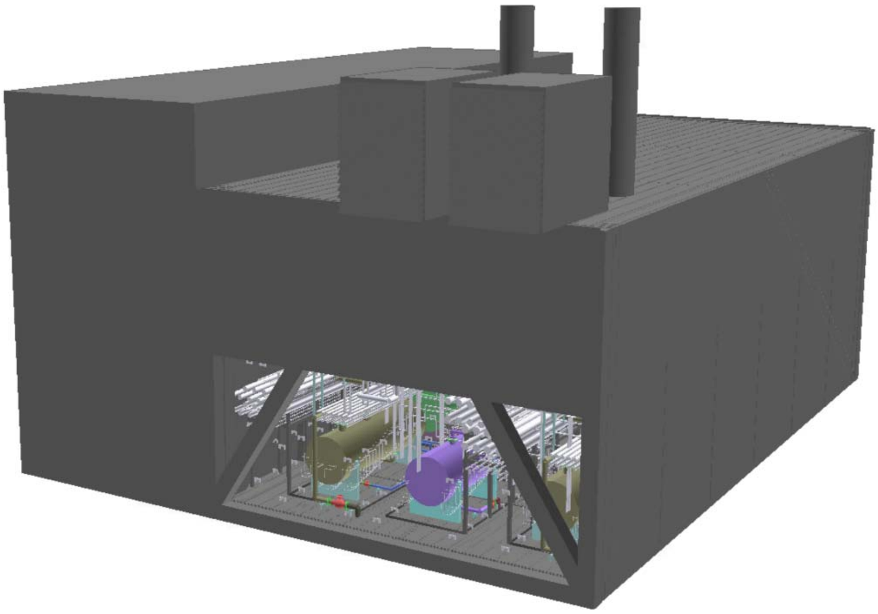


Figure 11.15 – CM132EW location of gas turbine air intakes

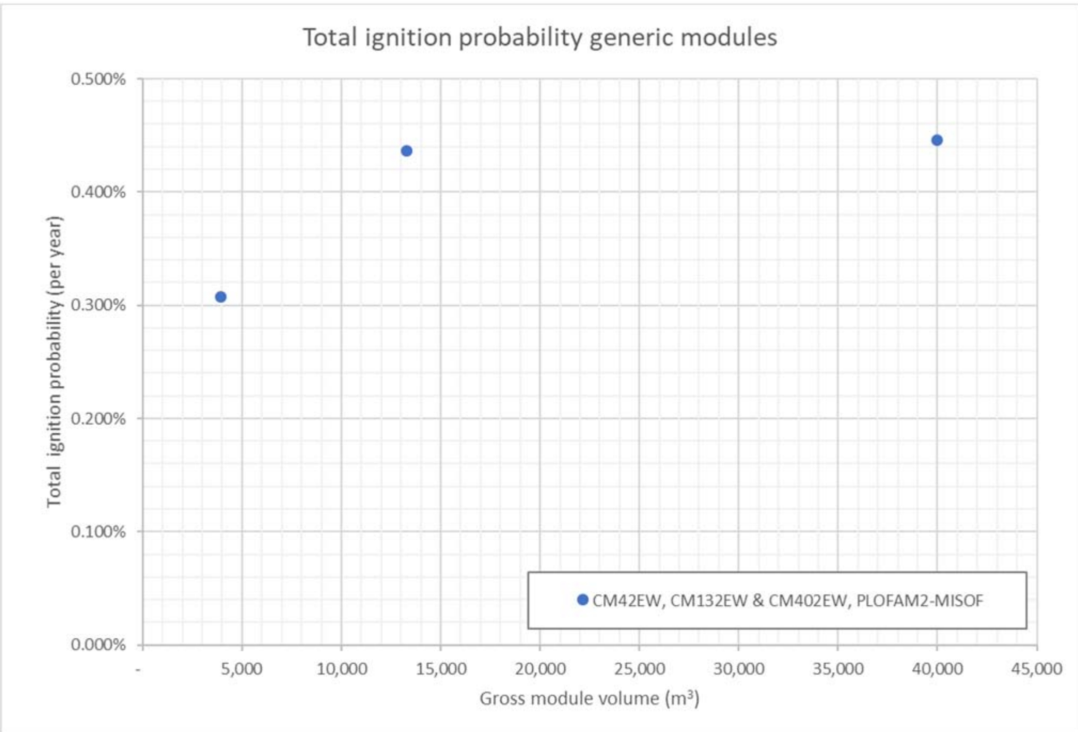


Figure 11.16 – Total ignition probability vs. module volume for the various modules

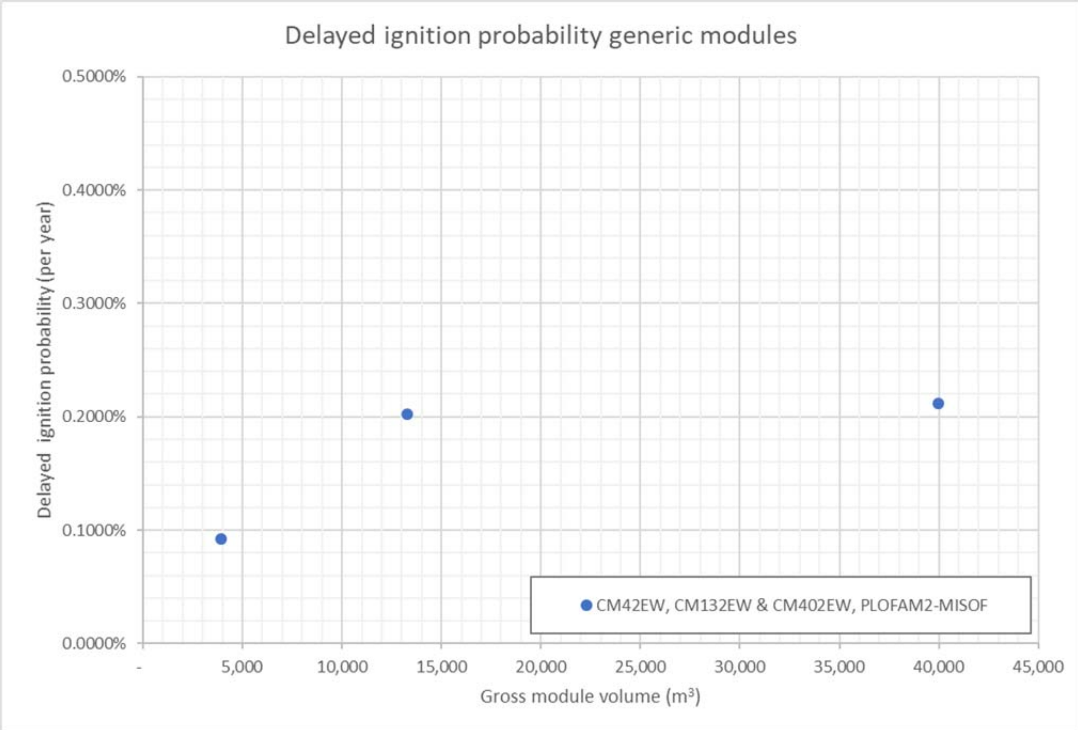


Figure 11.17 – Delayed ignition probability vs. module volume for the various modules

12 Concluding remarks

A comprehensive model for ignition probability modelling in quantitative risk analysis has been established based on thorough analysis of available statistical data and knowledge related to offshore oil and gas installations. MISOF is aiming to be the best available ignition model in industry for use in quantitative risk analyses for offshore installations located in the North Sea. The model can be used in other geographic areas if it is justified that the conditions of the specific installation or site can be considered similar with what are found generally on North Sea installations.

A thorough test of the MISOF combined with the best industry practice on leak frequency modelling (PLOFAM) and probabilistic modelling of exposure to flammable atmosphere has demonstrated that MISOF and PLOFAM are able to reproduce ignition probability and fire & explosion frequency at installations in the North Sea that are within the most probable range (see Chapter 11.2). But more importantly, the test underlines that specific modelling of gas turbine air intakes may have a significant effect on the resulting risk picture. In unfavourable cases, the contribution from gas turbine air intakes may constitute the major contributor to fire and explosion risk.

It is important to keep in mind that a fundamental basis for the validity of MISOF is that the observed data extracted from operating installations are applicable to the future design of offshore installations and the operational conditions in the years to come. Shifts in underlying casual factors (*e.g.* emerging unknown degradation mechanisms due to age or changing operational conditions) affecting the future trend in ignited leaks occurring on installations in the NCS and UKCS may affect the model parameters significantly. Although all relevant ignited leaks (3 relevant ignited leaks in hazardous areas altogether in the period from 1992 to 2017) have taken place after 2001, it has been concluded that this can be explained statistically as a stochastic effect. No casual arguments for an underlying trend with time have been identified. In order to monitor any possible underlying time trend, it is considered important to update the MISOF model at regular intervals. Then the MISOF model will be able to capture and incorporate any trends to ensure adequate safety design in the future.

No casual arguments have been found that supports a difference in the underlying ignition probability between NCS and UKCS installations. This does not mean that such a difference does not exist, only that the MISOF project has not identified any justification for such a difference. The same conclusion is established in the PLOFAM project. A hypothesis claiming that the underlying leak frequency is the same for the two domains cannot be rejected based on the available data.

In order to quantify the ignition probability based on MISOF, a model for the probability exposure of potential sources of ignition to a flammable mixture is required. The quality of the exposure probability model is decisive for the resulting accuracy of the ignition probability estimate as well as the quantification of the relative effect of the safety system barriers controlling the fire and explosion risk. This means that a risk analysis model stating compliance with MISOF does not imply an unambiguous estimate of the ignition probability. However, guidelines are implemented that are applicable to both simplified and advanced methods for estimation of the exposure probability. The selection of method should be aligned with the level of detail targeted in the risk analysis. In many cases, a simple exposure probability model suffices, but the limitations must be described in the report (which applies to any model being used, *i.e.* simple or advanced).

It is important to note that the delayed ignition parameters are derived based on actual leaks occurring at installations in the North Sea. The duration of these leaks tends to be shorter than the standard leak scenario modelled in a QRA as barriers other than the ESD/PSD and BD valves limit the inventory being released. This means that the longer duration of the leak scenario used in the QRA model will in general add a contribution to the delayed ignition probability in the late phase of the leak scenario. This is not entirely representative for actual leak scenarios. In a probabilistic model in a QRA based on PLOFAM, the duration of the leak scenario is based on a spontaneous leak occurring during normal operation, where only the ESD/PSD and BD valves limit the loss of containment. The motivation for this approach is to focus on the investigation of the performance of the loss of containment and ignition control barrier elements, rather than the estimation of the actual fire and explosion frequency observed in industry. The effect of the longer duration of leaks used in QRA's is hard to quantify, and will be also be very dependent on the exposure probability model used. A ramp down model for discrete ignition mechanisms has been implemented to partly represent this effect. The justification for the ramp down model is mainly to account for effect of reduction of ignition sources with time.

A fundamental challenge when building the model is that there are only a few relevant incidents to base the model upon, and the understanding of the actual mechanism causing the ignition in these events is generally poor. It is therefore likely that the knowledge gained from ignited events occurring in the future would result in an enhanced understanding of the ignition phenomena, and consequently a somewhat different model and/or methodology for assessment of the parameter values. This underlines the importance of the quality of the reporting of ignited events.

The assessment of the uncertainty has demonstrated that the MISOF model parameters on average are expected to generate a best estimate of the total ignition probability resulting from immediate and delayed ignition in hazardous areas.

The uncertainty associated with estimation of the delayed ignition probability (both due to exposure of objects intended for use in explosive atmospheres and objects not designed for use in explosive atmospheres) is dominated by the quality of the exposure probability model. It is therefore paramount that the exposure probability model used is aligned with the objective of the study being performed. The uncertainty associated with derivation of the MISOF delayed ignition parameters can be significantly reduced by running a project improving the estimate of the factors used to parameterise the delayed ignition conditional probabilities. The scope of work for such a project is described in Chapter 13. Execution of the described activities will potentially create a basis for reduction of the delayed ignition parameters in MISOF.

In general, the uncertainty associated with ignition probability modelling based on MISOF can be considered to be quite limited if the guidelines are followed. The likely interval for the underlying ignition probability is quite limited (*i.e.* 0.15 – 0.6% for ignition in hazardous areas, but somewhat wider for objects not intended for use in explosive atmospheres). Continued efforts to record leaks in the future will provide a basis for even lower uncertainty in the estimation of the model parameters.

It has been a clear objective for the project to establish a model where there is a consistent and transparent correlation with the statistical data for the North Sea. This will provide a basis for improved consistency when performing future updates of the model incorporating events that occur in the future. An update of the statistical data and classification of future events in accordance with the methodology described in this report should lead to a transparent update of the parameter values.

It is important to note that the MISOF ignition model and the PLOFAM leak frequency model (Ref. /1/) are interlinked. To ensure that the best possible estimate of fire and explosion frequency on offshore installations is obtained, and that the barrier elements affecting the risk picture is reflected as accurately as possible, it is highly recommended that both models are used as a basis when modelling fire and explosion risk for offshore oil and gas installations. However, the conditional ignition probabilities presented in MISOF can be combined with alternative leak frequency models.

13 Further work

In this chapter, future activities to improve the model are described. Considerable reduction in the uncertainty related to the model parameters can be achieved by execution of the following activities:

- The distribution of the immediate ignition probability versus initial leak rate has been shifted in the MISOF model opposed to the previous models, *i.e.* the JIP model and the OLF model. It is concluded that the immediate ignition probability is constant for all leak rates since ignition occurs immediately and no basis is found for arguing a correlation with leak rate or hole size. It is suggested that this assessment is revisited when the MISOF model is updated next time
- The fraction of the total ignition probability defined as delayed ignition probability is crucial for the estimate of the explosion frequency in a risk model based on MISOF. The uncertainty associated with determination of the delayed ignition parameters can be reduced significantly through a project aiming to improve the estimate of the parameters used to derive the conditional ignition probabilities. The following parameters should be addressed:
  - o The distribution of the fraction of delayed ignition with respect to equipment type and general ignition mechanisms (*i.e.* continuous vs. discrete). Improvement of this aspect of the model is limited by access to additional data sources. Access to any additional data would be valuable in this regard
  - o The estimate of the exposed volumes, denoted $V_{LEL,max}$ and $VT_{LEL:UEL,avg}$. The possible lack of accuracy here is a key factor adding uncertainty to the estimation of the model parameters. A quite coarse model is used to estimate the aggregated volume parameters for all leaks, except for a few cases where CFD simulations of the leaks were available. A study investigating the vapour cloud arising in each of the recorded leaks by use of an appropriate CFD tool (*e.g.* Kameleon FireEx KFX® or FLACS®) would reduce the uncertainty significantly. Geometrical models exist for most installations in the NCS, which provides an excellent basis for such a study
  - o The adjustment factor of exposed volume to account for isolation of ignition sources, *i.e.* F_{adj}. This can be achieved through data on the properties of the ignition control barrier gathered from installations in the North Sea. Such a study should address potential differences between installations located in the UKCS and the NCS. This is to investigate whether there are any underlying casual arguments for the observed difference in number of ignited leaks at installations in the UKCS and the NCS
  - o The free flow volume per rotating machinery (the free flow volume is used to link the generic ignition probability per unit volume, *i.e.* $\lambda_{i,C}$ and $\lambda_{i,D}$, with the conditional ignition per rotating machinery, see Table 8.10). This activity should include the collection of data to assess the drives powering the various types of rotating machinery (*e.g.* a single electrical motor typically driving a pump vs. several compressors typically mounted on one electrical drive). It is expected that such data could be gathered quite easily from operating installations in both the UKCS and the NCS

- The discrete and continuous ignition mechanism implemented in the model is an imperfect idealisation of what is going on in practice. More effort should therefore be put in understanding actual failure modes. This will improve the basis for the applied idealisation in the model. Acquired knowledge on this issue in the future will hopefully provide basis for reducing the uncertainty with respect to how to idealise the actual ignition mechanisms in the ignition model. One important aspect is that ignition due to continuous sources is considered to materialise upon the very first exposure. In practice, there will be an ignition time delaying onset of the combustion process because it will take some time to elevate the temperature in the burnable atmosphere. The ignition time is typically a few seconds. Furthermore, dependent on the equipment and failure mode, time may be required for the combustible atmosphere to migrate to the part of the equipment providing the energy

- Perform a comprehensive benchmark of the model based on an advanced probabilistic exposure model solely based on CFD for a large number of installations in the subset (*i.e.* installations at UKCS and NCS). The execution of such a study should preferably be done in parallel with the activity described above improving the estimation of $V_{LEL,max}$ and $VT_{LEL:UEL,avg}$. The same geometrical models would form the basis for both activities. The detailed benchmark study would enable a detailed assessment of the uncertainty associated with the overall methodology to estimate ignition probability in a QRA based on MISOF and PLOFAM. This would improve our understanding on how to interpret the fire and explosion risk picture estimated in QRA's
- Investigation of the performance of the ignition control safety function of pumps. It is judged that pump failure modes resulting in leaks are prone to ignition, but the probability set in MISOF based on the available data is believed to be somewhat high. This should be addressed in a project reviewing the potential failure modes associated with pumps. Access to additional data such as reports describing fires originating from pumps, would be valuable to improve the assessment of the ignition probability associated with leaks from pumps
- The model for ramp down of the discrete ignition intensity more than 300 seconds after onset of the start of the leak is important for the estimation of the delayed ignition probability in a probabilistic model. The data basis and the model properties ought to be investigated further
- Explore the possibility of adopting statistical data from other industries as well as other geographical regions to validate the model. Any additional data shared with the project team is valuable in this regard
- Expand the scope of the model by including other types of facilities (*e.g.* onshore petroleum facilities) and other combustible fluids than already covered by the current model (*e.g.* hydrogen)
- The MISOF model for gas turbine air intakes should be updated when Phase 1 of the JIP project investigating ignition control of gas turbine air intakes has been executed (Ref. /14/)

14 References

/1/ Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", report no: 107566/R1, Rev: Final, Date: December 2018.

/2/ DNV/Scandpower AS: "Guidelines for use of JIP ignition model", DNV report no. 99-3193, Scandpower report no. 27.29.03, rev. 1, April 1999

/3/ Scandpower AS: "Ignition modelling in risk analysis", report no. 89.390.008/R1, March 2007 (see Appendix A)

/4/ Lloyd's Register Consulting, "Modelling of ignition sources on offshore oil and gas facilities - MISOF", report no: 106364/R1, Rev: Final, Date: 25 November 2016.

/5/ Standards Norway: "Risk and emergency preparedness assessment", doc. no. Z-013, 3rd edition., October 2010.

/6/ Health and Safety Executive: "HSE Hydrocarbon Release system", https://www.hse.gov.uk/hcr3/, accessed June 2016

/7/ Operators taking part in the project and the Petroleum Safety Authority (PSA) has granted access to all available accident investigation reports to the project team. In addition, data from the RNNP reports has been used as well as annual reports from the Norwegian Petroleum Directorate.

/8/ Preventor AS: "Blast load Frequency Distribution, Assessment of historical Frequencies in the North Sea", Report No. 19816-04, Final report, Rev. 3, 26th November 1998.

/9/ Lloyd's Register Consulting, "Blowout and well release frequencies based on SINTEF offshore blowout database 2015", report no: 19101001-8/2016/R3, Rev: Final, Date: 04.04.2016

/10/ Scandpower AS: "Efficiency of isolation of electrical ignition sources", Report No. 100027/R1, December 15th 2010.

/11/ UKOOA: "Ignition probability review, model development and look-up correlations", IP research report, January 2006.

/12/ Wilday A. J., Wray A. M., Eickhoff F., Unruh M., Fae E., Halama S., Conde Lazaro E. and Reina Perbai P.,"Determination of Safety Categories of Electrical Devices used in Potentially Explosive Atmospheres (SAFEC)", Contract SMT4-CT98-2255, Final Report HSL/2000/01, 2001.

/13/ SINTEF Offshore Blowout Database, 2015.

/14/ Lloyd's Register Consulting: "Gas turbine ignition control – Phase 0", Joint Industry Project, Partners: ConocoPhillips Skandinavia AS, Maersk Olie & Gas A/S and Statoil ASA. Report No. 104998/R1, Rev. Final, Date: 22 June 2016. Report only distributed on client's acceptance.

/15/ Scandpower AS: "Tennmodell, Fase 1, Tennkilder - Aktivitetsrelaterte tennkilder", report no. 27.390.028/R1, March 2005.

/16/ Petroleum Safety Authority: "RNNP 2015 main report for land facilities", see www.ptil.no

Appendix A

Data basis for MISOF

Table of contents:

A1 Introduction

This appendix presents the data basis for the MISOF model. The data is presented in three attachments as follows:

Attachment A1 describes process leaks and ignitions at the NCS since 2001. The data set is limited to leaks with an initial leak rate exceeding 0.1 kg/s. Flammable gas exposure for the incidents is based on review of detailed investigation reports.

Attachment A2 describes process leaks and ignitions at the UKCS since 1992. Flammable gas exposure for the incidents is based primarily on recorded data on leak rate and duration, fluid type and other relevant information found in HCR.

Attachment A3 describes other sources of information considered relevant for ignition modelling for process leaks at offshore installations.

A2 Data sources

A2.1 NCS data

Detailed descriptions exist (accident investigation reports) for most of the 217 hydrocarbon process leaks at NCS in the period 2001-2017. This set of leaks is assumed to represent all process leaks with initial leak rate exceeding 0.1 kg/s for the period. Most of these leaks are small, and many leaks have initial leak rates close to the 0.1 kg/s mark. These incidents have been scrutinized in detail as basis for the PLOFAM leak frequency model.

A subset of the leaks covering the period 2001-2017 this (191 significant process leaks) constituted the primary basis for the process leak frequency model PLOFAM.

None of the 217 leaks ignited. The last known process leak that ignited at an installation on the NCS was a leak ignited by hot work in 1992.

The available information about leaks occurring at installations located on NCS before 2001 is not sufficient to establish data for this time period having similar quality as the data established for the period 2001 onwards. Some data is however available, which is utilized to provide an estimate of the number of leaks for the period 1992-2000 and the corresponding volume of combustible gas exposing equipment. The quality of the estimates is deemed adequate to form basis for parameterisation of the MISOF model.

A2.2 UKCS data

The HCRD includes significantly more leaks than the NCS data set. The main reason for that is that the criterion for including leaks in the data set is not a cut-off at 0.1 kg/s. Additionally, the data set is for a longer time period, extending back to 1992. The UKCS data is applied as additional data in the PLOFAM model, and affects the hole size distributions and contributions from different types of equipment and potential leak sources. The PLOFAM project concluded that the process leak frequency is similar at the NCS and the UKCS.

Initial leak rate is not a parameter in the HCR data. Leak rates could be derived from released quantity and duration, or hole size, actual pressure and fluid phase and density. The two ways to calculate leak rate appears to give inconsistent results in many cases, and counting leaks exceeding 0.1 kg/s is not straight-forward. Again, the interpretations performed as part of the PLOFAM project will form the basis for the UKCS leak data to be applied in the update of the ignition model.

The number of process leaks is then 327 for the period 2001-2017 and 360 for the period 1992-2000. There are 4 relevant ignitions in the dataset in terms of the definition of a process leak in PLOFAM, of which 1 was ignited by a gas turbine. Hence, 3 ignitions are relevant with regards to parameterization of model parameters covering ignition in hazardous area.

A2.3 Other data

A2.3.1 Process leaks and ignitions at the DCS

There are some statistics on unintentional gas releases for the DCS available from Energistyrelsen for the period 2003 – 2012 (9 years). There were 5 large gas leaks and 89 significant leaks. For the latter there is a very significantly falling trend.

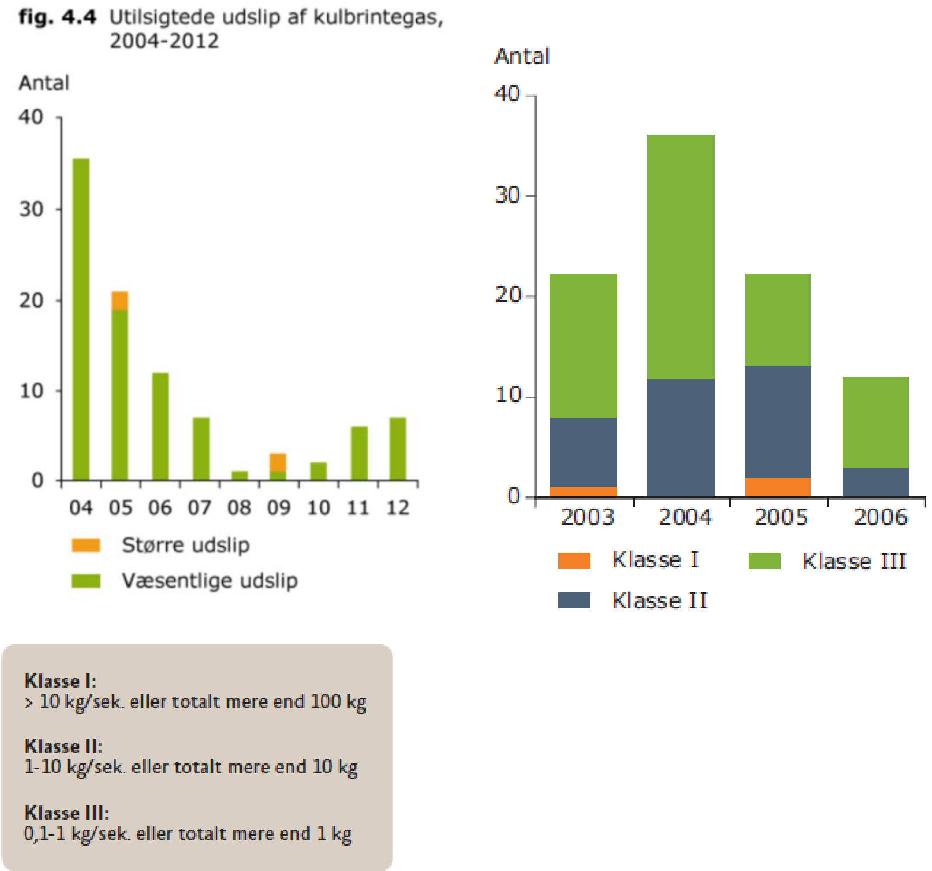


Figure A 2.1 Hydrocarbon leaks on DCS

- A significant release is described as a release of 1 to 300 kg gas, or a leak rate in the range 0.1 kg/s to 1 kg/s for 2 – 5 minutes
- A large release is defined as a release of more than 300 kg gas, or a leak rate exceeding 1 kg/s for more than 5 minutes (which means more than 300 kg is released anyway)

The Gorm C explosion accident is highly relevant for this project. There is a detailed description of the incident in Energistyrelsen's report from 2007.

This scenario appears similar to the accident at Centrica Rough B at the UK sector in 2006; pipe rupture with a large gas cloud ignited within a few seconds, possibly with a turbine as the source of ignition. Turbine driven compressors were located in process areas. The two accidents are a strong indication that the use of turbine driven compressors is unfortunate, even if the exact mechanisms igniting the gas are not known.

A2.3.2 Blowout ignition statistics

Offshore blowout statistics is available from the SINTEF Offshore Blowout Database, as described in more detail in Attachment A3.

From the blowout descriptions there are only some indications of the ignition mechanisms and the nature of the ignition sources. The description of the event as an explosion or a fire may also tell something about the ignition mechanism. Blowout data are summarized in attachment A3.

An important lesson from the blowout data is the relatively high overall ignition probability. About 10% ignition probability within the first 5 minutes for a blowout is a figure generally applied in the industry. These ignitions may be event ignitions or ignitions resulting from exposure of continuous or discrete ignition sources.

12% of ignited topside blowouts were reported to have ignited between 5 and 60 minutes after the blowout started. In one of these cases (ID 254 Cerveza), ignition is reported as “immediate” upon diverter line rupture. One of the other is the West Vanguard blowout at Haltenbanken at the NCS (ID 278). The last event reported to have ignited between 5-60 minutes (ID 507, Diamond Ocean King Platform C) seems to have had some additional delay. The lack of ignitions in the period 5 minutes to 60 minutes may be taken as an indication that continuous ignition sources dominate over intermittent sources.

About 11% of ignited blowouts ignited later than one hour, in many cases days and weeks after the start of the blowout. In some cases these ignitions seems related to well kill operations. The West Atlas blowout, ignited after more than two months during a well kill operation through a relief well is a recent example (but this blowout is not included in the data set, as it occurred in a region not considered in the statistics).

An interesting question is whether there is statistical or other evidence to support using a lower ignition probability for large process leaks compared to blowouts. The following is observed in the data:

1. Some of the process leaks have short duration. In order to compare ignition probability, only leaks with duration more than 5 minutes are fully relevant. Large process leaks have in general shorter durations.
2. In many blowout accidents, there are additional ignition sources present. This may be related to sand in the wellstream (potentially causing sparks), personnel at the scene attempting to kill the blowout, or equipment present that has less effective ex-protection than what is generally applicable in process areas.
3. For a high fraction of the leaks, the leak location is different from process leaks, and the probability for exposure of non-protected equipment outside the hazardous area may be higher. If we look at release points at tree or wellhead at jackets or jacket/jack-up constellations, we find 1/21 ignitions within 5 minutes and 1/21 delayed ignitions. This is 5% ignition probability within 5 minutes, which is lower than for blowouts in general, but the number of blowouts is too low to use as anything other than an indication.

4. Blowout ignition data is dominated by installations operating in the US. Comparing the statistics from NCS/UKCS with the US GoM OCS, there is again insufficient data to conclude with certainty, but for ignitions within 5 minutes the data are practically the same. For ignitions delayed with more than 5 minutes, there is a lower fraction ignited in the North Sea.

A2.3.3 Data from other industries

The use of other data sources than from the offshore industry has been considered. Without doubt there can be things to learn related to the probability and sources for leaks and the ignition of such. Roger M Cooke, included an interesting example in a book on probabilistic risk analysis where he referred to a large number of studies on the leak frequency for a flanged connection. The deviations in results were, as might be expected, huge. The most important lesson from that exercise is that to consider the leak frequency as a property of the flanged connection is a fundamental mistake. Dimension, pressure class, number of bolts and design are certainly properties of the flanged connection, but leak frequency or hole size distributions are not. The observed leak frequency should rather be considered a measure of the operators' performance in the use of flanged connections.

Just as a simple analogy, consider a car. What is the frequency of the car to collide? From accident statistics, it is not difficult to find that figure, but for the very same car we will find different number in each region or country considered. So, if you are going to drive a car in Norway, what would be the relevance of car accident statistics from Hungary? Obviously, we could gain useful information on consequences, while the information on frequencies would be of less value.

In conclusion, experience from other industries and regions can be useful in learning about mechanisms and the chains of events, but will probably be of limited value in predicting leak frequencies or ignition probabilities for the Norwegian offshore industry. Even the use of statistical data for the UKCS or DCS is likely to be less relevant than NCS data when applied to Norwegian offshore installations.

A3 Ignited PLFOAM leaks

A3.1 Overview

For process leaks exceeding 0.1kg/s, there have been no ignitions at the NCS for the period 1992-2017. At the UKCS, there have been 12 ignitions for these leaks, using the PLOFAM categorization. Since PLOFAM applied an automatic categorization of the UKCS leaks based on a set of parameters, each of the 44 ignited leaks are reassessed, with particular focus at the 12 leaks with rate exceeding 0.1 kg/s. A summary of the data set is given in **Table A 3.1**.

Table A 3.1: Ignited PLOFAM leaks in the HCR data set

PLOFAM leak data basis	# leaks	# ignitions	# leaks > 0.1 kg/s	# ignitions, leaks > 0.1 kg/s
NCS 2001-2017	-	-	217	0
NCS 1992-2000	-	-	229	0
UKCS 2001-2016	1,690	15	327	6
UKCS 1992-2000	1,258	26	360	6
UKCS and NCS 1992-2000	NA	NA	1,133	6

A3.2 Categorization of PLOFAM leaks

Many of the ignition mechanisms of the 44 ignited events are either covered by separate parts of the MISOF model (such as hot work), or not relevant in QRA context (flare carryover, ignitions inside turbine hoods etc.). A first categorization of the PLOFAM leaks is shown in Table A 3.2.

Table A 3.2: First categorization of the ignited PLOFAM leaks

	Period (HCRD ignition ID in parenthesis)		
Incident description	1992-2000	2001-2017	1992-2017
Flare carryover ignited by flare	2 (4,30)	0	2
Hydrocarbons ignited by hot work	15 (15,11,5,56,69,65, 87,93,92,111,110, 113 ,122,119,131)	3 (152,153, 6646[1)])	17
Fuel gas ignition within turbine hood	4 (14,86,33,120)	2 (154,120)	6
Leak from pump immediately ignited at pump	0	5 (164,226,150, 149,144)	5
Leak ignited by gas turbine air intake	0	1 (184)	1
Immediate ignitions with rate < 0.1 kg/s	4 (28,32,83,108)	2 (145,194)	6
Remaining incidents (none of the above)	1 (88)	5 (151,165,208, 4680, 4690)	6
Total	**26**	**18**	**44**

1) Due to cutting torch, occurred in 2016

Descriptions of the 4 “remaining incidents” are given in Table A 3.3.

Descriptions of all 44 events are given in attachment A3.

Table A 3.3 Description of 4 ignited events (grey headers from HCRD)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1997-1998-133	88	99999	SPARK FROM DAMAGED TRACE HEATING CABLE	PRIOR TO IGNITION THE WIND SPEED WAS SUFFICIENT TO PREVENT GAS BUILD UP FROM THIS MINOR LEAK SOURCE. (WHEN THE WIND SPEED DROPPED TO LESS THAN 4 KNOTS GAS BUILT UP UNTIL IGNITION FROM THE DAMAGED TRACE HEATING SOURCE OCCURED).	LEAKING FITTING WAS IDENTIFIED AT 14:00 HOURS. 2 DEC JOB CARD RAISED TO REPAIR AT TIME OF IDENTIFICATION. LEAK CONSIDERED MINOR.	No (leak rate < 0.01 kg/s, detection by ignition, very long delay)
2003-2004-207	151	900	Under investigation by Petrofac and the HSE	Portable gas detection adjacent the valve indicated 4% LEL. the fixed CH4 gas detector approx. one metre from the valve did not indicate LEL. Liquid washed away to hazardous drains in the area using sea water.	Liquid condensate samples to be sent to the HSE and Petrofac Boroscope and portable gas detector required by HSE for inspection.	No (not relevant leak scenario – cleanup?)
2004-2005-29	165	10	Air mover was positioned at manway entrance; when the air mover was switched on a vapour flash occurred at entrance to manway. As a result of the vapour flash, hot exhaust gases were emitted from the	Lazy condensate gas within vessel migrated out of manway opening when door was opened. Condensate not under pressure therefore unable to determine amount of condensate gas dispersion or quantity. No detection activated due to this dispersion, therefore duration not applicable as condensate gas within	BLANK	No (not relevant leak scenario, man inside scrubber?)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
			manway opening	vessel flashed off immediately when air mover started and the GPA activation followed due to flame detection.		
2009-2010-146	208	120	Electrostatic spark from an insulated conductor, charged by the electrostatically charged mist created by primary release is thought to be the most likely source of ignition	Liquid condensate thought to have rained out from leak, accumulating upon flat surfaces and equipment and to run down vertical surfaces to collect wherever the conditions allowed. This is apparent on the deck level and around well W4/KA with wax deposition on all surfaces. There is also evidence of condensate deposition and run off on the East end of the solid deck by the HPU and significant deposition of wax on the 9 m level. It is not clear whether this is the initial deposition or the melting and spread of wax following the fire. Gas escaping from the leak dispersed away from the installation under natural windflow. Modelling suggests that the gas cloud produced was not significantly large enough to cause detection by the installation gas detectors.	Erskine is a Normally Unattended Installation and was unmanned at the time of the incident. Manual operation of export pipeline SSSV and blowdown of the export pipeline was carried out by BG Lomond OIM.	Yes

A3.3 The importance of exposure to flammable mixture

Ignition modelling (using MISOF) is based on an assumed linear relation between the size of the flammable gas cloud from a leak and the probability for ignition. The rationale behind this model is that potential ignition sources are distributed in space, and a larger gas cloud is consequently more likely to expose a live ignition source. Further, ignition probability is modelled to increase with the duration of the release. This is based on the assumption that not all ignition mechanisms are present at all times (intermittent sources).

In order to derive the model parameters, the size of the flammable gas exposure for each of the experienced leaks has been estimated by use of a simple model (see Attachment A2 Chapter A2-3.1). Quantifying gas exposure based on the available information is very uncertain, but the cumulative result is still considered useful for analysis and evaluations. For instance, to evaluate the rational for the model.

In the following graph, the cumulative gas cloud size for all process releases (according to the definition in PLOFAM) in the HCR database and at NCS (3447 in all) is plotted as a function of leak rate. As a total for all leaks, the gas cloud size (within process modules) is about 100 000 m^3. The total number of ignitions for this data set is 44. The next graph shows the cumulative number of ignitions divided by the cumulative gas cloud volume as a function of leak rate for all process leaks in the HCR database. For example, at 930kg/s, the value is $4 \cdot 10^{-4}$ and results from 44 ignitions[1] and 100 000m^3 gas exposure.

[1] This includes one diesel leak and one that is likely a double-count

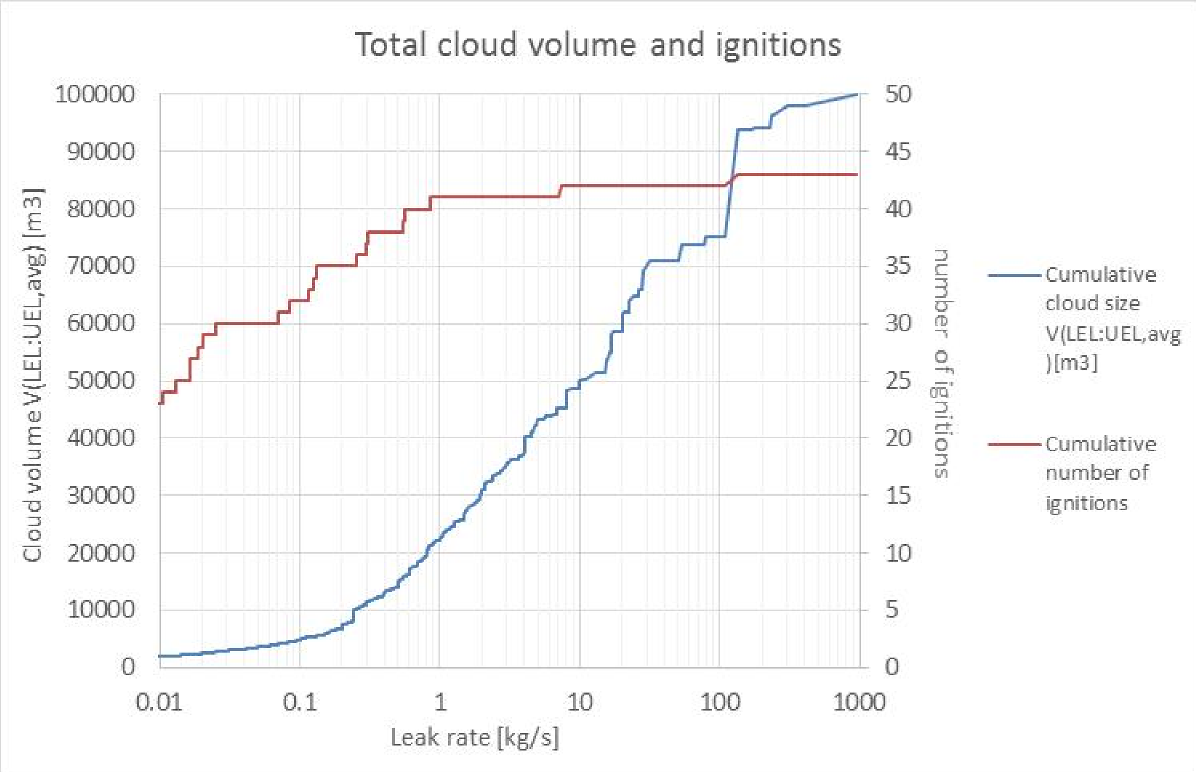


Figure A 3.4: Cloud sizes and ignitions

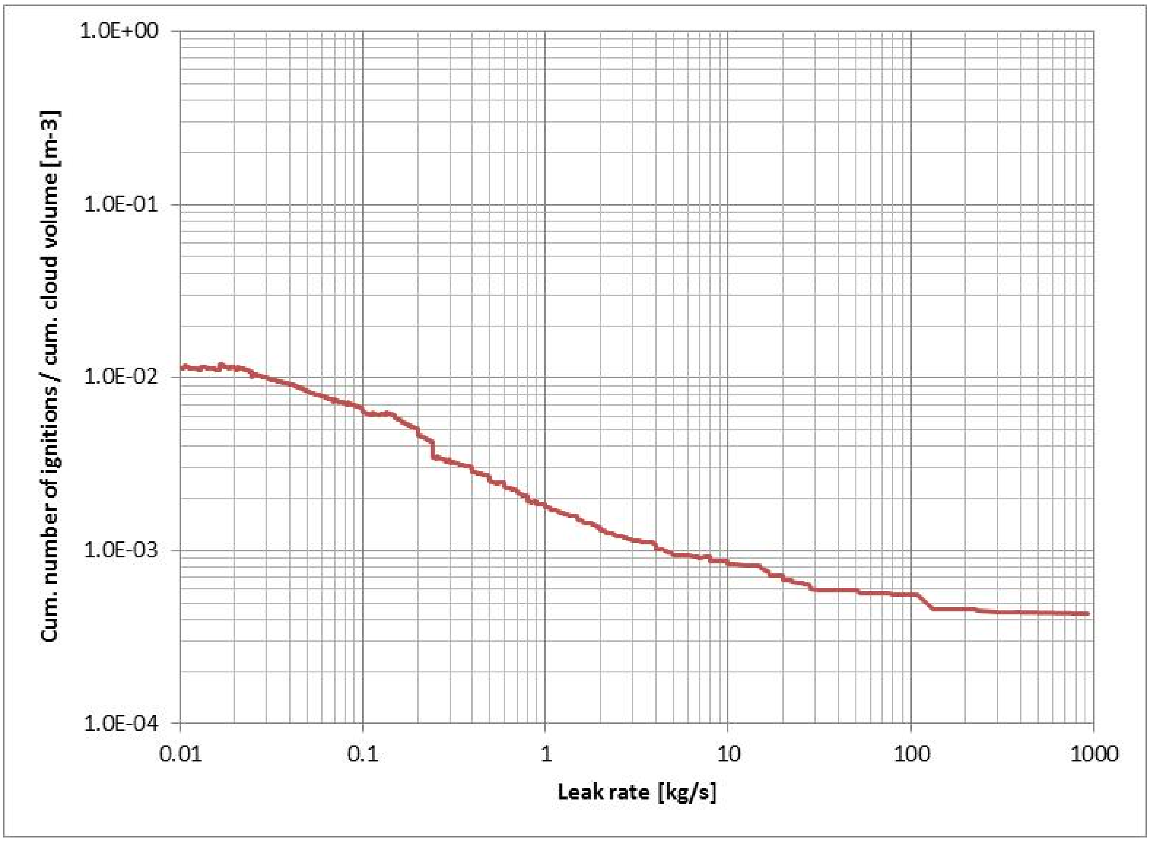


Figure A 3.5: Ignitions, cloud sizes and leak rates

From the first graph it is seen that about 22% of the estimated gas exposure is for leaks smaller than 1 kg/s. These leaks contain 41 of the 44 ignitions, or 95%. For leak rates less than 1 kg/s, there are 42 ignitions in about 22 000 m^3 exposure, or about $2 \cdot 10^{-3}$ ignitions per m^3 exposed. For leak rates exceeding 1 kg/s, there are 2 ignitions for about 78 000m^3 exposed volume or $3 \cdot 10^{-5}$ ignitions per m^3 exposed. There is about a factor 70 between these two figures. Hence, the data does confirm that other variables than the exposure probability is important for the underlying ignition probability.

Two model features have been included in the ignition model that reflects this observation. Firstly, ignition may not always be a result of exposing an ignition source that is present before the onset of the release. Such ignitions are called event ignitions, and may for example result from an operator causing a leak and its ignition, or a pump that fails, resulting in a leak and ignition of the same leak. In these cases, there is a dependency between the failure mode causing the leak and causing ignition to occur. In MISOF, the parameter covering this aspect is denoted immediate ignition.

The second model feature is to incorporate the effect of ignition source isolation and process plant shut down upon detection (ignition source control, ISC, and ESD). The objective is to reduce the probability for delayed ignition of the release, by shutting potential sources of ignition down prior to exposure to combustible fluid. To what extent ignition source isolation and process shut down has contributed to prevent ignitions is not readily found from the leak and ignition statistics.

A3.4 Summary

Considering the period 1992-2017 for UKCS and NCS, there are 1,133 relevant process leaks exceeding 0.1 kg/s, of which 6 ignited. 4 are considered relevant in terms of the definition of a process leak in PLOFAM. The quality of the data is considered to be good, as judged to be applicable for as basis for ignition probability quantification.

The number of ignited events is quite modest, and fire and explosion consequences were small or moderate in all the ignited cases, except for the Rough B and Gorm C incident at the UKCS and Danish Continental Shelf respectively.

Attachment A1

NCS PLOFAM leaks and ignitions

Table of contents

Page

1 Introduction

The recorded leaks occurring on installations located on the Norwegian Continental Shelf (NCS) in the period 01.01.2001 – 31.12.2017 (17 years) are described in this attachment.

The main objective is to estimate the exposure of equipment to combustible gas resulting from the recorded leaks.

A more comprehensive description of the leaks in the period 01.01.2001 – 31.12.2017 can be found in the report describing the PLOFAM leak frequency model (see Ref. /1/ in the main report).

Detailed information about all leaks occurring at installations located in the NCS before 2001 is not available. Data of high quality covering about 50% of the installations is available, which is utilised to provide an estimate of the total number of leaks for the period 1992-2000 and the corresponding volume of combustible gas exposed to equipment. The assessment of the data for the period 1992-2000 is presented in Chapter 4.

2 Overview data for the period 2001 - 2017

The data of recorded leaks in the NCS have been established based on the following data sources:

1. RNNP dataset collated by Petroleumstilsynet (Ptil) and Safetec
2. Review of accident investigation reports. Accident investigation reports have been available for the major fraction of the incidents.

All recorded leaks have an initial hydrocarbon leak rate of 0.1 kg/s or larger.

The dataset consists of191 significant leaks and 26 marginal leaks occurring in the period 01.01.2001 – 31.12.2017 found relevant for modelling of topside process leak frequencies in the PLOFAM model. Hence, the total number of leaks presented in Table 6.2 in Chapter 0 is 217. These are considered relevant for risk modelling of leaks stemming from process systems according to the definition of a process leak in PLOFAM.

None of the 217 PLOFAM leaks occurring in the period 01.01.2001 – 31.12.2017 did ignite. None of the remaining 43 leaks reported as occurring on NCS installations in the period 01.01.2001 – 31.12.2017 ignited (in total 260 leaks are reported in RNNP for this period, Ref. /3/). Despite these incidents being considered as irrelevant for modelling of process leaks in PLOFAM, it is worthwhile noting that they did not ignite. Typical properties of the disregarded incidents are as follows:

- The leak is a release through a vent or a dump line where the rate is not considered to exceed the design specification for the vent or dump line
- The leak is originating from a piece of equipment not being relevant, such as a pipeline or a riser
- The leak is stemming in the well system during a drilling operation.

These leaks are however considered relevant when evaluating the general performance of the ignition control barrier.

3 Estimation of cloud size for observed leaks at NCS in the period 2001-2017

3.1 Methodology

The exposure of equipment in process areas, intended for use in potentially explosive atmospheres, to combustible gas is a first step in estimating the observed leaks in the NCS by the simple generic model described in Chapter 3.1 in Attachment A.2.

The resulting estimate of the following gas cloud parameters are presented in Chapter 0 for each of the i leaks in the NCS dataset presented in Chapter 5:

$$V_{>LEL,max} = \sum_{i=1}^{N_{leak}} V_{>LEL,max,i} \tag{3.1}$$

$$VT_{LEL:UEL,avg} = \sum_{i=1}^{N_{leak}} V_{LEL:UEL,avg,i} \cdot t_{exp,i} \tag{3.2}$$

where $V_{LEL:UEL,avg,i}$ ideally is given by:

$$V_{LEL:UEL,avg,i,exact} = \frac{1}{t_{dur,i}} \int_{t=0}^{t_{dur,i}} V_{LEL:UEL,i}(t)dt \tag{3.3}$$

All parameters in the equations are described in Table 3.1. $V_{>LEL,i}$, $V_{>LEL,max,i}$, t_{max}, t_{dur} and $V_{LEL:UEL,i}$ are illustrated in Figure 3.2, which displays the time dependent development of a gas cloud for a typical transient leak scenario, denoted i, in an offshore oil and gas process module.

Equation (3.3) gives the exact value of the time average volume of gas (for one particular leak scenario) between $t = 0$ and $t = t_{dur,i}$ having a concentration between LEL and UEL. However, as both $t_{dur,i}$ and $V_{LEL:UEL,i}(t)$ are unknown for most historical leak scenarios, $V_{LEL:UEL,avg,i}$ is unknown and instead estimated based on formulas given in chapter 3.1 (Attachment A.2) for incidents in the UKCS, and by use of CFD simulations or by manual assessment of investigation reports (see Chapter 0).

Table 3.1 – Equation parameters

Parameter	Description
$V_{>LEL,i}(t)$	The time dependent volume of gas (for one particular leak scenario) having a concentration above LEL within the boundary of the area being studied
$t_{max,i}$	The time when $V_{>LEL,i}(t)$ reaches its maximum
$V_{>LEL,max,i}$	The maximum value of $V_{>LEL,i}(t)$, thus $V_{>LEL,max,i} = V_{>LFL,i}(t_{max})$.
N_{leak}	The number of leaks in the dataset
$V_{LEL:UEL,i}(t)$	The time dependent volume of gas (for one particular leak scenario) is having a concentration between LEL and UEL within the boundary of the area being studied.
$t_{dur,i}$	The moment in time where the combustible volume generated by the leak is considered negligible
$V_{LEL:UEL,avg,i,exact}$	The time average volume of gas (for one particular leak scenario) between $t = 0$ and $t = t_{dur,i}$ having a concentration between LEL and UEL.
$V_{LEL:UEL,avg,i}$	Estimate of the time average volume of gas (for one particular leak scenario) between $t = 0$ and $t = t_{dur,i}$ having a concentration between LEL and UEL. The parameter is estimated based on formulas given in chapter 3.1 in Attachment A.2 for incidents at UKCS, and by use of CFD simulations or by manually assessment of investigation reports (see Chapter 0).
$t_{exp,i}$	The assumed leak duration given in the dataset. This is not necessarily the same as $t_{dur,i}$. In many cases this is roughly estimated.
$VT_{LEL:UEL,avg}$	The sum product of $t_{exp,i}$ and the estimated time average volume of gas (for one particular leak scenario) between $t = 0$ and $t = t_{dur,i}$ having a concentration between LEL and UEL

The generic gas exposure model (presented in chapter 3.1 in Attachment A.2.) targets the aggregated gas exposure and the integral of the transient gas exposure with respect to time for all leaks in the dataset, i.e. $V_{>LEL,max}$ and $VT_{LEL:UEL,avg}$. The constants in the model are set based on the average for CFD simulations for a set of leak scenarios for a few modules where LR has been responsible for the explosion risk assessments. The results are presented in Figure 3.1. A description of the scenarios and installations are given in Table 3.2. The results show that the spread between the various datasets is prominent, but that the average is in accordance with the constants used in the equation presented in chapter 3.1, Attachment A.2 (150 and 225).

Table 3.2 – Description of installations and leaks scenarios simulated to estimate constants in generic gas exposure model

Case	Description?
Platform 5, Oil export module	Based on 48 leak scenarios at a jacket installation with leak rate 16.7 kg/s and wind speed 9 m/s.
Platform 5, Compression module	Based on 48 leak scenarios at a jacket installation with leak rate 16.7 kg/s and wind speed 9 m/s.
Platform 5, Separation module A	Based on 48 leak scenarios at a jacket installation with leak rate 16.7 kg/s and wind speed 9 m/s.
Platform 5, Separation module B	Based on 48 leak scenarios at a jacket installation with leak rate 16.7 kg/s and wind speed 9 m/s.
Platform 82, 5kg/s_4m/s	Based on 96 leak scenarios at a drilling platform with leak rate 5 kg/s and wind speed 4 m/s.
Platform 82, 5kg/s_10m/s	Based on 96 leak scenarios with leak rate 5 kg/s and wind speed 10 m/s.
Platform 82, 30kg/s_4m/s	Based on 96 leak scenarios with leak rate 30 kg/s and wind speed 4 m/s.
Platform 82, 30kg/s_10m/s	Based on 96 leak scenarios at a drilling platform with leak rate 30 kg/s and wind speed 10 m/s.
Platform 82, 5kg/s_4m/s_hg	Based on 96 leak scenarios at a drilling platform with leak rate 5 kg/s and wind speed 4 m/s. The leaking medium is heavy gas.
Platform 82, 5kg/s_10m/s_hg	Based on 96 leak scenarios at a drilling platform with leak rate 5 kg/s and wind speed 10 m/s. The leaking medium is heavy gas.
Platform 82, 30kg/s_4m/s_hg	Based on 96 leak scenarios at a drilling platform with leak rate 30 kg/s and wind speed 4 m/s. The leaking medium is heavy gas.
Platform 82, 30kg/s_10m/s_hg	Based on 96 leak scenarios at a drilling platform with leak rate 30 kg/s and wind speed 10 m/s. The leaking medium is heavy gas.
Platform 14, Process module_8 kg/s	Based on 73 leak scenarios at a jacket installation with leak rate 8 kg/s
Platform 14, Process module_30 kg/s	Based on 73 leak scenarios at a jacket installation with leak rate 30 kg/s
Platform 14, Well head area_8kg/s	Based on 39 leak scenarios at a jacket installation with leak rate 8 kg/s
Platform 14, Well head area_30kg/s	Based on 39 leak scenarios at a jacket installation with leak rate 30 kg/s

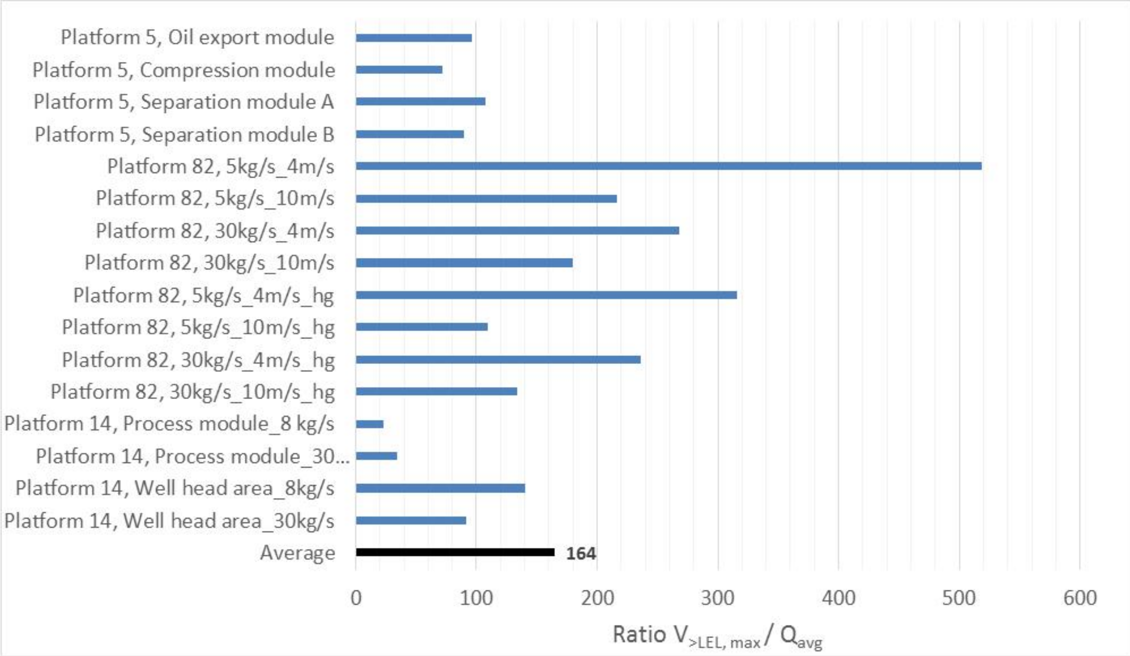


Figure 3.1 - Average ratio $V_{>LEL,max,i}/Q_{avg}$ for all CFD simulations performed in 4 different typical offshore modules (anonymization in accordance with nomenclature in PLOFAM, see Ref. /1/ in main report)

Leak scenario specific parameters, such as geometrical layout and wind conditions, adds considerable variance to the regression of leak rate vs cloud size. Hence, the variance around the mean estimated by the model is prominent (as demonstrated in Figure 3.1). This implies that the generic model can be expected to be rather inaccurate for a single scenario or a small subset of leak scenarios. This is exemplified in Figure 3.3 through to Figure 3.5. Note that the model also assumes that there is no drift of the combustible part of the gas cloud throughout the lifetime of the scenario.

In Figure 3.3, a graphical representation of scenario i and the estimation by the generic model is shown. This figure illustrates a case where the volume parameters are quite well estimated by the generic model.

Figure 3.4 and Figure 3.5 show two other typical cases where the parameters are over- or underestimated, respectively. t_{exp} is not consistently estimated for each scenario in the dataset, which means that t_{exp} does not necessarily correspond to t_{dur}. In many cases, t_{dur} is unknown and t_{exp} is set to 300 sec (see Attachment A.2 and data for NCS presented in Chapter 0). It should be noted that it is a general observation that t_{dur} for many recorded leaks is shorter than the duration given by the industry practice for modelling of the same leak scenario in a quantitative risk analysis. The reason for this is that other physical barriers than the ESD and BD valves, such as process control valves and manual valves, limit the loss of containment in many actual leak scenarios. In a quantitative risk analysis, normally only the ESD and BD valves are accounted for.

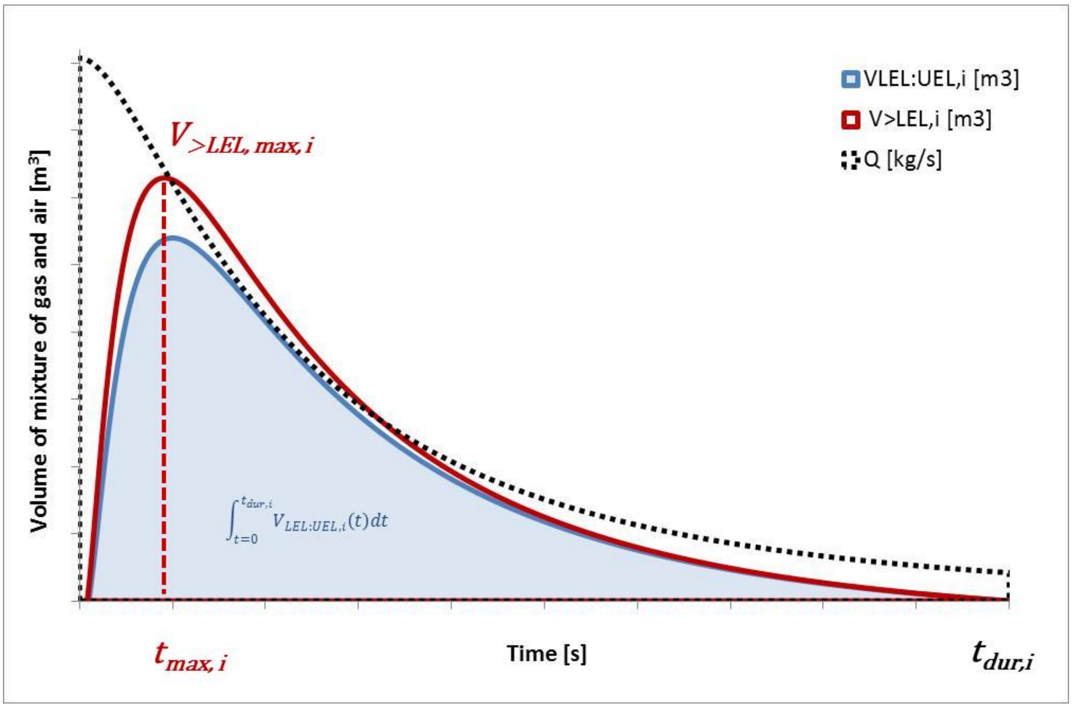


Figure 3.2 - Example time dependent gas cloud volume for a transient leak, denoted i, in a typical offshore process module

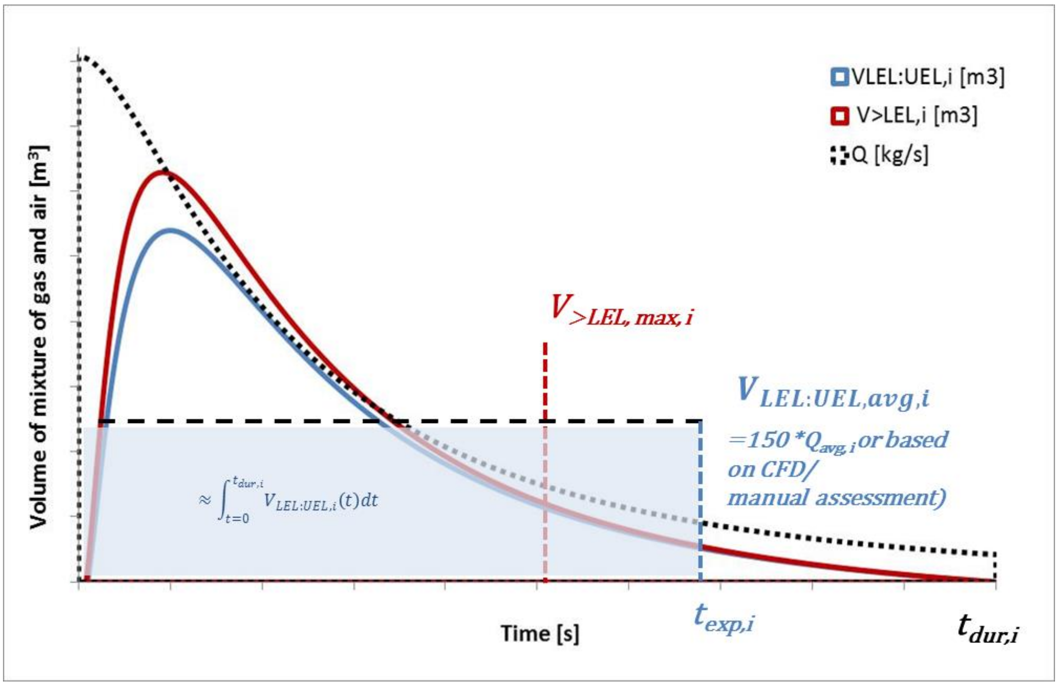


Figure 3.3 - Example a); time dependent gas cloud volume for a transient leak in a typical offshore process module and corresponding graphical representation of the estimation by generic gas exposure model. The example displays a case where the generic model generates quite accurate estimate of the actual gas cloud parameters

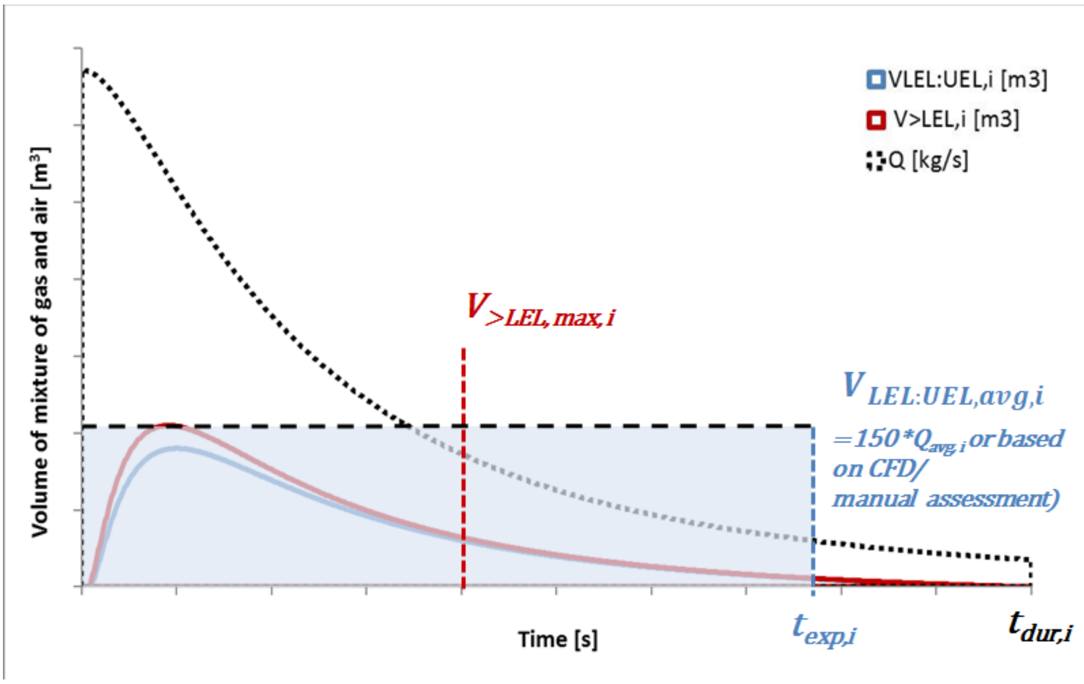


Figure 3.4 - Example b); time dependent gas cloud volume for a transient leak in a typical offshore process module and corresponding graphical representation of the estimation by generic gas exposure model. The example displays a case where the generic model overestimates the actual gas cloud parameters

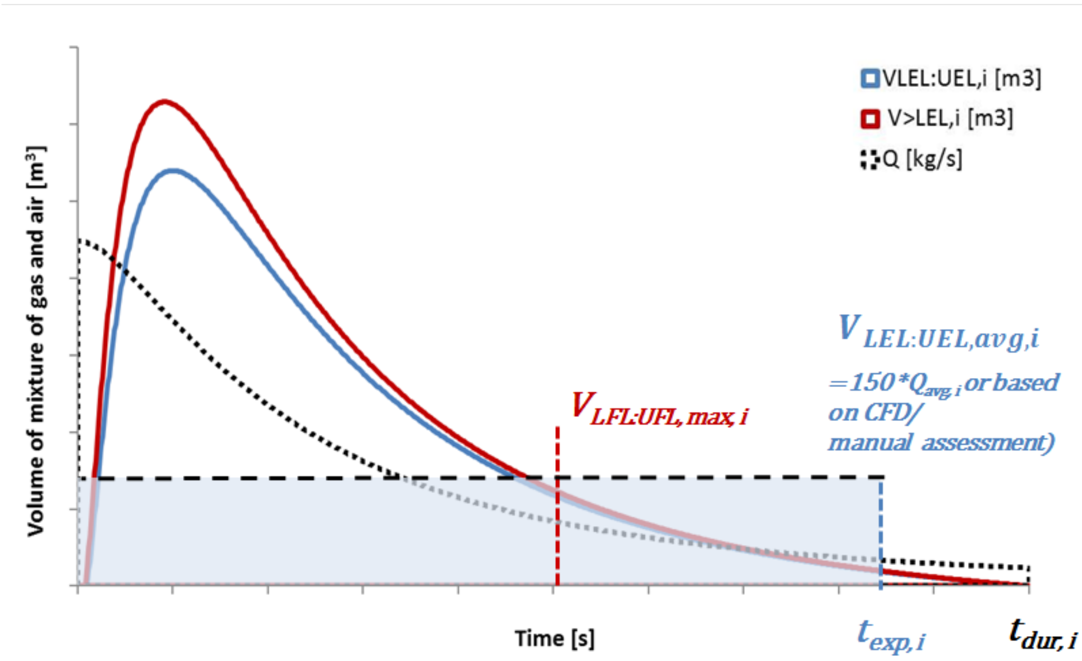


Figure 3.5 - Example c); time dependent gas cloud volume for a transient leak in a typical offshore process module and corresponding graphical representation of the estimation by generic gas exposure model. The example displays a case where the generic model underestimates the actual gas cloud parameters

For the leaks on UKCS installations, the gas cloud parameters are strictly estimated according to the available data in the HCR database (no supplementary information has been identified). Some additional information has been provided by Centrica on the large leak at Rough B in 2006, which has been incorporated in the dataset.

In the NCS dataset, accident investigation reports are available for most leaks occurring 2001 onwards where the initial leak rate was larger than 1 kg/s. The information in the accident investigation reports has enabled specific assessment of some of the parameters. In most cases, only some of the parameters can be quantified from the information in the accident investigation report. Hence, the resulting estimation of the gas cloud parameters is partly estimated by manual assessment, and partly by the generic model. The parameters for the cases where manual assessment has been possible are reported explicitly in Table 6.2 in Chapter 0.

It has been focused to improve the accuracy of the estimate of the gas cloud exposure resulting from the largest leaks constituting the major contribution to the aggregated gas exposure volumes. In a few of cases, CFD simulations were run to evaluate such leaks and have been utilised to set the gas exposure. In a couple of cases, the original simulation case has been rerun with Kameleon FireEx® to improve the precision of the assessment of the exposed volume within the volume enveloping the platform. The assessment of these scenarios is described separately in the following section. The uncertainty related to the estimate of the gas exposure is largely governed by the accuracy of the assessment for these few large leaks.

3.2 Specific Assessment of the contribution from largest leaks

The major contributors to the gas exposure parameters are shown in Figure 3.6 and Figure 3.7. The leaks in these figures constitute about 2/3 of the aggregated gas exposure for all leaks for both parameters. The specific evaluation of 5 out these leaks is presented in Table 3.3. These 5 leaks constitute about 40% of $V_{LFL:UFL,max,NCS,01-17}$ and 60% of $V_{LFL:UFL,max,NCS,01-17} \cdot t_{exp}$. The detailed investigation of these scenarios enhances the precision of the estimate of the gas cloud parameters for these scenarios considerably.

The accuracy of the estimate of aggregated $V_{LFL:UFL,max,NCS,01-17}$ and $V_{LFL:UFL,avg,NCS,01-16}$ would be significantly improved if CFD simulations were carried out for more of the large leaks. Geometrical models with adequate quality are expected to be available for many of the relevant installations and most accident investigation reports provide a sufficient basis to establish good estimates of the boundary conditions. It is suggested to perform this work when the MISOF model is updated/revised next time or in a separate project initiated by stakeholders in the industry.

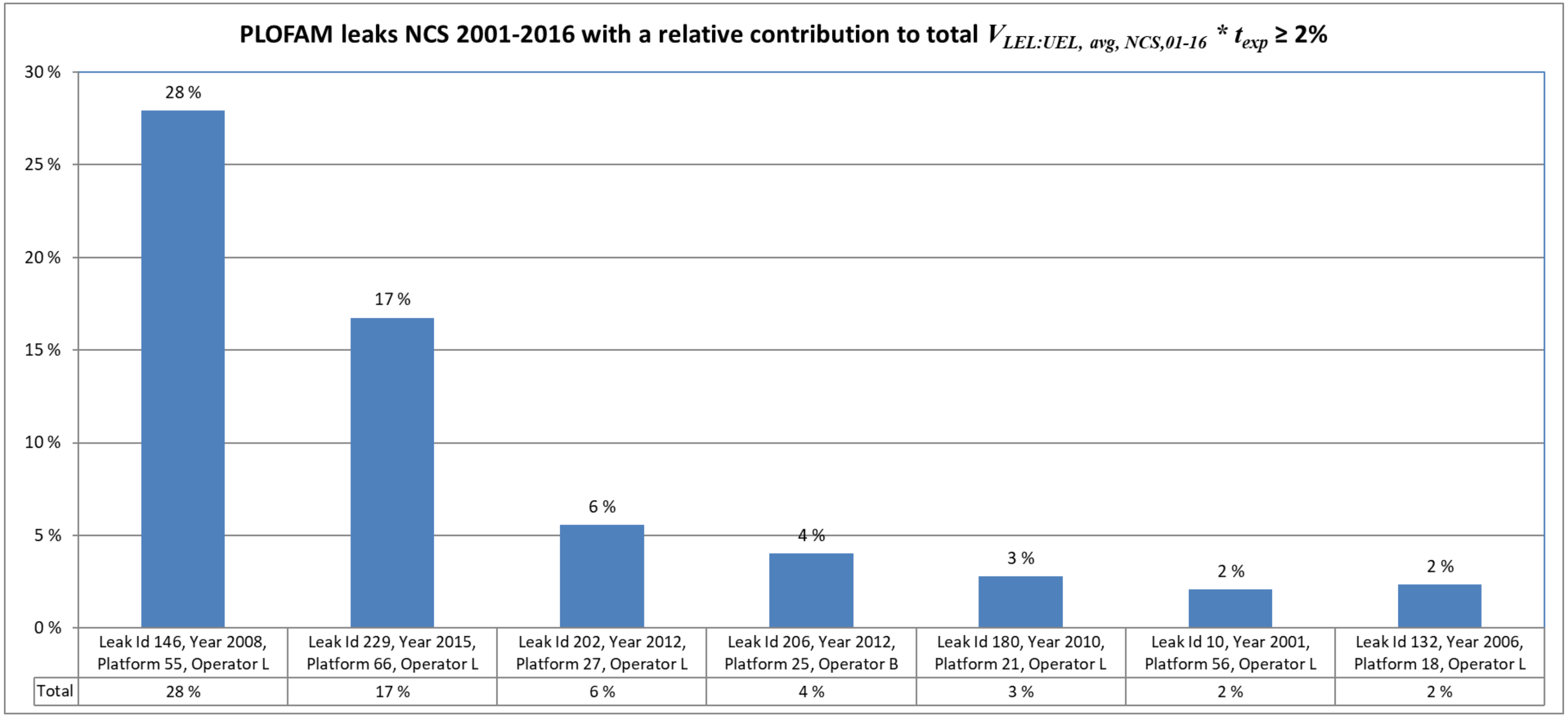


Figure 3.6 - Major contributors to $V_{LFL:UFL,avg,NCS,01-16}$. In total, these leaks constitute about 61% of $VT_{LFL:UFL,avg,NCS,01-16}$

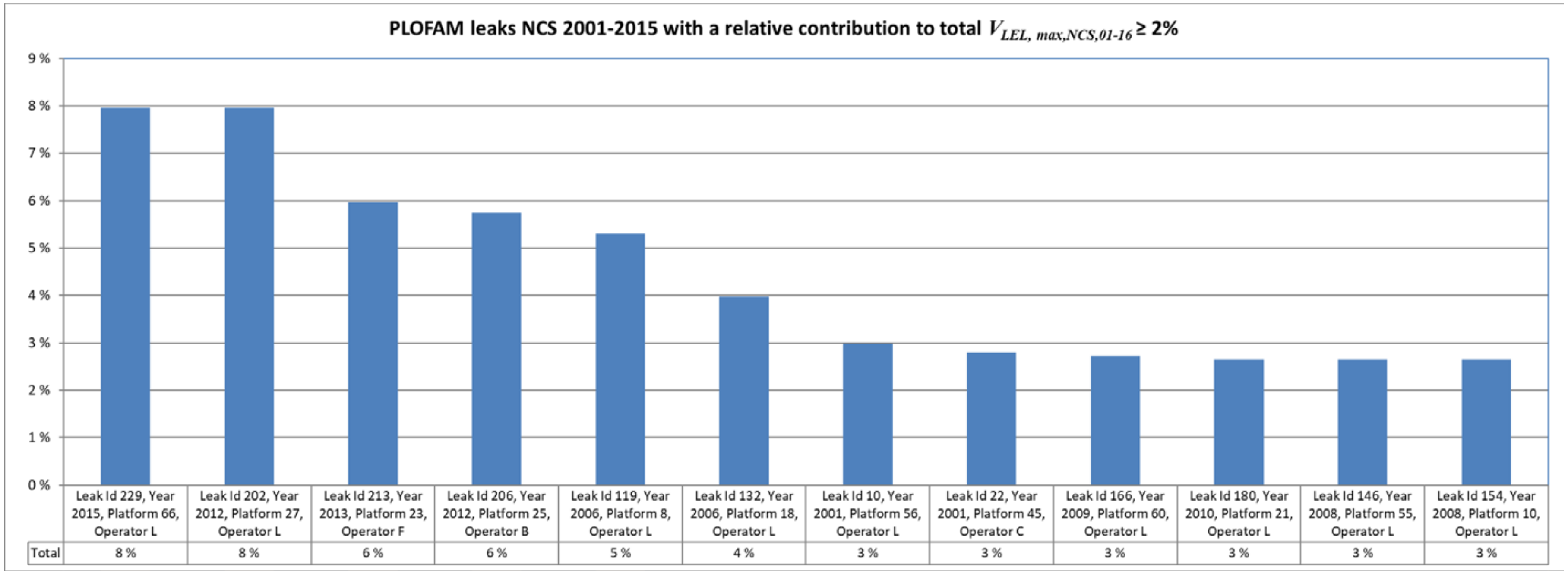


Figure 3.7 - Major contributors to $V_{LFL:UFL,max,NCS,01-16}$. In total, these leaks constitute about 60% of $V_{LFL:UFL,max,NCS,01-16} \cdot t_{exp}$

Table 3.3 – Large leaks in the dataset for NCS

ID	Year	Initial leak rate [kg/s]	General description	Assessment of scenario
119	2006	930	Massive leak of 26 tons of gas in windy conditions in process area at semi-submersible with effective natural ventilation rate. The gradient of transient leak rate was very steep.	Gas exposure parameters set based on CFD simulations performed with Kameleon FireEx KFX®. Only the gas within the boundaries of the process module is logged. The resulting gas exposure is shown in Figure 3.8 and Figure 3.9.
146	2008	10	Oil leak in substructure with long duration. A fraction of the leak evaporated forming a big combustible gas cloud in parts of the substructure. The substructure is mechanically ventilated allowing the quite small evaporation rate to generate a substantial gas cloud.	Parameters set based on an assessment of the description of the gas exposure in the accident investigation report. The uncertainty associated with the assessment is prominent. A more precise estimate could be obtained by running a CFD simulation.
154	2008	26	Short duration (about 1.5 minute) gas leak in typical offshore process module. The gradient of the transient leak rate is very steep.	Gas exposure parameters set based on CFD simulations performed with Kameleon FireEx KFX®. Only the gas within the boundaries of the process module is logged. The resulting gas exposure is shown in Figure 3.10 and Figure 3.11 .
202	2012	16.90	Gas leak with long duration in a process area with high natural ventilation rate	Parameters set based on evaluation of the CFD simulations presented in the accident investigation report
229	2015	8	3-phase leak with long duration in a typical process module.	Parameters set based on evaluation of the CFD simulations presented in the accident investigation report

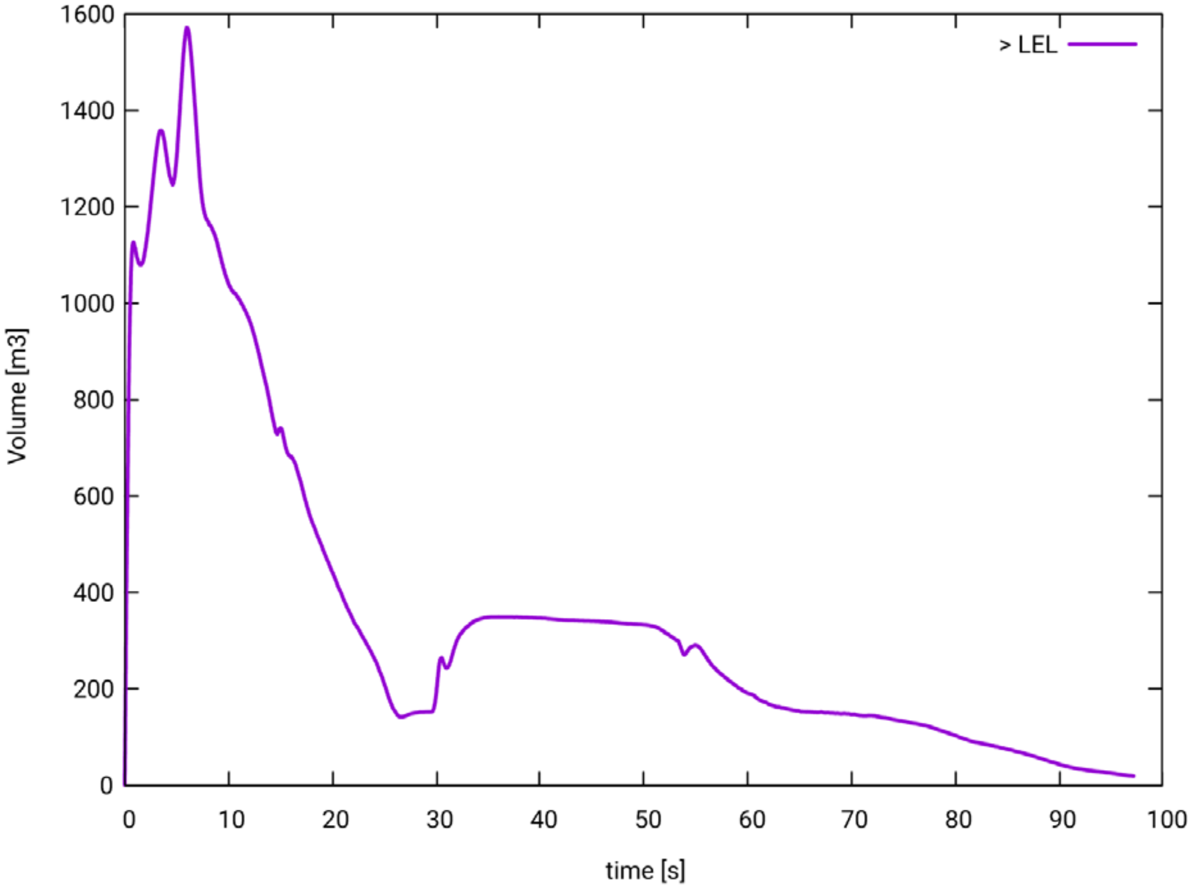


Figure 3.8 - Leak ID 146: Time history for the volume of gas with concentration higher than LFL, $V_{>LFL,146}(t)$, estimated by CFD simulation performed with Kamelon FireEx KFX®

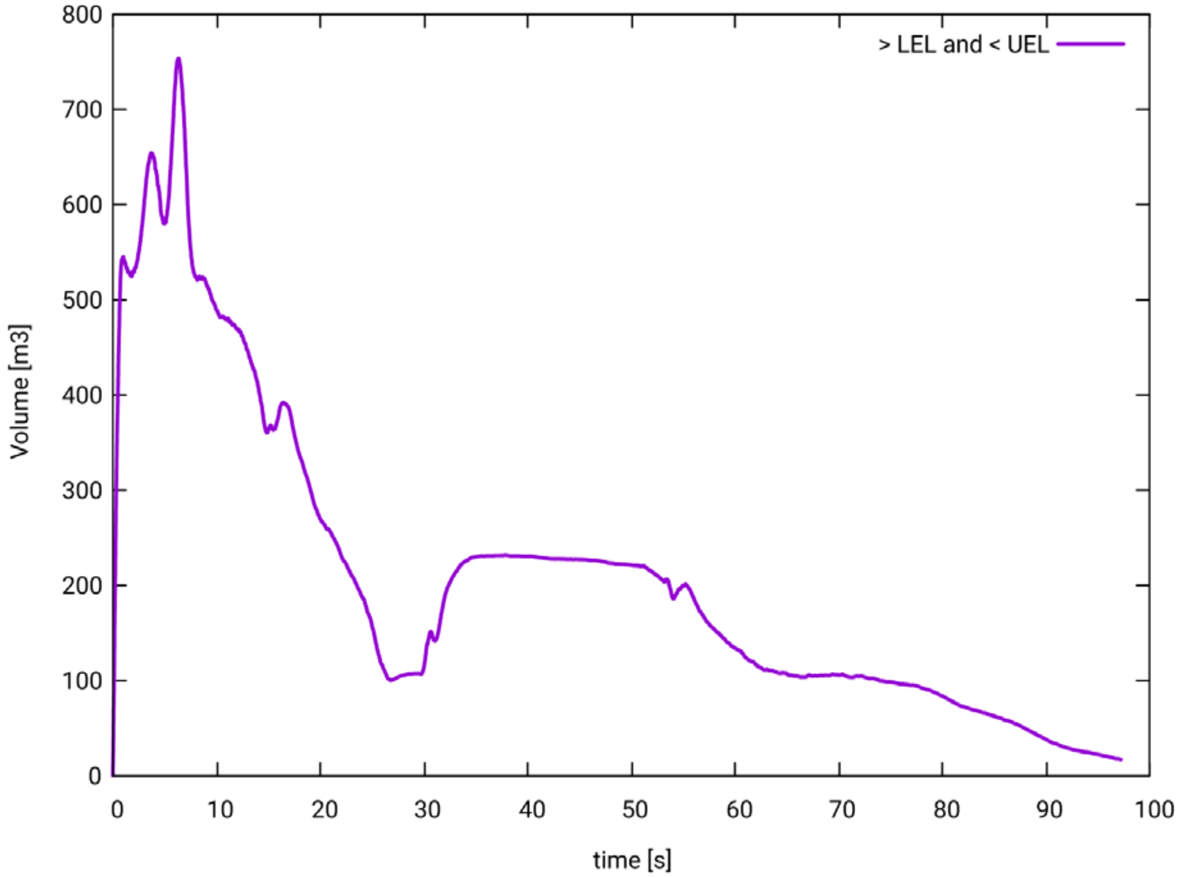


Figure 3.9 - Leak ID 146: Time history for the combustible volume of gas, $V_{\mathrm{LFL}:LFL,146}(t)$, estimated by CFD simulation performed with Kamelon FireEx KFX®

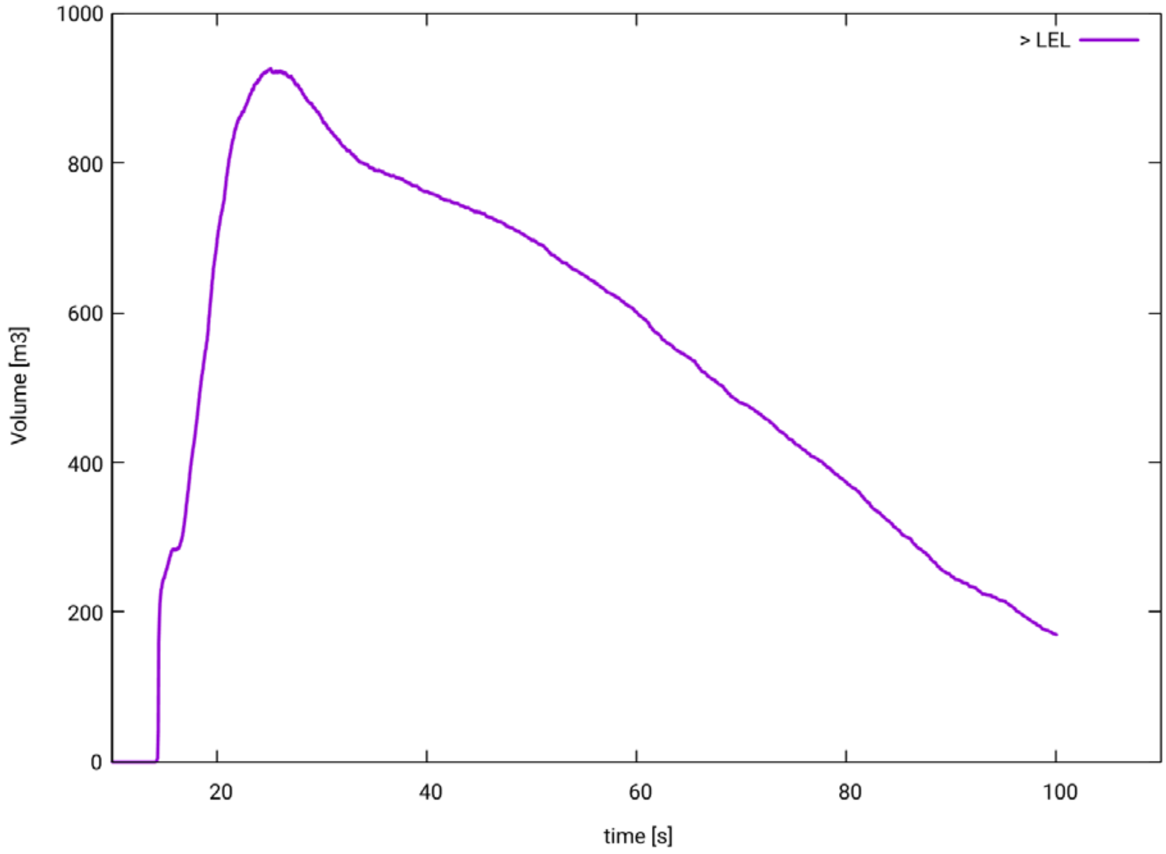


Figure 3.10 - Leak ID 154: Time history for the volume of gas with concentration higher than LFL, $V_{>LFL,154}(t)$, estimated by CFD simulation performed with Kamelon FireEx KFX®

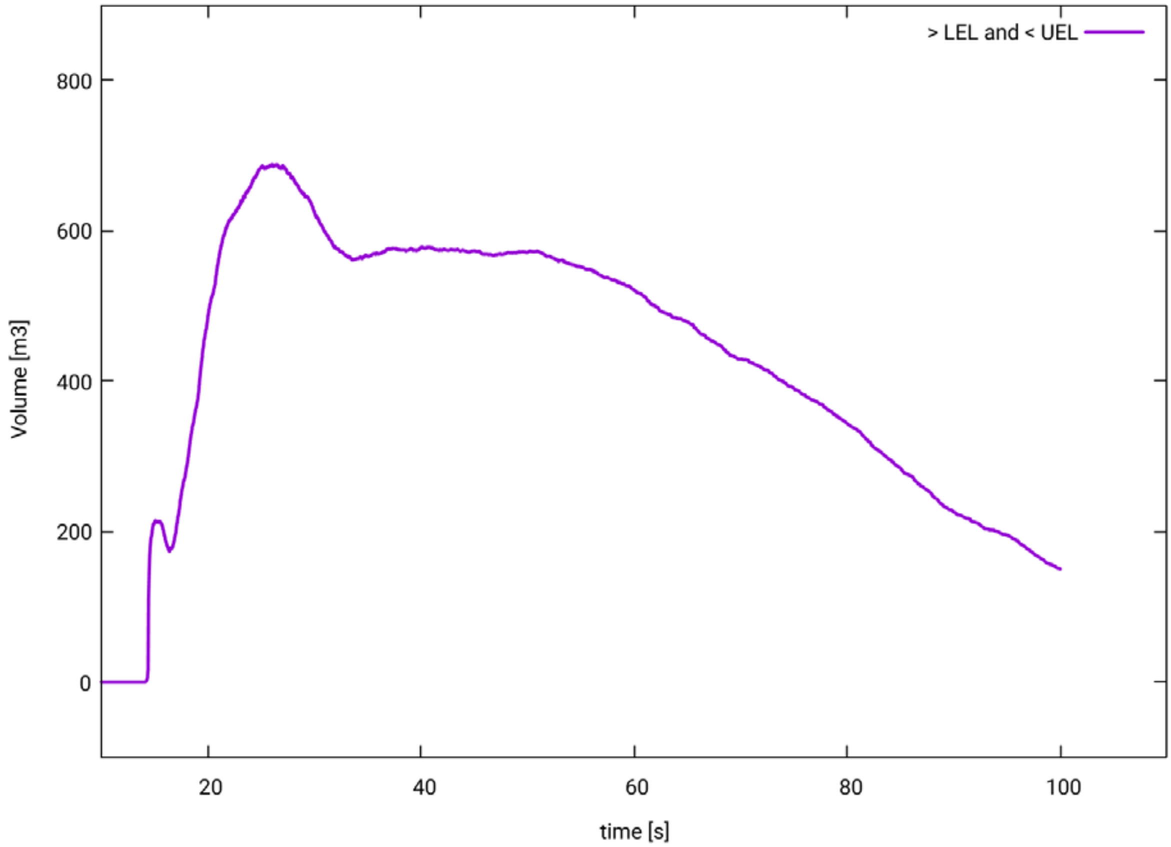


Figure 3.11 - Leak ID 154: Time history for the combustible volume of gas, $V_{\mathrm{LFL}:LFL,154}(t)$, estimated by CFD simulation performed with Kamelon FireEx KFX®

3.3 Estimate of exposed volume

The resulting aggregated gas exposure for all leaks at NCS in the period 01.01.2001 – 31.12.2017 is as follows:

$$V_{LFL:UFL,max,NCS,01-17} = 39\ 686\ m^3$$

$$VT_{LFL:UFL,avg,NCS,01-17} = 10\ 830\ 476\ m^3 \cdot sec$$

The contributions from each incident are presented in Table 6.2.

4 Estimation of key parameters for the period 1992 - 2000

4.1 Estimate of number of leaks

Detailed information about all leaks occurring at installations located in the NCS before 2001 is not available. However, data from the authorities; "Oljedirektoratet" (OD)/Norwegian Petroleum Directorate (NPD), "Petroleumstilsynet" (Ptil)/Petroleum Safety Authority (PSA), the former operator Norsk Hydro and the operator Statoil provides sufficient information to generate a good estimate of the number of leaks per year. The estimate in terms of initial leak rate is also quite good, but more uncertain than the estimated number of leaks.

The recorded number of leaks at the Norsk Hydro and Statoil installations is considered to have the same quality as the data for the period 01.01.2001-31.12.2017, which has been used as the main basis for the PLOFAM model.

The available data are as follows:

- Leaks reported by Petroleumstilsynet in the period 1996– 2000 presented in Table 4.2 (taken from the Trends in Risk Level report (RNNP))
- Leaks reported by NPD presented in Table 4.1. These leaks include leaks from any system having any initial leak rate. Hence, the number of leaks is very different from those specifically covering leaks from process leaks. For the two overlapping years (1996 and 1997) where the data coincides with PSA data (see Table 4.2), the relative factor becomes 0.23 (~ (36 + 34)/(128+177)). In another year, 1 out of 4 leaks in the NPD data set is expected to be a process leak according to the definition in PLOFAM
- Reported incidents by Norsk Hydro and Statoil for the period 1994-2000 presented in Ref. /1/ (see *Scandpower, Validering/uttesting av ny lekkasjefrekvensmodell, report number 80.207.118/R1, 17.04.2009* included as part of the report). These leaks are shown in Table 4.4
- The number of equipment years per year extracted from the database generated in the PLOFAM project. The data describing the relevant subset of equipment years is presented in Table 4.5.

The number of leaks for the entire period 01.01.1992-31.12.2000 is obtained by scaling the incidents at Norsk Hydro and Statoil installations proportionally with the corresponding equipment years. The calculations are shown in Table 4.6. The resulting estimate becomes:

$$N_{leak,NCS,92-00} = 228.8\ leaks$$

The incidents that form the basis for the method, *i.e.* the incidents at Norsk Hydro and Statoil installations, are considered to correspond to the definition of process leaks in PLOFAM. This data is considered more reliable than the RNNP data for the same period. The number of leaks at NCS used as a basis for PLOFAM is given in Table 4.3 together with the ratio between the number of PLOFAM leaks and RNNP leaks (0.84). As explained in Chapter 4.1.2, the total number of leaks in the period 1992 – 2000 estimated from the NPD and RNNP data is 266 leaks. These leaks correspond to the leaks reported by RNNP. Multiplying this number by ratio between the number of PLOFAM leaks and RNNP leaks (0.84), gives an estimated number of PLOFAM leaks as 223.2 for the period 1992 - 2000. This supports the theory that the leak incidents from Norsk Hydro and Statoil installations correspond to the definition of process leaks in PLOFAM.

An estimate of the distribution of leaks per year based on the data provided by NPD and PSA is presented in the following section.

Table 4.1 – Leaks reported by Norwegian Petroleum Directorate (NPD), Ref. /2/. These leaks include leaks from any system having any initial leak rate

Year	Number of leaks
1992	106
1993	97
1994	124
1995	120
1996	128
1997	177
Total	752

Table 4.2 – Trends in Risk Level 2015 (RNNP), Ref. /3/

Year	0.1 kg/s ≤ Q < 1 kg/s	1 kg/s ≤ Q ≤ 10 kg/s	10 kg/s < Q	0.1 kg/s ≤ Q
1996	27	9	0	36
1997	28	6	0	34
1998	21	8	0	29
1999	16	5	1	22
2000	28	14	0	42
2001	15	6	0	21
2002	33	7	1	41
2003	18	7	0	25
2004	14	5	1	20
2005	13	4	1	18
2006	12	1	2	15
2007	6	4	0	10
2008	10	3	1	14
2009	10	6	0	16
2010	13	1	1	15
2011	8	3	0	11
2012	3	1	2	6
2013	8	1	0	9
2014	5	1	1	7
2015	6	4	0	10
Total	294	96	11	401

Table 4.3 – PLOFAM leaks and ratio PLOFAM leaks/RNNP leaks

Year	PLOFAM 0.1 kg/s ≤ Q	RNNP 0.1 kg/s ≤ Q	Ratio PLOFAM/RNNP
2001	19	21	0.90
2002	27	41	0.66
2003	18	25	0.72
2004	19	20	0.95
2005	15	18	0.83
2006	14	15	0.93
2007	8	10	0.80
2008	13	14	0.93
2009	15	16	0.94
2010	14	15	0.93
2011	9	11	0.82
2012	6	6	1.00
2013	9	9	1.00
2014	5	7	0.71
2015	9	10	0.90
Total	**200**	**238**	**0.84**

Table 4.4 – Leaks at Norsk Hydro installations in the period 01.07.1994 – 31.12.2000 and Statoil installations in the period 01.01.1996 – 31.12.2000 (RNNP), Ref. /1/

Year	0.1 kg/s ≤ Q < 1 kg/s	1 kg/s ≤ Q ≤ 10 kg/s	10 kg/s < Q	0.1 kg/s ≤ Q
Norsk Hydro	23	7	1 [1)]	31
Statoil	45	21	1	67
Total	68	29	2	98

1) The leak at Platform 62 in 1998 (see Chapter 0).

Table 4.5 – Equipment years in the period 01.01.1992 – 31.12.2000, (see Ref. /1/ in the main report)

Subset of installations	Equipment years [1)] (equipment per year)
Norsk Hydro (NH) installations in the period 01.07.1994-31.12.2000	252,447
Norsk Hydro (NH) installations in the period 01.01.1992-31.12.2000	324,571
Statoil installations in the period 01.01.1996-31.12.2000	425,462
Statoil installations in the period 01.01.1992-31.12.2000	656,780
All other operators than Statoil & NH in in the period 01.01.1992-31.12.2000	585,994
All installations on NCS in the period 01.01.1992-31.12.2000	**1,567,344**

1) Total of valves, standard flanges, instruments, pumps, heat exchangers, compressors and vessels

Table 4.6 – Resulting estimate of number of leaks at NCS in the period 1992 – 2000 based on leaks reported by Norsk Hydro and Statoil

Year	0.1 kg/s ≤ Q < 1 kg/s	1 kg/s ≤ Q ≤ 10 kg/s	10 kg/s < Q	0.1 kg/s ≤ Q	Comment
Norsk Hydro 1992-2000	29.6	9.0	1.3	39.9	Norsk Hydro leaks in Table 4.4 scaled with 324,571/252,447 taken from Table 4.5.
Statoil 1992-2000	69.5	32.4	1.5	103.4	Statoil leaks in Table 4.4 scaled with 656,780/425,462 taken from Table 4.5.
Total Norsk Hydro & Statoil 1992-2000	99.0	41.4	2.8	143.3	Total Norsk Hydro and Statoil in the period 1992-2000.
NCS 1992-2000 without PLOFAM adjustment	158.2	66.1	4.5	228.8	Norsk Hydro and Statoil leaks scaled with 1,567,344/(324,571+656,780) taken from Table 4.5.
Distribution	0.69	0.29	0.02	1.00	Relative distribution

4.1.1 Number of pump leaks

In order to estimate the ignition probability associated with leaks originating from pumps, the number of leaks from pumps in the period before 2001, , is assumed to be proportional to the fraction of leaks from pumps in the period after 2000. The fraction of leaks from pumps in the period 2001 onwards is 3/217. The number of leaks from pumps in the period 01.01.1992 – 31.12.2000 becomes:

$$N_{leak,pump,NCS,92-00} = \frac{228.8 \cdot 3}{217} = 3.2\ leaks$$

4.1.2 Distribution of leaks per year in the period 1992-2000

The estimated total number of leaks for the entire period 01.01.1992 – 31.12.2000 presented in the previous section (228.8 leaks having an initial leak rate ≥ 0.1kg/s) is distributed per year by utilising the NPD and PSA data presented in Table 4.1 and Table 4.2. Firstly, the NPD leaks for the period 1992-1995 are scaled with the factor established for the overlapping years (1996 and 1997). The factor becomes 0.23 (~ (36 + 34)/(128+177)). Using this factor, the number of process leaks according to the NPD data set can be estimated for the period 1992-1995. This ensures a complete time series for the period 1992 through 2000 is obtained, and is presented in the second column from the left in Table 4.7. The relative distribution based on this result is presented in the neighbouring column on the right, which enables the redistribution of the estimate of the total number of leaks (228.8 leaks). The result is shown in the rightmost column.

Note that the total number of leaks for the period 1992-2000 estimated from the NPD and RNNP data is 266 leaks, which is somewhat higher than the estimate obtained based on Statoil/Norsk Hydro data. One reason for this is uncertainty is related to the estimate in the NPD data and the applied factor scaling the leaks relative to the RNNP data. Another factor explaining the deviation is probably related to the reported leaks by some operators for the period 1996-2000 which were based on an assessment of expected number of small leaks. Interview with experts compiling the data at that time suggests that the number of small leaks (< 1 kg/s) was slightly overestimated due to this practice (Ref. /4/).

Table 4.7 – Resulting estimate of distribution of the total number of leaks 1992 – 2000 based on leaks reported by NPD, Petroleumstilsynet and Statoil/Norsk Hydro.

Year	Distribution of leaks (Q ≥ 0.1 kg/s) obtained from the NPD and PSA data (see Table 4.1 and Table 4.2)	Best estimate relative distribution based on NPD and PSA data of leaks	Best estimate of the distribution of leaks (Q ≥ 0.1 kg/s) per year for the period 1992-2000 based on incidents at Statoil/Norsk Hydro installations
1992	24 [1)]	0.09	**21.0**
1993	22 [1)]	0.08	**19.2**
1994	28 [1)]	0.11	**24.5**
1995	28 [1)]	0.10	**23.7**
1996	36 [2)]	0.14	**31.0**
1997	34 [2)]	0.13	**29.3**
1998	29 [2)]	0.11	**25.0**
1999	22 [2)]	0.08	**19.0**
2000	42 [2)]	0.16	**36.2**
Total	266	1.0	228.8

1) Obtained by scaling the NPD data for these years with 0.23 (based on a factor established based on overlapping years 1996 and 1997)

2) From Trends in Risk Level (RNNP)

4.2 Ignited leaks

One ignited process leak (i.e. judged to comply with a definition of a process leak according to the PLOFAM leak frequency model, see Ref. /1/ in main report) occurring at an installation located in the NCS after 1992 has been identified. The incident occurred at Platform 57 (according to anonymising of installations in the PLOFAM project) in November 1992. The source of ignition was concluded to be grinding. This demonstrates that hot work class A is an important source of ignition. This incident is however not relevant for setting the parameters covering objects intended for use in explosive atmospheres in the MISOF model.

Furthermore, it is not known whether there were any cases of ignited hydrocarbon leaks from other systems such as risers or wells, with a leak rate beyond 0.1 kg/s in the same period.

The ignited leaks reported in Ref. /5/, addressing ignited leaks in the period 1980-1997, have been reviewed as part of this investigation, and none of the listed incidents are relevant ignitions in accordance to the definition of PLOFAM leaks. For instance, the explosion at Ekofisk in 1992 classified as significant (see 2.4.1), was an internal explosion in a gas turbine resulting from re-ignition of fuel gas following flame out. This is equivalent with what is found in the HCR database covering UKCS installations. There are quite a few recorded ignited leaks, but only 3 are deemed relevant in QRA context addressing process leaks.

Figure 4.1 displays the data basis for the evaluation of a possible time trend in ignited significant explosions (significant explosion means load > 0.2 bar) from the 1980's till the mid 1990's. Figure 4.2 displays the same data, but in this case the sum is irrespective of the assumed explosion load per category with regard to time. The data indicates a downward trend with time, but the uncertainty associated with the data is judged to be significant.

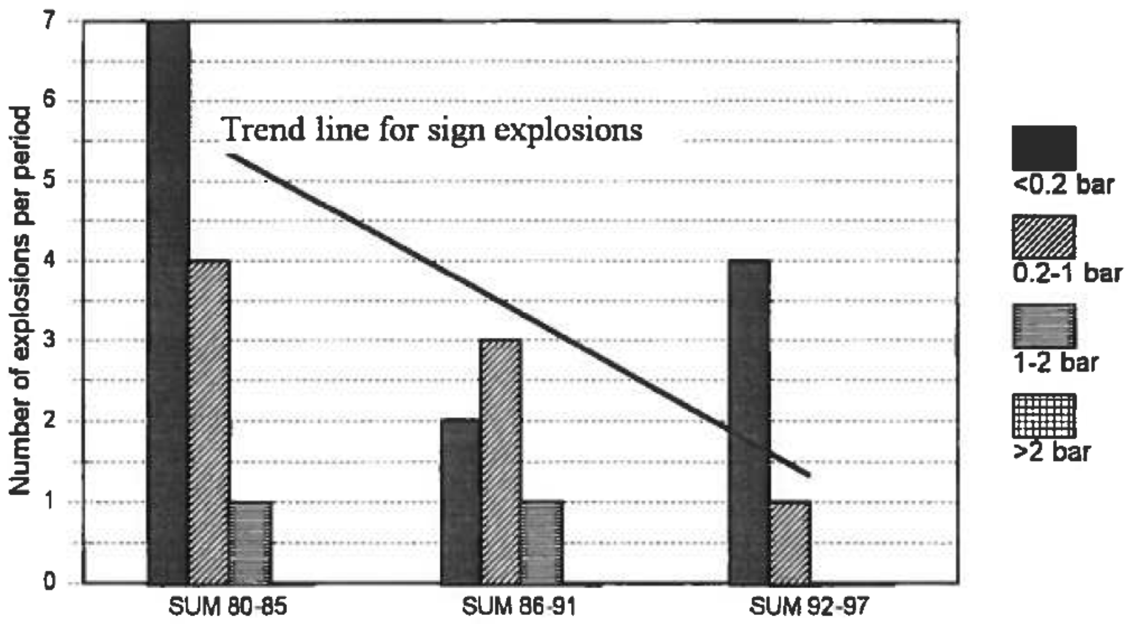


Figure 4.1 - Time trend in significant explosions indicated in Ref. /5/. The data are gathered from installations in the North Sea

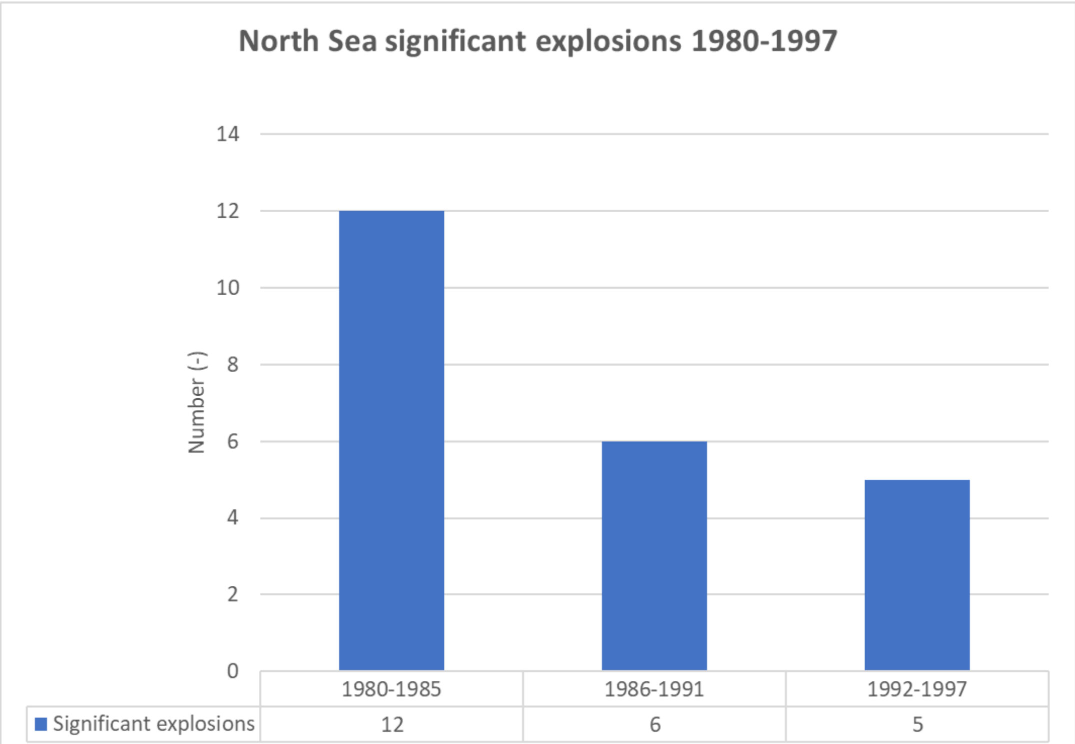


Figure 4.2 - Time trend in significant explosions based on Ref. /5/ presented in Figure 4.1

4.3 Exposed volume

The exposed volume associated with the leaks occurring before 2001 can be estimated assuming that the exposed volume is proportional to the number of leaks. The number of leaks occurring before year 2001 was estimated to about 229 in the previous section.

The estimate of the exposed volume for leaks occurring after year 2000 is dominated by large leaks (*i.e.* initial leak rate > 10 kg/s). Hence, it is important to assess whether the distribution of leaks with respect to initial leak rate is different for the periods before 2001 and 2001 onwards.

The available data indicates that the fraction of leaks occurring before 2001, having an initial leak rate beyond 10 kg/s, was about 2% (2 out of 98 leaks, see Table 4.4).

It is believed that the most severe leak at the Norsk Hydro installations (occurring at Platform 62 according to anonymization procedure in PLOFAM) was a multiphase leak due to the rupture of a ¾″ piping connected to a 1st stage separator outlet piping. This resulted in an initial leak rate of about 18 kg/s (classified as less than 10 kg/s in Table 4.4) and the gas fraction was around 10 mass%. The total amount of oil released was several tons and the dominant fluid phase was liquid (about 10 mass% of the initial leak was gaseous). The most severe leak at Statoil installations in the period 1996-2001 occurred at Platform 2 (according to anonymization procedure in PLOFAM) in 1999. The released amount was about 400 kg. The initial leak has been assessed to be somewhat bigger than 10 kg/s.

The fraction of recorded PLOFAM leaks after 2000, having an initial leak rate beyond 10 kg/s is approximately 7% (15 out of 217 leaks). For 3 of the large leaks, the initial leak rate was beyond 100 kg/s (3 out of 217 leaks).

It is reasonable to believe that the actual leak rate was somewhat higher for some of the leaks occurring before 2001 than reported in RNNP. Several of the RNNP leaks occurring after 2000 were reclassified in terms of leak rate following the detailed review of leaks performed in the PLOFAM project: The actual initial leak rate was concluded to be less for some incidents, but generally more leaks were reclassified as having a higher initial leak rate.

Based on above, the fraction of large leaks in the period before year 2001 is believed to be somewhat less than in the period 2001 onwards. One approach is to try to set a general adjustment factor to account for this as the average exposed volume for all leaks before 2001 is expected to be less than for the recorded leaks occurring after 2000. It is however hard to set to an average adjustment factor accurately. It is therefore suggested to scale the estimated aggregated exposed volumes, for the period after 2000, by excluding the three biggest contributors. This will ensure that we account for leaks equivalent with the known large leaks which occurred after the year 2000 which possibly did not occur in the 1990's. It should be noted that underestimating the exposed volume will add conservatism to the methodology used for the estimation of the parameters in MISOF based on the NCS data before year 2001. However, the obtained estimates below should be considered best estimates.

The three largest contributors to the exposed volume parameters are presented in Figure 3.6 and Figure 3.7. Excluding the three contributors to the estimate of $V_{LFL:UFL,max,NCS,01-17}$ and $VT_{LFL:UFL,avg,NCS,01-17}$, the estimates become as follows (marked with an apostrophe):

$$V'_{LFL:UFL,max,NCS,01-17} = 31\,436\ m^3$$

$$VT'_{LFL:UFL,avg,NCS,01-17} = 5\,430\,476\ m^3 \cdot sec$$

Then scaling these estimates proportionally, the resulting estimate for the entire period becomes:

$$V_{LFL:UFL,max,NCS,92-17} = V_{LFL:UFL,max,NCS,01-17} + V'_{LFL:UFL,max,NCS,01-17} \cdot \frac{N_{leak,NCS,92-00}}{N_{leak,NCS,01-17}} =$$

$$= 39\,686\, m^3 + 31\,436\, m^3 \cdot \left(\frac{228.8}{217}\right) = 77\,482\, m^3$$

$$VT_{LFL:UFL,avg,NCS,92-17} = VT_{LFL:UFL,avg,NCS,01-17} + VT'_{LFL:UFL,avg,NCS,01-17} \cdot \frac{N_{leak,NCS,92-00}}{N_{leak,NCS,01-17}}$$

$$= 10\,830\,476\, m^3 \cdot sec + \cdot 5\,430\,476\, m^3 \cdot sec \left(\frac{228.8}{217}\right) = 16\,557\,312\, m^3 \cdot sec$$

5 Recorded incidents at NCS 2001-2017

Table 5.2 lists the relevant incidents recorded at NCS with an initial leak rate ≥ 0.1 kg/s in the period 01.01.2001 – 31.12.2017. In total 217 incidents are listed. They are given a unique ID ranging from 1 – 254. Descriptions of the data fields in Table 5.2 are given in Table 5.1.

Table 5.1 - Description of the data fields in Table 5.2

Heading	Description
ID	ID running from 1 to 254.
Year	The year that the leak occurred
Installation	Anonymized name of the installation
In NCS population dataset	"Yes", if the leak occurred at an installation that is included in the NCS population data set. "No" otherwise. See TN-2
Initial leak rate 2015/2016 [kg/s]	Initial leak rate based on a thorough review of investigation reports performed by LR and Safetec in 2015 and 2016.
Medium	"G"=Gas, "L" = Liquid
Equipment type	The equipment type associated with the leak
Leak scenario	Leak scenario according to PLOFAM (see TN-4 in Ref. /1/ in main report)
Commissioned before 01.01.2001	"Yes" if the leak occurred at an installation commissioned before 01.01.2001. No otherwise
Decommissioned before 31.12.2017	"Yes" if the leak occurred at an installation decommissioned before 31.012.2017. No otherwise
System	The system associated with the leak

Table 5.2 – All relevant incidents recorded at NCC, with initial leak rate ≥0.1 kg/s, in the period 01.01.2001 – 31.12.2017. The total number of leaks is 217. The leak scenario is in accordance with the PLOFAM model, Ref. /6/ (see TN-4)

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
3	2001	Platform 57	YES	0.2	L	Valve	Significant leak	YES	NO	Process system
4	2001	Platform 55	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
5	2001	Platform 48	YES	0.15	G	Valve	Significant leak	YES	NO	Process system
6	2001	Platform 22	YES	0.5	L	Valve	Significant leak	YES	NO	Process system
8	2001	Platform 41	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
9	2001	Platform 41	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
10	2001	Platform 56	YES	5	G	Valve	Significant leak	YES	NO	Open drain system
11	2001	Platform 56	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
12	2001	Platform 22	YES	0.5	G	Standard flange	Significant leak	YES	NO	Fuel gas system
13	2001	Platform 2	YES	0.125	G	Valve	Significant leak	YES	NO	Process system
14	2001	Platform 21	YES	1.5	G	Hose	Significant leak	YES	NO	Process system
15	2001	Platform 2	YES	1	G	Instrument	Significant leak	YES	NO	Process system
17	2001	Platform 9	YES	0.7	G	Valve	Significant leak	YES	NO	Process system
18	2001	Platform 53	YES	1.5	G	Instrument	Significant leak	YES	NO	Process system
19	2001	Platform 7	YES	0.6	G	Steel pipe	Significant leak	YES	NO	Flare system
20	2001	Platform 51	YES	0.9	L	Hose	Significant leak	YES	NO	Unknown
21	2001	Platform 23	YES	1.6	G	Unknown	Significant leak	YES	NO	Unknown
22	2001	Platform 45	YES	4.7	G	Hose	Significant leak	NO	NO	Unknown
23	2001	Platform 42	YES	0.1	G	Unknown	Significant leak	NO	NO	Unknown
24	2002	Platform 55	YES	0.2	G	Steel pipe	Significant leak	YES	NO	Process system
25	2002	Platform 64	YES	0.5	G	Instrument	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
26	2002	Platform 22	YES	0.2	G	Valve	Marginal leak	YES	NO	Process system
27	2002	Platform 22	YES	2.5	G	Vent	Significant leak	YES	NO	Fuel gas system
29	2002	Platform 60	YES	0.8	G	Instrument	Significant leak	YES	NO	Process system
31	2002	Platform 8	YES	0.3	G	Valve	Significant leak	YES	NO	Process system
32	2002	Platform 1	YES	0.15	G	Valve	Significant leak	YES	NO	Process system
33	2002	Platform 29	YES	22	G	Valve	Significant leak	YES	NO	Flare system
34	2002	Platform 54	YES	2	G	Vent	Significant leak	NO	NO	Produced water system
36	2002	Platform 4	YES	0.36	G	Standard flange	Significant leak	YES	NO	Process system
37	2002	Platform 29	YES	0.5	G	Instrument	Significant leak	YES	NO	Process system
38	2002	Platform 55	YES	0.84	G	Standard flange	Significant leak	YES	NO	Process system
39	2002	Platform 9	YES	0.8	G	Valve	Significant leak	YES	NO	Process system
40	2002	Platform 57	YES	10	G	Valve	Significant leak	YES	NO	Process system
41	2002	Platform 62	YES	0.13	L	Valve	Significant leak	YES	NO	Process system
42	2002	Platform 2	YES	0.15	G	Standard flange	Marginal leak	YES	NO	Process system
43	2002	Platform 17	YES	1.51	G	Hose	Significant leak	YES	NO	Process system
44	2002	Platform 56	YES	0.55	G	Valve	Significant leak	YES	NO	Process system
45	2002	Platform 18	YES	0.6	G	Steel pipe	Significant leak	YES	NO	Process system
47	2002	Platform 57	YES	0.17	G	Steel pipe	Significant leak	YES	NO	Process system
48	2002	Platform 57	YES	0.4	G	Valve	Significant leak	YES	NO	Process system
49	2002	Platform 4	YES	0.4	L	Valve	Marginal leak	YES	NO	Process system / Well system
51	2002	Platform 60	YES	0.8	G	Valve	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
52	2002	Platform 60	YES	0.3	G	Valve	Significant leak	YES	NO	Process system
53	2002	Platform 2	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
54	2002	Platform 55	YES	1.16	G	Valve	Significant leak	YES	NO	Process system
56	2002	Platform 22	YES	0.1	G	Valve	Significant leak	YES	NO	Process system
57	2003	Platform 56	YES	0.4	G	Instrument	Significant leak	YES	NO	Process system
60	2003	Platform 7	YES	0.3	L	Standard flange	Marginal leak	YES	NO	Process system
61	2003	Platform 22	YES	2	G	Valve	Significant leak	YES	NO	Process system
63	2003	Platform 51	YES	0.1	L	Standard flange	Marginal leak	YES	NO	Process system / Well system
64	2003	Platform 27	YES	0.34	L	Standard flange	Significant leak	YES	NO	Process system
65	2003	Platform 17	YES	0.34	L	Standard flange	Significant leak	YES	NO	Process system
67	2003	Platform 44	YES	9.5	L	Valve	Significant leak	NO	NO	Flare system
68	2003	Platform 8	YES	0.5	G	Valve	Significant leak	YES	NO	Closed drain
69	2003	Platform 62	YES	0.3	G	Instrument	Significant leak	YES	NO	Process system
70	2003	Platform 7	YES	1	G	Standard flange	Significant leak	YES	NO	Process system / Fuel gas system
71	2003	Platform 7	YES	2.1	G	Valve	Significant leak	YES	NO	Process system
72	2003	Platform 48	YES	0.2	G	Filter	Significant leak	YES	NO	Process system
73	2003	Platform 41	YES	0.2	G	Instrument	Significant leak	YES	NO	Process system
74	2003	Platform 7	YES	1	G	Valve	Marginal leak	YES	NO	Process system / Well system
75	2003	Platform 47	YES	0.1	G	Pig trap	Significant leak	NO	NO	Process system
76	2003	Platform 2	YES	1.41	G	Valve	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
77	2003	Platform 69	NO	1.2	G	Standard flange	Significant leak	NO	NO	Process system
79	2003	Platform 56	YES	0.1	G	Valve	Significant leak	YES	NO	Process system / Open drain
80	2004	Platform 70	NO	0.16	L	Filter	Significant leak	YES	NO	Process system
81	2004	Platform 71	NO	0.2	L	Storage tank	Significant leak	NO	NO	Process system / Storage
82	2004	Platform 64	YES	3	L	Filter	Significant leak	YES	NO	Process system
83	2004	Platform 17	YES	2.8	G	Standard flange	Significant leak	YES	NO	Flare system
84	2004	Platform 62	YES	17.2	L	Steel pipe	Significant leak	YES	NO	Process system
85	2004	Platform 57	YES	0.71	G	Hose	Marginal leak	YES	NO	Process system / Well system
86	2004	Platform 69	NO	0.3	G	Steel pipe	Significant leak	NO	NO	Process system
87	2004	Platform 10	YES	0.8	G	Valve	Significant leak	YES	NO	Process system
89	2004	Platform 43	YES	1.65	L	Steel pipe	Significant leak	NO	NO	Process system
90	2004	Platform 46	YES	0.22	G	Standard flange	Significant leak	NO	NO	Process system
91	2004	Platform 72	NO	0.1	L	Valve	Significant leak	YES	NO	Process system
92	2004	Platform 20	YES	0.25	L	Valve	Significant leak	YES	NO	Process system
93	2004	Platform 10	YES	0.8	G	Steel pipe	Significant leak	YES	NO	Process system
94	2004	Platform 22	YES	0.2	G	Process vessel	Significant leak	YES	NO	Process system
95	2004	Platform 23	YES	0.4	G	Instrument	Significant leak	YES	NO	Process system
96	2004	Platform 19	YES	10	G	Standard flange	Significant leak	YES	NO	Flare system
97	2004	Platform 17	YES	0.35	G	Valve	Marginal leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
98	2004	Platform 57	YES	0.6	G	Valve	Significant leak	YES	NO	Process system / Well system
100	2004	Platform 17	YES	2.4	G	Hose	Significant leak	YES	NO	Process system
101	2005	Platform 45	YES	0.1	G	Valve	Significant leak	NO	NO	Process system / Well system
102	2005	Platform 27	YES	0.7	G	Steel pipe	Significant leak	YES	NO	Process system
103	2005	Platform 28	YES	1.8	G	Hose	Significant leak	YES	NO	Process system
104	2005	Platform 5	YES	240	L	Standard flange	Significant leak	NO	NO	Process system
105	2005	Platform 8	YES	0.8	G	Standard flange	Significant leak	YES	NO	Closed drain / Process system
106	2005	Platform 2	YES	1.6	G	Valve	Significant leak	YES	NO	Process system
107	2005	Platform 27	YES	0.12	G	Steel pipe	Significant leak	YES	NO	Process system
108	2005	Platform 21	YES	0.3	G	Valve	Marginal leak	YES	NO	Process system
109	2005	Platform 57	YES	0.68	G	Compressor	Significant leak	YES	NO	Process system
110	2005	Platform 2	YES	2	G	Vent	Significant leak	YES	NO	Produced water / Sea water / Open drain
113	2005	Platform 27	YES	8.03	G	Hose	Marginal leak	YES	NO	Process system
114	2005	Platform 70	NO	1.7	L	Producing well	Marginal leak	YES	NO	Well system
115	2005	Platform 7	YES	0.6	G	Valve	Significant leak	YES	NO	Process system / Flare system
117	2005	Platform 8	YES	0.21	G	Steel pipe	Significant leak	YES	NO	Process system
118	2005	Platform 46	YES	0.5	G	Valve	Significant leak	NO	NO	Process system
119	2006	Platform 8	YES	930	G	Steel pipe	Significant leak	YES	NO	Flare system
121	2006	Platform 28	YES	0.28	G	Valve	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
122	2006	Platform 33	YES	0.15	G	Hose	Significant leak	NO	NO	Process system
123	2006	Platform 62	YES	11.11	G	Standard flange	Marginal leak	YES	NO	Closed drain
124	2006	Platform 9	YES	0.52	G	Valve	Significant leak	YES	NO	Process system
125	2006	Platform 1	YES	0.15	G	Valve	Marginal leak	YES	NO	Process system
127	2006	Platform 56	YES	0.6	G	Instrument	Significant leak	YES	NO	Process system
128	2006	Platform 39	YES	0.5	L	Process vessel	Significant leak	YES	NO	Flare system
129	2006	Platform 44	YES	0.7	G	Instrument	Significant leak	NO	NO	Process system
130	2006	Platform 27	YES	0.2	G	Instrument	Significant leak	YES	NO	Process system
131	2006	Platform 61	YES	0.1	L	Hose	Significant leak	YES	NO	Process system
132	2006	Platform 18	YES	80	G	Standard flange	Significant leak	YES	NO	Flare system
133	2006	Platform 27	YES	0.87	L	Valve	Significant leak	YES	NO	Process system
134	2006	Platform 59	YES	0.14	G	Steel pipe	Significant leak	YES	NO	Process system
136	2007	Platform 62	YES	0.25	G	Valve	Significant leak	YES	NO	Process system
137	2007	Platform 63	YES	1.8	G	Standard flange	Significant leak	YES	NO	Process system
138	2007	Platform 12	YES	0.15	G	Steel pipe	Significant leak	YES	NO	Fuel gas system
140	2007	Platform 56	YES	0.3	G	Instrument	Significant leak	YES	NO	Process system
141	2007	Platform 18	YES	2.83	G	Standard flange	Significant leak	YES	NO	Process system
142	2007	Platform 43	YES	2.5	L	Valve	Significant leak	NO	NO	Process system / Well system
143	2007	Platform 43	YES	1	G	Valve	Significant leak	NO	NO	Process system / Well system
144	2007	Platform 47	YES	1.93	G	Standard flange	Significant leak	NO	NO	Fuel gas system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
146	2008	Platform 55	YES	10	L	Steel pipe	Significant leak	YES	NO	Process system / Storage
147	2008	Platform 4	YES	1.2	G	Valve	Significant leak	YES	NO	Process system
148	2008	Platform 41	YES	0.4	G	Instrument	Significant leak	YES	NO	Process system
149	2008	Platform 17	YES	0.4	G	Steel pipe	Significant leak	YES	NO	Process system
150	2008	Platform 60	YES	0.2	G	Steel pipe	Significant leak	YES	NO	Process system / Well system
151	2008	Platform 7	YES	0.3	G	Valve	Significant leak	YES	NO	Process system / Flare system
152	2008	Platform 37	YES	0.26	G	Steel pipe	Significant leak	NO	NO	Process system / Flare system
153	2008	Platform 37	YES	0.5	G	Standard flange	Significant leak	NO	NO	Process system / Produced water?
154	2008	Platform 10	YES	26	G	Valve	Significant leak	YES	NO	Process system
155	2008	Platform 4	YES	2.8	L	Valve	Significant leak	YES	NO	Process system / Utility system
156	2008	Platform 22	YES	0.24	G	Standard flange	Significant leak	YES	NO	Fuel gas system
157	2008	Platform 22	YES	0.9	G	Valve	Significant leak	YES	NO	Process system
159	2008	Platform 2	YES	0.8	G	Steel pipe	Marginal leak	YES	NO	Process system / Seal oil system
160	2009	Platform 14	YES	0.5	G	Valve	Significant leak	NO	NO	Process system
161	2009	Platform 5	YES	9	G	Valve	Significant leak	NO	NO	Process system
163	2009	Platform 37	YES	0.44	G	Valve	Significant leak	NO	NO	Process system
164	2009	Platform 55	YES	2.8	L	Standard flange	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
165	2009	Platform 22	YES	0.5	G	Valve	Significant leak	YES	NO	Fuel gas system / Diesel system
166	2009	Platform 60	YES	3.42	G	Instrument	Significant leak	YES	NO	Process system / Gas lift system
167	2009	Platform 10	YES	0.815	L	Instrument	Significant leak	YES	NO	Process system
168	2009	Platform 57	YES	0.3	L	Valve	Significant leak	YES	NO	Process system
169	2009	Platform 57	YES	0.2	L	Valve	Significant leak	YES	NO	Process system / Closed drain
170	2009	Platform 2	YES	0.45	L	Valve	Marginal leak	YES	NO	Process system
171	2009	Platform 63	YES	0.66	L	Valve	Significant leak	YES	NO	Process system / Well system
172	2009	Platform 18	YES	1.5	G	Valve	Significant leak	YES	NO	Flare system
173	2009	Platform 72	NO	2	L	Steel pipe	Significant leak	YES	NO	Process system
174	2009	Platform 23	YES	0.25	L	Instrument	Significant leak	YES	NO	Process system
175	2009	Platform 60	YES	0.27	L	Valve	Significant leak	YES	NO	Process system
176	2010	Platform 63	YES	0.276	G	Valve	Marginal leak	YES	NO	Process system / Well system
177	2010	Platform 2	YES	0.4	G	Valve	Marginal leak	YES	NO	Process system
178	2010	Platform 69	NO	0.8	G	Valve	Significant leak	NO	NO	Process system
179	2010	Platform 2	YES	0.4	G	Valve	Significant leak	YES	NO	Process system
180	2010	Platform 21	YES	12.7	G	Valve	Significant leak	YES	NO	Process system
181	2010	Platform 8	YES	0.55	G	Steel pipe	Significant leak	YES	NO	Process system
182	2010	Platform 48	YES	0.1	G	Standard flange	Significant leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
183	2010	Platform 3	YES	1.3	L	Valve	Significant leak	YES	NO	Process system / Well system
184	2010	Platform 31	YES	0.5	L	Standard flange	Significant leak	NO	NO	Process system
185	2010	Platform 28	YES	0.22	G	Valve	Significant leak	YES	NO	Process system
186	2010	Platform 63	YES	0.1	G	Steel pipe	Marginal leak	YES	NO	Process system / Well system
188	2010	Platform 7	YES	0.62	L	Valve	Significant leak	YES	NO	Process system
189	2010	Platform 72	NO	0.8	L	Valve	Significant leak	YES	NO	Process system
190	2010	Platform 5	YES	0.1	G	Pump	Significant leak	NO	NO	Process system / Well system
191	2011	Platform 67	YES	3.9	L	Standard flange	Significant leak	YES	NO	Process system
192	2011	Platform 27	YES	0.5	G	Standard flange	Significant leak	YES	NO	Process system
193	2011	Platform 7	YES	0.51	G	Valve	Significant leak	YES	NO	Process system
194	2011	Platform 9	YES	0.6	G	Valve	Significant leak	YES	NO	Process system
195	2011	Platform 6	YES	0.9	G	Valve	Significant leak	YES	NO	Process system
196	2011	Platform 20	YES	0.25	G	Hose	Significant leak	YES	NO	Process system
197	2011	Platform 61	YES	0.58	L	Steel pipe	Significant leak	YES	NO	Process system
198	2011	Platform 10	YES	0.11	G	Valve	Significant leak	YES	NO	Process system
201	2011	Platform 16	YES	0.34	G	Valve	Marginal leak	YES	NO	Fuel gas system
202	2012	Platform 27	YES	16.9	G	Standard flange	Significant leak	YES	NO	Flare system
203	2012	Platform 22	YES	1.6	L	Standard flange	Significant leak	YES	NO	Process system
204	2012	Platform 7	YES	0.17	G	Compressor	Significant leak	YES	NO	Process system
205	2012	Platform 51	YES	0.48	L	Valve	Marginal leak	YES	NO	Process system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
206	2012	Platform 25	YES	230	L	Valve	Significant leak	YES	NO	Process system
207	2012	Platform 73	NO	0.16	G	Standard flange	Significant leak	YES	NO	Process system
208	2013	Platform 48	YES	0.3	G	Valve	Significant leak	YES	NO	Process system / Well system
209	2013	Platform 37	YES	0.39	G	Valve	Significant leak	NO	NO	Process system / Well system
210	2013	Platform 62	YES	0.1	G	Steel pipe	Significant leak	YES	NO	Process system
211	2013	Platform 21	YES	0.83	G	Valve	Significant leak	YES	NO	Process system
212	2013	Platform 18	YES	0.75	G	Valve	Significant leak	YES	NO	Process system
213	2013	Platform 23	YES	20	G	Compressor	Significant leak	YES	NO	Process system
214	2013	Platform 32	YES	0.9	G	Valve	Marginal leak	NO	NO	Process system / Well system
215	2013	Platform 17	YES	0.73	G	Valve	Significant leak	YES	NO	Process system
216	2013	Platform 55	YES	0.131	L	Pump	Significant leak	YES	NO	Process system
217	2014	Platform 3	YES	0.15	G	Steel pipe	Significant leak	YES	NO	Process system / Flare system
219	2014	Platform 4	YES	0.65	L	Instrument	Significant leak	YES	NO	Process system
220	2014	Platform 57	YES	20.8	L	Vent	Significant leak	YES	NO	Closed drain / Open drain system
221	2014	Platform 17	YES	0.2	G	Valve	Significant leak	YES	NO	Process system
222	2014	Platform 10	YES	2.2	G	Valve	Marginal leak	YES	NO	Process system
224	2015	Platform 8	YES	0.7	G	Valve	Significant leak	YES	NO	Process system
225	2015	Platform 33	YES	0.11	G	Hose	Significant leak	YES	NO	Well system

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
226	2015	Platform 54	YES	3.11	G	Standard flange	Significant leak	NO	NO	Process system
227	2015	Platform 9	YES	6.9	L	Instrument	Significant leak	YES	NO	Process system
228	2015	Platform 29	YES	0.28	G	Instrument	Significant leak	YES	NO	Process system
229	2015	Platform 66	YES	8	L	Steel pipe	Significant leak	NO	NO	Process system
230	2015	Platform 22	YES	0.21	G	Valve	Marginal leak	YES	NO	Process system
234	2015	Platform 52	NO	0.1	G	Valve	Marginal leak	NO	NO	Process system
235	2015	Platform 2	YES	0.31	G	Hose	Marginal leak	YES	NO	Well system
236	2016	Platform 64	YES	2	G	Shell and tube heat exchanger	Significant leak	YES	NO	Process system / Sea water
237	2016	Platform 37	YES	1.2	G	Instrument	Significant leak	YES	NO	Process system
240	2016	Platform 7	YES	0.239	G	Vent	Marginal leak	YES	NO	Sea water / Open drain
241	2016	Platform 65	YES	4	G	Valve	Significant leak	YES	NO	Process system
243	2016	Platform 35	YES	0.58	G	Valve	Significant leak	NO	NO	Process
244	2016	Platform 35	YES	6.5	L	Valve	Significant leak	NO	NO	Process
245	2016	Platform 35	YES	1.11	G	Valve	Significant leak	NO	NO	Process
246	2016	Platform 35	YES	0.7	L	Pump	Significant leak	NO	NO	Process
247	2016	Platform 35	YES	0.1	G	Standard flange	Significant leak	NO	NO	Process
248	2017	Platform 2	YES	0.12	G	Instrument	Significant leak	YES	NO	Process
249	2017	Platform 57	YES	6.4	L	Hose	Significant leak	YES	NO	Process
250	2017	Platform 62	YES	0.25	G	Instrument	Significant leak	YES	NO	Process

ID	Year	Installation	In NCS population dataset	Initial leak rate [kg/s]	Medium	Equipment type	Leak scenario	Commissioned before 01.01.2001	Decommissioned before 31.12.2017	System
251	2017	Platform 16	YES	0.62	G	Valve	Significant leak	YES	NO	Process
252	2017	Platform 17	YES	0.17	G	Standard flange	Significant leak	YES	NO	Process
253	2017	Platform 63	YES	0.16	G	Instrument	Significant leak	YES	NO	Process
254	2017	Platform 73	NO	0.79	G	Standard flange	Significant leak	YES	NO	Process

6 Estimated combustible volume per leak recorded at NCS 2001-2017

The table below lists the relevant incidents and the estimate of the gas exposure parameters. The parameters are described in Table 6.1.

Table 6.1 - Description of the data fields in Table 6.2

Heading	Description
ID	ID running from 1 to 254.
Year	The year that the leak occurred
Installation	Anonymized name of the installation
Gas fraction	The mass fraction of the released mass that is gas
Detected automatically	Yes, if the gas release was detected automatically. No if not.
Manual assessment, $V_{>LEL,max}$	$V_{>LEL,max}$ estimated manually
Manual assessment, $t_{exp,i}$	$t_{exp,i}$ estimated manually
Manual assessment, $V_{LEL:UEL,avg,i} \cdot t_{exp,i}$	$V_{LEL:UEL,avg,i} \cdot t_{exp,i}$ estimated manually
Model and manual $V_{>LEL,max}$	$V_{>LEL,max}$, applied estimate, manual assessment is used if available
Model and manual , $t_{exp,i}$	$t_{exp,i}$, applied estimate, manual assessment is used if available
Model and manual , $V_{LEL:UEL,avg,i} \cdot t_{exp,i}$	$V_{LEL:UEL,avg,i} \cdot t_{exp,i}$, applied estimate, manual assessment is used if available

Table 6.2 – All relevant incidents recorded at NCC, with initial leak rate ≥0.1 kg/s, in the period 01.01.2001 – 31.12.2017. The total number of leaks is 217. '-' indicate that the parameter value is unknown

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL,Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL,Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL,Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL,Avg,i} * t_{exp}$ [m^3·s]
3	2001	Platform 57	0.02	-	-	-	-	1	300	180
4	2001	Platform 55	1	-	-	-	-	45	300	9,000
5	2001	Platform 48	1	-	-	-	-	34	300	6,750
6	2001	Platform 22	0.1	-	-	-	-	11	300	2,250
8	2001	Platform 41	1	-	-	-	-	45	300	9,000
9	2001	Platform 41	1	-	-	-	-	45	300	9,000
10	2001	Platform 56	1	-	-	-	-	1,125	300	225,000
11	2001	Platform 56	1	-	-	-	-	45	300	9,000
12	2001	Platform 22	1	-	-	-	-	113	300	22,500
13	2001	Platform 2	1	-	-	-	-	28	300	5,625
14	2001	Platform 21	1	-	-	-	-	338	300	67,500
15	2001	Platform 2	1	-	-	-	-	225	300	45,000
17	2001	Platform 9	1	-	-	-	-	158	300	31,500
18	2001	Platform 53	1	-	-	-	-	338	300	67,500
19	2001	Platform 7	1	-	-	-	-	135	300	27,000
20	2001	Platform 51	0.02	-	-	-	-	4	300	810
21	2001	Platform 23	1	-	-	-	-	360	300	72,000
22	2001	Platform 45	1	-	-	-	-	1,058	300	211,500
23	2001	Platform 42	1	-	-	-	-	23	300	4,500
24	2002	Platform 55	1	-	-	-	-	45	300	9,000

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m^3·s]
25	2002	Platform 64	1	-	-	-	-	113	300	22,500
26	2002	Platform 22	1	-	-	-	-	40	300	7,950
27	2002	Platform 22	1	-	75	300	22,500	75	300	22,500
29	2002	Platform 60	1	-	-	-	-	180	300	36,000
31	2002	Platform 8	1	-	-	-	-	68	300	13,500
32	2002	Platform 1	1	-	-	-	-	34	300	6,750
33	2002	Platform 29	1	NO	10	300	3,000	10	300	3,000
34	2002	Platform 54	1	YES	20	300	6,000	20	300	6,000
36	2002	Platform 4	1	-	-	-	-	81	300	16,200
37	2002	Platform 29	1	-	-	-	-	113	300	22,500
38	2002	Platform 55	1	-	-	-	-	189	300	37,800
39	2002	Platform 9	1	-	-	-	-	180	300	36,000
40	2002	Platform 57	1	NO	-	-	-	10	300	3,000
41	2002	Platform 62	0.02	-	-	-	-	1	300	117
42	2002	Platform 2	1	-	-	-	-	34	300	6,750
43	2002	Platform 17	1	-	-	60	-	151	60	6,000
44	2002	Platform 56	1	-	-	-	-	124	300	24,750
45	2002	Platform 18	1	-	-	-	-	135	300	27,000
47	2002	Platform 57	1	-	-	-	-	38	300	7,650
48	2002	Platform 57	1	-	-	-	-	90	300	18,000
49	2002	Platform 4	0.1	-	-	-	-	9	300	1,800

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m³]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m³·s]
51	2002	Platform 60	1	-	-	-	-	180	300	36,000
52	2002	Platform 60	1	-	-	-	-	68	300	13,500
53	2002	Platform 2	1	-	-	-	-	45	300	9,000
54	2002	Platform 55	1	-	-	-	-	131	300	26,250
56	2002	Platform 22	1	-	-	-	-	23	300	4,500
57	2003	Platform 56	1	-	-	-	-	90	300	18,000
60	2003	Platform 7	0.1	-	-	-	-	7	300	1,350
61	2003	Platform 22	1	-	-	-	-	450	300	90,000
63	2003	Platform 51	0.02	-	-	-	-	0	300	90
64	2003	Platform 27	0.1	-	-	-	-	8	300	1,530
65	2003	Platform 17	0.1	-	-	-	-	8	300	1,530
67	2003	Platform 44	0.33	-	-	600	-	97	600	38,610
68	2003	Platform 8	1	-	-	-	-	113	300	22,500
69	2003	Platform 62	1	-	-	-	-	68	300	13,500
70	2003	Platform 7	1	-	-	900	-	225	900	135,000
71	2003	Platform 7	1	-	-	-	-	473	300	94,500
72	2003	Platform 48	1	-	-	-	-	45	300	9,000
73	2003	Platform 41	1	-	-	-	-	45	300	9,000
74	2003	Platform 7	1	-	10	10	50	10	10	50
75	2003	Platform 47	1	-	-	-	-	23	300	4,500
76	2003	Platform 2	1	-	-	717	-	68	717	32,250

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m^3·s]
77	2003	Platform 69	1	-	-	120	-	225	120	18,000
79	2003	Platform 56	1	-	-	-	-	23	300	4,500
80	2004	Platform 70	0.02	-	-	-	-	1	300	144
81	2004	Platform 71	0.02	-	-	-	-	1	300	180
82	2004	Platform 64	0.1	YES	400	600	180,000	400	600	180,000
83	2004	Platform 17	1	-	-	2,143	-	16	2,143	22,500
84	2004	Platform 62	0.1133	YES	400	120	36,000	400	120	36,000
85	2004	Platform 57	1	-	-	-	-	40	300	7,950
86	2004	Platform 69	1	-	-	-	-	68	300	13,500
87	2004	Platform 10	1	-	-	-	-	180	300	36,000
89	2004	Platform 43	0.1	-	-	-	-	37	300	7,425
90	2004	Platform 46	1	-	-	-	-	50	300	9,900
91	2004	Platform 72	0.02	-	-	-	-	0	300	90
92	2004	Platform 20	0.1	-	-	-	-	6	300	1,125
93	2004	Platform 10	1	-	-	-	-	180	300	36,000
94	2004	Platform 22	1	-	-	-	-	45	300	9,000
95	2004	Platform 23	1	-	-	-	-	90	300	18,000
96	2004	Platform 19	1	NO	400	120	36,000	400	120	36,000
97	2004	Platform 17	1	-	-	-	-	40	300	7,950
98	2004	Platform 57	1	-	-	-	-	135	300	27,000
100	2004	Platform 17	1	-	-	71	-	473	71	22,500

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$[s]	Manual assessment, $V_{LEL:UEL, Avg,i}$ * t_{exp} [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$[s]	Model and manual $V_{LEL:UEL, Avg,i}$ * t_{exp} [m^3·s]
101	2005	Platform 45	1	-	-	-	-	23	300	4,500
102	2005	Platform 27	1	-	-	-	-	158	300	31,500
103	2005	Platform 28	1	-	-	606	-	74	606	30,000
104	2005	Platform 5	0.0042	NO	60	20	1,200	60	20	1,200
105	2005	Platform 8	1	-	-	-	-	180	300	36,000
106	2005	Platform 2	1	-	-	1,190	-	95	1,190	75,000
107	2005	Platform 27	1	-	-	-	-	27	300	5,400
108	2005	Platform 21	1	-	-	-	-	40	300	7,950
109	2005	Platform 57	1	-	-	-	-	153	300	30,600
110	2005	Platform 2	1	-	-	301	-	299	301	60,000
113	2005	Platform 27	1	-	10	2	10	10	2	10
114	2005	Platform 70	0.1	-	1	1	1	1	1	1
115	2005	Platform 7	1	-	-	-	-	135	300	27,000
117	2005	Platform 8	1	-	-	-	-	47	300	9,450
118	2005	Platform 46	1	-	-	-	-	113	300	22,500
119	2006	Platform 8	1	YES	2,000	1,200	52,500	2,000	1,200	52,500
121	2006	Platform 28	1	-	-	-	-	63	300	12,600
122	2006	Platform 33	1	-	-	-	-	34	300	6,750
123	2006	Platform 62	1	-	10	1	5	10	1	5
124	2006	Platform 9	1	-	-	-	-	117	300	23,400
125	2006	Platform 1	1	-	-	-	-	34	300	6,750

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL,Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL,Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL,Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL,Avg,i} * t_{exp}$ [m^3·s]
127	2006	Platform 56	1	-	-	-	-	135	300	27,000
128	2006	Platform 39	0.02	-	-	-	-	2	300	450
129	2006	Platform 44	1	-	-	-	-	158	300	31,500
130	2006	Platform 27	1	-	-	-	-	45	300	9,000
131	2006	Platform 61	0.02	-	-	-	-	0	300	90
132	2006	Platform 18	1	YES	1,500	360	252,000	1,500	360	252,000
133	2006	Platform 27	0.1	-	-	-	-	20	300	3,915
134	2006	Platform 59	1	-	-	-	-	32	300	6,300
136	2007	Platform 62	1	-	-	-	-	56	300	11,250
137	2007	Platform 63	1	-	-	360	-	56	360	13,500
138	2007	Platform 12	1	-	-	-	-	34	300	6,750
140	2007	Platform 56	1	-	-	-	-	68	300	13,500
141	2007	Platform 18	1	YES	500	60	30,000	500	60	30,000
142	2007	Platform 43	0.1	-	-	-	-	56	300	11,250
143	2007	Platform 43	1	-	-	-	-	225	300	45,000
144	2007	Platform 47	1	-	-	-	-	434	300	86,850
146	2008	Platform 55	0.05	YES	1,000	3,000	3,000,000	1,000	3,000	3,000,000
147	2008	Platform 4	1	-	-	1,700	-	23	1,700	25,500
148	2008	Platform 41	1	-	-	-	-	90	300	18,000
149	2008	Platform 17	1	-	-	-	-	90	300	18,000
150	2008	Platform 60	1	-	-	-	-	45	300	9,000

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m^3·s]
151	2008	Platform 7	1	-	-	-	-	68	300	13,500
152	2008	Platform 37	1	-	-	-	-	59	300	11,700
153	2008	Platform 37	1	-	-	-	-	113	300	22,500
154	2008	Platform 10	1	YES	1,000	120	42,000	1,000	120	42,000
155	2008	Platform 4	0.02	-	-	-	-	6	300	1,260
156	2008	Platform 22	1	-	-	-	-	54	300	10,800
157	2008	Platform 22	1	-	-	-	-	203	300	40,500
159	2008	Platform 2	1	-	-	-	-	40	300	7,950
160	2009	Platform 14	1	-	-	-	-	113	300	22,500
161	2009	Platform 5	1	-	-	2	90	60	2	90
163	2009	Platform 37	1	-	-	-	-	99	300	19,800
164	2009	Platform 55	0.02	-	-	1,000	-	5	1,000	3,000
165	2009	Platform 22	1	-	-	-	-	113	300	22,500
166	2009	Platform 60	1	YES	1,026	50	25,650	1,026	50	25,650
167	2009	Platform 10	0.02	-	-	-	-	4	300	734
168	2009	Platform 57	0.02	-	-	-	-	1	300	270
169	2009	Platform 57	0.02	-	-	-	-	1	300	180
170	2009	Platform 2	0.1	-	-	-	-	10	300	2,025
171	2009	Platform 63	0.02	-	-	-	-	3	300	594
172	2009	Platform 18	1	-	-	-	-	338	300	67,500
173	2009	Platform 72	0.02	-	-	900	-	9	900	5,400

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m^3·s]
174	2009	Platform 23	0.02	-	-	-	-	1	300	225
175	2009	Platform 60	0.02	-	-	-	-	1	300	243
176	2010	Platform 63	1	-	-	-	-	40	300	7,950
177	2010	Platform 2	1	-	-	-	-	40	300	7,950
178	2010	Platform 69	1	-	-	-	-	180	300	36,000
179	2010	Platform 2	1	-	-	-	-	90	300	18,000
180	2010	Platform 21	1	YES	1,000	600	300,000	1,000	600	300,000
181	2010	Platform 8	1	-	-	-	-	124	300	24,750
182	2010	Platform 48	1	-	-	-	-	23	300	4,500
183	2010	Platform 3	0.1	-	-	1,800	-	5	1,800	5,400
184	2010	Platform 31	0.02	-	-	-	-	2	300	450
185	2010	Platform 28	1	-	-	-	-	50	300	9,900
186	2010	Platform 63	1	-	-	-	-	23	300	4,500
188	2010	Platform 7	0.02	-	-	-	-	3	300	558
189	2010	Platform 72	0.02	-	-	-	-	4	300	720
190	2010	Platform 5	1	-	-	-	-	23	300	4,500
191	2011	Platform 67	0.05	NO	20	900	9,000	20	900	9,000
192	2011	Platform 27	1	-	-	-	-	113	300	22,500
193	2011	Platform 7	1	-	-	-	-	115	300	22,950
194	2011	Platform 9	1	-	-	-	-	135	300	27,000
195	2011	Platform 6	1	-	-	-	-	203	300	40,500

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [$m^3 \cdot s$]
196	2011	Platform 20	1	-	-	-	-	56	300	11,250
197	2011	Platform 61	0.02	-	-	-	-	3	300	522
198	2011	Platform 10	1	-	-	-	-	25	300	4,950
201	2011	Platform 16	1	-	-	-	-	40	300	7,950
202	2012	Platform 27	1	YES	3,000	240	600,000	3,000	240	600,000
203	2012	Platform 22	0.02	-	-	-	-	7	300	1,440
204	2012	Platform 7	1	-	-	-	-	38	300	7,650
205	2012	Platform 51	0.02	-	-	-	-	2	300	432
206	2012	Platform 25	0.105	YES	-	-	-	2,166	300	433,172
207	2012	Platform 73	1	-	-	-	-	36	300	7,200
208	2013	Platform 48	1	-	-	-	-	68	300	13,500
209	2013	Platform 37	1	-	-	-	-	88	300	17,550
210	2013	Platform 62	1	-	-	-	-	23	300	4,500
211	2013	Platform 21	1	-	-	-	-	187	300	37,350
212	2013	Platform 18	1	-	-	-	-	169	300	33,750
213	2013	Platform 23	1	YES	2,250	60	75,000	2,250	60	75,000
214	2013	Platform 32	1	-	-	-	-	40	300	7,950
215	2013	Platform 17	1	-	-	-	-	164	300	32,850
216	2013	Platform 55	0.02	-	-	-	-	1	300	118
217	2014	Platform 3	1	-	-	-	-	34	300	6,750
219	2014	Platform 4	0.02	-	-	-	-	3	300	585

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [m^3·s]
220	2014	Platform 57	0.01	-	-	600	-	47	600	18,720
221	2014	Platform 17	1	-	-	-	-	45	300	9,000
222	2014	Platform 10	1	-	1	6	6	1	6	6
224	2015	Platform 8	1	YES	10	30	300	10	30	300
225	2015	Platform 33	1	YES	20	80	1,600	20	80	1,600
226	2015	Platform 54	1	YES	120	1,003	120,360	120	1,003	120,360
227	2015	Platform 9	0.171	YES	100	120	12,000	100	120	12,000
228	2015	Platform 29	1	YES	30	360	10,800	30	360	10,800
229	2015	Platform 66	1	YES	3,000	1,500	1,800,000	3,000	1,500	1,800,000
230	2015	Platform 22	1	YES	1	40	40	1	40	40
234	2015	Platform 52	1	NO	1	15	15	1	15	15
235	2015	Platform 2	1	YES	1	15	15	1	15	15
236	2016	Platform 64	1	YES	562	1,000	200,000	562	1,000	200,000
237	2016	Platform 37	1	YES	30	100	1,500	30	100	1,500
240	2016	Platform 7	1	YES	1	30	30	1	30	30
241	2016	Platform 65	1	YES	-	1,020	-	124	1,020	84,000
243	2016	Platform 35	1	YES	-	480	-	68	480	21,600
244	2016	Platform 35	0.28	YES	-	38	-	409	38	10,350
245	2016	Platform 35	1	YES	-	38	-	80	38	2,003
246	2016	Platform 35	0.1	YES	-	720	-	8	720	3,780
247	2016	Platform 35	1	YES	-	-	-	23	300	4,500

ID	Year	Installation	Gas fraction [mass fraction]	Detected automatically [YES, NO]	Manual assessment, $V_{>LEL, Max,i}$ [m3]	Manual assessment, $t_{exp,i}$ [s]	Manual assessment, $V_{LEL:UEL, Avg,i} * t_{exp}$ [m3·s]	Model and manual, $V_{>LEL, Max,i}$ [m^3]	Model and manual, $t_{exp,i}$ [s]	Model and manual $V_{LEL:UEL, Avg,i} * t_{exp}$ [$m^3 \cdot s$]
248	2017	Platform 2	1	YES	-	-	-	720	300	4,500
249	2017	Platform 57	0.01	YES	-	-	-	180	300	2,880
250	2017	Platform 62	1	YES	-	-	-	240	300	11,250
251	2017	Platform 16	1	YES	-	-	-	111	300	27,973
252	2017	Platform 17	1	YES	-	-	-	109	300	7,650
253	2017	Platform 63	1	YES	-	-	-	302	300	7,200
254	2017	Platform 73	1	YES	-	-	-	240	300	18,000

1) 669 = 6,817,672 sm^3/ 10,193 m^3 (the contributors to the denominator not documented in the table)
2) 470 = 10,749,914 sm^3/ 22,891 m^3 ((the contributors to the denominator not documented in the table)

7 References

/1/ DNV, Offshore QRA – Standardised Hydrocarbon Leak Frequencies, report number 2009-1768, rev. 1, 16.01.2009.

/2/ Norwegian Petroleum Directorate: NPD Annual Reports for the period 1992-97, see http://www.npd.no/en/Publications/NPD-annual-reports/

/3/ Petroleum Safety Authority Norway, "Trends in Risk Level in the Norwegian Petroleum Activity", summary report 2015, Date April 28th 2016.

/4/ Personal conversation with Jan Erik Vinnem, Professor at NTNU, Trondheim.

/5/ Preventor AS: "Blast load Frequency Distribution, Assessment of historical Frequencies in the North Sea", Report No. 19816-04, Final report, Rev. 3, 26th November 1998.

/6/ Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", report no: 105586/R1, Rev: Final B, Date: 18.03.2016

Attachment A2

UKCS PLOFAM leaks and ignitions

Table of contents

A2-1 Introduction

This attachment contains a summary of the UKCS PLOFAM leaks and ignitions used as basis for the MISOF model

A2-2 PLOFAM process leaks

Leaks from the UKCS based on the HCR data are presented in this appendix. Process leaks as defined in the PLOFAM project and applied as part of the basis for PLOFAM model are referred to as "PLOFAM leaks". A total of 687 leaks covering the period 1992-2017 defined as a PLOFAM leak is found in the HCR data base.

The PLOFAM [1] model defines strictly what is considered to be a process leak. For process leaks as defined in PLOFAM the following is of interest:

- Ignited events (number, causes/ignition mechanism, delay etc.)
- The number of leaks (for immediate ignition)
- Gas exposure (for delayed ignition)

The PLOFAM leak frequency model has been based on 191 significant process leaks on NCS for the period 2001-2017. None of these leaks ignited. The NCS data set is limited to leaks with an initial rate exceeding 0.1 kg/s.

A2-2.1 Ignited PLOFAM leaks, UKCS

PLFOAM leaks for the two different time periods are shown in Table A2 2.1 and Table A2 2.2

The number of relevant leaks for P_{im} and $P_{im,pump}$ (rate >0.1 kg/s) is

- 1992-2017: 687
- 2001-2017: 327

Table A2 2.1 PLOFAM leaks (UKCS 1992-2017), ignitions in brackets

Average rate (kg/s)	Quantity released (kg)					
	A(<10)	B(10-100)	C(100-1000)	D(1000-10000)	E(>10000)	Total
E (>100)	-	-	1	1 (1)	-	2 (1)
D (10-100)	-	-	4	9	10	23
C (1-10)	3	22	80	28	1	134
B (0.1-1)	56 (3)	198 (2)	225 (5)	30 (1)	10 (1)	519 (12)
A (<0.1)	1539 (23)	638 (4)	131 (2)	14	1	2323 (29)
Total	**1598 (26)**	**858 (6)**	**441 (7)**	**82 (2)**	**22 (1)**	**3001 (41)**

Table A2 2.2: PLOFAM leaks (UKCS 2001-2017), ignition in brackets

Average rate (kg/s)	Quantity released (kg)					
	A(<10)	B(10-100)	C(100-1000)	D(1000-10000)	E(>10000)	Total
E (>100)	-	-	-	1 (1)		1 (1)
D (10-100)	-	-	-	5	3	8
C (1-10)	2	11	37	7	1	58
B (0.1-1)	37 (2)	93 (1)	93 (1)	18 (1)	8	249 (5)
A (<0.1)	977 (6)	375 (2)	65 (1)	7		1424 (9)
Total	**1016 (8)**	**479 (3)**	**195 (2)**	**39 (2)**	**12**	**1740 (15)**

The number of relevant leaks for P_{im} and $P_{im,pump}$ (rate >0.1 kg/s) is 327.

A2-2.2 PLFOAM leaks ignited

For an ignited release event to be deemed relevant in a quantitative risk analysis context, the following criteria must be fulfilled:

- Defined as a significant leak in the PLOFAM report
- The ignition occurred by a gas cloud exposing an active ignition source inside a process module (for λ_i)
- The leak and the ignition had a common cause or the leak itself caused the ignition (for P_{im} and $P_{im,pump}$)
- The initial leak rate was larger than 0.1kg/s (for P_{im} and $P_{im,pump}$)
- Other ignition mechanisms are either considered not relevant (*e.g.* flare carryover) or considered by other parts of the ignition model (e.g. hot work ignitions)

Table A2 2.3: PLOFAM leaks 1992-2017 with average rate > 0.1 kg/s (13 off)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1992-1993-11	4	0	THE HP FLARE, WHICH WAS LIT AT THE TIME OF OIL CARRYOVER	BLANK	A QUANTITY OF OIL WASCARRIED OVER FROM THE TEST SEPARATOR TO THE FLARE SYSTEM DURING AN OPERATION TO PRESSURISE VO3 USING WELL TO ASSIST SAND DISPLACEMENT. A LARGE PERCENTAGE OF THE OIL CARRY OVER WAS COLLECTED IN THE HP KNOCK OUT DRUM & THIS RESULTED IN HI-LEVEL ALARM IN THE MOL CONTROL ROOM. THE REMAINDER OF THE OIL WAS CARRIED UP THE HP FLARE WHERE NOT ALL OF IT WAS BURNED BY THE MARDAIR, A SMALL AMOUNT FALLING AS OIL DROPLETS TO THE MAIN DECK (REPORT RECEIVED BY CONTROL ROOM TECHNICIAN & OTHER OIL OBSERVED AS BURNING ON THE FLARE ANTI-RADIATION PLATFORM DECK.	No (flare carryover)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1993-1994-3	14	0	HOT GASES IGNITED IN EXHAUST STACK	FIRE SELF EXTINGUISHED AS FUEL SUPPLY WAS CONSUMED.	A FUEL CHANGE OVER FROM DIESEL TO GAS WAS ATTEMPTED ON GT2 BUT THE TURBINE RESISTED THE CHANGE OVER AND TRIPPED, THE TURBINE WAS RESET AND RESTARTED ON GAS. THE MACHINE WAS MANUALLY SHUTDOWN ABOUT 15 SECONDS LATER AFTER ABNORMAL SPEEDS AND TEMPERATURE WERE OBSERVED. HIGH TEMPERATURES WERE NOTED ON THE EXHAUST STACK AND WHEN CHECKED, FLAMES WERE SEEN TO BE EMITTING FROM THE STACK. THE GENERAL ALARM WAS SOUNDED AND FIRE PARTIES SENT TO THE SEEN.	No (fuel gas ignited inside turbine hood)
1993-1994-265	15	0	HOT EXHAUST STACK.	N/A	WHILST LOADING THE COMPRESSORS PRIOR TO COMING ON LINE, UNIT AK-K-040 INDICATED HIGH GAS GENERATOR VIBRATION. AT THIS STAGE THE DISCHARGE	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
					PRESSURE FROM THE MACHINE WAS IN EXCESS OF 600 PSIG AND A SURGING OF SOME DESCRIPTION WAS EXPERIENCED IN THE CONTROL ROOM. UNIT AK-K-040 SHUTDOWN ON HIGH GAS GENERATOR VIBRATION. DURING THE INVESTIGATION INTO THE SHUTDOWN, IT WAS NOTICED THAT SOME FUEL GAS PRESSURE WAS STILL INDICATED ON THE 3 WAY VALVE PRESSURE GUAGE AND THAT THE NEWLY INSTALLED AUTOMATIC VENT VALVE WAS HALF OPEN. FUEL GAS BLOCK AND VENT VALVE OPERATED MANUALLY BY THE TECHNICIANS. EXHAUST STACK FIRE INDICATED IN THE CONTROL ROOM. FIRE EXTINGUISHED BY MANUAL OPERATION OF CO2 SNUFFING SYSTEM.	

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1993-1994-4	30	0	IGNITION SOURCE WAS FLARE SYSTEM WHICH WAS LIT AT THE TIME OF THE CARRYOVER.	DROPS OF UNBURNED OIL RESIDUE FELL ON TOP DECK - WASHED INTO DRAINS OR WIPED UP FROM STRUCTURE. OIL FROM FLARE PILOT SYSTEM AT BASE OF FLARE TOWER - TO DECK.	A QUANTITY OF CRUDE OIL WAS CARRIED OVER FROM THE PRODUCTION SEPARATOR (VO2) TO THE FLARE SYSTEM VIA THE PRODUCTION SCRUBBERS VO4/V05. PRODUCTION FROM THE SATTELITE PLATFORM FE WAS BEING ESTABLISHED AT THE ACCIDENT, A LARGE SLUG OF LIQUID WAS RECEIVED FROM THE FE PRODUCTION LINE, WHICH TRIPPED THE SEPARATOR. HOWEVER, LIQUID WAS CARRIED OUT THROUGH THE SEPARATOR GAS OFF TAKE INTO THE FLARE SYSTEM. SOME OF THE OIL WAS NOT BURNED IN THE HP FLARE AND FELL AS DROPLETS ON THE MAIN DECK (WEST). NO INJURY TO PERSONNEL. NO DAMAGE TO PLANT.	No (flare carryover)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1994-1995-206	32	0	CONDENSATE IGNITED DUE TO ELECTROSTATIC SOURCE (UNSATISFACTORY EARTHING BOND)	N/A	BLANK	Marginal leak (quantity released 6 kg)
1997-1998-71	86	30	EXCESS GAS IGNITED BY BURNERS	OVERFUELLED GAS ACCUMULATED IN ENGINE.	EXPLOSION IN EXHAUST DUCTING RUPTURED A FLEXIBLE BELLOWS	No (fuel gas ignited inside turbine hood)
2003-2004-45	153	0	The welder struck his arc to commence welding	A satisfactory gas test had just been taken by portable gas monitors (MSA Passport 5 Triple detector & MSA Tankscope meter). Very short duration flash/jet fire exhausted finite hydrocarbon inventory.	The workparty had failed to fit by Method the Stopple Plug (required Statement) to maintain the inert atmosphere & segregate the residual hydrocarbon atmosphere within the pipework from the workpiece to be welded.	No (hot work)
2003-2004-62	164	0	High pressure spray probably ignited on hot surface (of turbine/motor) on pump	None	BLANK	Yes (Pim, pump)
2004-2005-29	165	10	Air mover was positioned at manway entrance, when the air mover was switched on a vapour flash occurred at entrance to manway. As a result of the vapour flash, hot exhaust	Lazy condensate gas within vessel migrated out of manway opening when door was opened. Condensate not under pressure therefore unable to determine amount of condensate gas dispersion or quantity. No	BLANK	No (not relevant leak scenario)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
			gases were emitted from the manway opening	detection activated due to this dispersion, therefore duration not applicable as condensate gas within vessel flashed off immediately when air mover started and the GPA activation followed due to flame detection.		
2005-2006-191	184	5	Gas ignited on ingestion into combustion chamber of Ruston Gas turbine C (power generation)	Enveloped BP jacket topsides. 3 Jackets bridge linked. BD accommodation, BP process, CD Wellheads	Catastrophic failure of train 3 production cooler (shell and tube). Resulted in the release of approx. 7000kg HC gas which ignited on ingestion into R6T 'c' combustion chamber	No (turbine ignition)
2009-2010-146	208	120	Electrostatic spark from an insulated conductor, charged by the electrostatically charged mist created by primary release is thought to be the most likely source of ignition	Liquid condensate thought to have rained out from leak, accumulating upon flat surfaces and equipment and to run down vertical surfaces to collect wherever the conditions allowed. This is apparent on the deck level and around well W4/KA with wax deposition on all surfaces. There is also evidence of condensate deposition and run off on the East end of the solid deck by the HPU and significant deposition of wax on the 9 m level. It is not clear	Erskine is a Normally Unattended Installation and was unmanned at the time of the incident. Manual operation of export pipeline SSSV and blowdown of the export pipeline was carried out by BG Lomond OIM.	Yes (Pim or λ_i)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
				whether this is the initial deposition or the melting and spread of wax following the fire. Gas escaping from the leak dispersed away from the installation under natural windflow. Modelling suggests that the gas cloud produced was not significantly large enough to cause detection by the installation gas detectors.		
2013-2014-99	226	0	Frictional heat from the mechanical seal	N/A	No loss of hydrocarbons to sea	Yes (Pim, pump)
Year: 2016 URN: 6646	-	-	CUTTING TORCH WAS IGNITION SOURCE WITH SPARKS OR HOT SLAG PROVIDING THE IGNITION	BLANK	Only the cutting activity ceased with the work party remove the damaged hose from service before resuming work (other normal activities on the installation continued as planned)	NO

Table A2 2.4 PLOFAM leaks 1992-2017 with average rate < 0.1 kg/s (29 off)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
1993-1994-108	11	0	WELDERS SPARK FROM HOT WORK SITE ADJACENT TO (AND ABOVE) THE LEAK. THIS PRODUCED A "GAS RING" TYPE OF FLAME, - STEADY BLUE CIRCULAR FLAME, 2 OR 3 INCHES HIGH.	DISPERSION MUST HAVE BEEN VERY LOCAL TO THE CHOKE - IT WAS NOT DETECTED BY FIXED GAS HEADS ABOVE, OR BY THE WELDERS PORTABLE MONITOR.	THE LEAK WAS FROM THE COLLAR OF A "GRAYTOOLS" PBS 30 CHOKE VALVE (VIA THE GLAND).	No (hot work)
1993-1994-133	5	0	WELDER CUTTING INTO REDUNDANT PIPEWORK.	BLANK	BLANK	No (hot work)
1994-1995-189	33	0	INTERNAL COMBUSTION OF EXTRANEOUS MATERIAL/GAS IN EXHAUST DUCTING	N/A	DURING NORMAL START SEQUENCE ON THE GAS COMPRESSOR ON REACHING GAS GEN LIT, A LOUD BANG WAS HEARD. ON INVESTIGATION SOME DISTORTION WAS FOUND ON THE EXHAUST TRUNKING. AN EXPANSION JOINT WAS FOUND TO BE BADLY	No (fuel leak inside turbine hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					DAMAGED ALSO A FLANGE APPEARED TO HAVE SPREAD ON THE PIPEWORK. AN INTERNAL INSPECTION WAS CARRIED OUT AN ACCESSABLE PARTS AND APART FROM THE DISTORTION NOTHING WAS FOUND.	
1993-1994-237	29	0	POSSIBLY STATIC ELECTRICITY FROM CONTAINER AND/OR FROM OPERATOR'S CLOTHING.	OIL CONTAINED IN OPEN TOP METAL CONTAINER HAVING BEEN DRAINED FROM BOOSTER PUMP SUMP.	SOME OF THIS INFORMATION TAKEN FROM AN OIR/12 FOR SUBSEQUENT GAS LEAK OCCURING FROM EXCESS FIREWATER IN THE OPEN DRAIN SYSTEM.	No (immediate ignition)
1995-1996-26	56	0	FLAME FROM BURNING TORCH (OXYACETYLENE)	FLAME CONFINED TO SMALL AREA. SMALL POCKET OF TRAPPED GAS WITHIN PIPEWORK CAUGHT FIRE WHEN BOLTS WERE CUT TO RELEASE FLANGE. ALL PIPEWORK HAD BEEN NITROGEN FOAM INERTED.	AS PART OF THE CONSTRUCTION ACTIVITY ON THE PLATFORM, A 2" VALVE ON THE CONDENSATE HEADER SYSTEM REQUIRED TO BE REMOVED. PRIOR TO THE VALVE REMOVAL WORK TAKING PLACE THE SYSTEM HAD BEEN NITROGEN FOAM	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					INERTED. AFTER REMOVING 6 BOLTS FROM THE FLANGES BY USE OF A BURNING TORCH, A GAS CHECK WAS INITIATED. ONCE THIS WAS COMPLETED SATISFACTORILY THE JOB RECOMMENCED TO BURN THROUGH THE LAST REMAINING BOLTS. DURING THIS PROCESS FLAMES WERE SEEN TO EMANATE FROM BETWEEN THE FLANGE FACES. THE JOB WAS IMMEDIATELY STOPPED WITH THE FIRE QUICKLY EXTINGUISHED BY USING A COMBINATION OF FIRE HOSE AND DRY POWDER. NO INJURY TO PERSONNEL OR DAMAGE TO EQUIPMENT ENSUED. SUBSEQUENT INVESTIGATION CONCLUDED THAT A TRAPPED POCKET OF GAS	

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					WAS PROBABLY IGNITED IN THE PROCESS TO RELEASE THE FLANGES. HSE WERE INFORMED AT 00:42 HRS.	
1996-1997-52	69	0	WELDING OPERATIONS	UNFLUSHABLE DEAD LEG OF PIPE	BLANK	No (hot work)
1996-1997-38	65	0	WHILE REMOVING A CHECK VALVE FROM 12" FLOW LINE USING A 110 VOLT GRINDER TO REMOVE THE BOLTS.	APPROX. 1 LTR OF CONDENSATE RELEASED ONTO SCAFFOLD STAGING AND PASSED ON DOWN THROUGH THE OPEN DECK GRATING TO THE SEA.	PLATFORM WAS SHUT DOWN AND DE PRESSURISED - CAMELOT FREEFLOW LINE WAS FLUSHED WITH WATER TO REMOVE CHECK VALVE - DURING BOLT REMOVAL WITH HAND GRINDER THE FLANGE CRACKED OPEN - A SMALL AMOUNT OF LIQUID MAINLY WATER WITH SOME CONDENSATE SPILLED ONTO BOARDS AND IGNITED - IMMED EXTUING- UISHED WITH DRY POWER - NO INJURIES	No (hot work)
1997-1998-163	83	0	STATIC, CAUSED BY POOR ELECTRICAL CONTINUITY OF EARTH STRAP.	GAS DISPLACED FROM DRUM DURING SAMPLING OPERATION, DISPERSED LOCALLY TO THE DRUM OPENING.	GAS DISPLACED FROM DRUM DURING SAMPLING OPERATION (AS NORMAL), IGNITED AT SAMPLING	No (immediate ignition)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					DRUM OPENING BY STATIC CAUSED BY POOR ELECRICAL CONTINUITY OF EARTH STRAP.	
1997-1998-67	87	0	ARC WELDING OF FLANGE TO PIPE STUB	N/A	BLANK	No (hot work)
1997-1998-133	88	99999	SPARK FROM DAMAGED TRACE HEATING CABLE	PRIOR TO IGNITION THE WIND SPEED WAS SUFFICIENT TO PREVENT GAS BUILD UP FROM THIS MINOR LEAK SOURCE. (WHEN THE WIND SPEED DROPPED TO LESS THAN 4 KNOTS GAS BUILT UP UNTIL IGNITION FROM THE DAMAGED TRACE HEATING SOURCE OCCURED).	LEAKING FITTING WAS IDENTIFIED AT 14:00 HOURS. 2 DEC JOB CARD RAISED TO REPAIR AT TIME OF IDENTI FICATION. LEAK CONSIDERED MINOR.	No (leak rate < 0.01, detection by ignition)
1998-1999-65	93	0	AIR OPERATED GRINDER	3M SECTION OF 10in PIPE - OPEN AT BOTH ENDS - VERY SMALL AMOUNT OF GAS ASSUMED TO HAVE MIGRATED INTO AREA DURING/FOLLOWING NITROGEN PURGING	BLANK	No (hot work)
1998-1999-61	92	0	THERE WAS NO HYDROCARBON RELEASE. AFFECTED SYSTEM WAS COMPLETELY	N/A	BLANK	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
			ISOLATED FROM HYDROCARBON SOURCE AND HAD BEEN ISOLATED, PURGED, FLUSHED. A SMALL RESIDUE (IMMEASURABLE BUT SUGGEST LESS THAN HALF A CUP FULL) WAS CONTAINED IN A SECTION OF PIPE BEING CUT UP FOR REMOVAL. IGNITED BY SPARK/ HEAT FROM GRINDER			
1999-2000-113	111	0	WELDING OPERATION (BEING UNDERTAKEN)	AREA APPROXIMATELY 18"SQUARE.	BLANK	No (hot work)
1999-2000-59	110	0	WELDERS ARC	1 METRE FROM PIPE STUB AND IMMEDIATE DISPERSAL.	HOT WORK IN AREA WAS STOPPED AND INVESTIGATION INTO SOURCE OF HYDROCARBON RELEASE COMMENCED. IP RECEIVED BURNS TO THE BACK OF HIS LEFT HAND AND LOWER ARMS -	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					RECEIVED TREATMENT FROM MEDIC AND WAS THEN EVACUATED TO HOSPITAL.	
1999-2000-28	113	0	BURNING TORCH FROM ADJACENT RED HOT WORK.	SMALL QUANTITY OF GAS PERMEATING FROM 6in FLANGE AND PERSONNEL WORKING NEARBY WERE UNAWARE. GAS DETECTOR AT THE SCENE.	PLATFORM ON ANNUAL SHUTDOWN:- INSPECTION OF WELL MANIFOLD "DOWNCOMERS" ONGOING. DOWNCOMER REMOVED AND THEN REINSTATED - PARTIALLY MADE UP. SMALL VOLUME OF GAS BUILT UP VIA PASSING VALVE (PREVIOUSLY UNNOTICED) AND BEGAN TO LEAK PAST THE PARTIALLY MADE UP FLANGE - IGNITION AS DESCRIBED.	No (hot work)
1998-1999-188	108	0	FILTER BASKET HAD BEEN REMOVED FROM PIEPLINE WHICH HAD ALREADY BEEN BROKEN INTO TO REMOVE DOWNSTREAM	THERE WAS AN INSTANTANEOUS BLUE FLASH. BUT NOT ENOUGH HYDROCARBON PRESENT TO SUPPORT CONTINUOUS BURNING.	BLANK	No. Immediate ignition (Marginal leak)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
			TURBINE METER WITH NO HYDROCARBON PRESENT. THE BASKET WAS REMOVED AND ALTHOUGH NO EVIDENCE OF LIGHT END HYDROCARBONS A BLUE FLASH WAS APPARENT WHEN IT WAS FLUSHED WITH WATER FROM A HOSE STATION. IT IS THOUGHT THAT THE HOSE WAS NOT ANTI-STATIC AND WAS THE SOURCE OF IGNITION.			
2000-2001-136	131	0	SOURCE OF IGNITION WAS SPARK FROM GRINDING OF PIPE WITH DISC GRINDER.	VERY SMALL POOL ON SCAFFOLD BOARD. AREA APPROX. 1/22 DIAMETER.	BLANK	No (hot work)
2000-2001-133	122		ASSUMED TO BE AS A RESULT OF WELDING WORK ONGOING NEAR THE FLANGE IN	WITNESS STATEMENTS INDICATE A "SMALL, FLICKING FLAME 3 - 4 INCHES IN LENGTH.	INVESTIGATIONS ARE ON GOING TO DETERMINE EXACT CAUSE BUT NO WITNESS STATEMENTS	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
			A SPECIALLY CONSTRUCTED HABITAT. NO WITNESS STATEMENYS CAN CONFIRM OR DENY THIS.		INDICATE EXACTLY AND PRECISLEY HOW THIS OCCURRED NOR HOW A SPARK/ SLAG ESCAPED FROM THE PURPOSE BUILT HABITAT.	
2000-2001-61	119	60	IGNITION OCCURRED WHEN SHELL WAS BEING PRE-HEATED BY MEANS OF NAKED FLAME. OXY-ACETYLENE WAS THE FLAME.	LOCAL TO OUTLET OF 8in PIPE. IR DETECTION FOR THE AREA WAS ACTIVATED. THE AUTOMATIC FUNCTION OF THESE DETECTORS HAD BEEN INHIBITED PRIOR TO CARRYING OUT THE REPAIR WORK.	KTO1 Gas Compressor Train Inspection, pitting repairs to 1st stage cooler shell. The train was purged 3 times with nitrogen & spaded . All 5 scrubbers had their access doors removed & the 3 coolers had the end covers removed. The train had been open for 24 hrs prior to the accident. Prior to EO2 repairs the area had been correctly checked out for the issuing of the Hot Work Permit. Two fire watchers were on station at the site. The welder, Mr Ali Scott had completed 15 min of grinding in the cooler. When he lit his torch to apply heat treatment to the shell the 8" inlet pipe above him must have	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					had a pocket of residue gas in it which flashed. His firewatch went to put it out with his glove when his mate used a dry powder extinguisher. This 8" pipe had just been internally NDT& no gas was detected. As a precaution the 8" pipe was blanked & a further spade fitted on the start up gas line (which was locked off). On fitting of this spade no gas was detected. The welding repairs continued without further incident.	
2000-2001-56	120	0	HOT TUBING CASING	CONTAINED WITHIN HOOD AND DISSIPATED THROUGH EXTRACT VENTILATION DUCT.	BLANK	No (fuel gas in hood)
2000-2001-219	121	0	HOT SURFACE	N/A	Platform was on normal production when Turbine generator AGT#2 shutdown automatically and the turbine enclosure automatic fixed CO2 extinguishant fired off. Operators were in attendance at the machine within two minutes and on local alarm panel, alarm 400 "Fire in enclosure" was active. Operator	No (fuel gas in hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					checked through hood window and no flames could be seen. CO2 had automatically activated and extinguished fire. Internal inspection of turbine found a nut backed off half turn on the fuel gas inlet to burner #4 causing the Dowty seal to be loose. Further investigation ongoing with equipment manufacturer (AGT).	
2002-2003-47	150	0	Heat source from pump bearings	Localised - contained within skid and closed drain system	BLANK	No (immediate ignition)
2002-2003-9	149	120	Crude oil Booster Pump - suspect thruster bearing failure i.e. heat from friction causing flash fire followed by jet fire	Flame alarm activated in MCR, and fire/smoke was observed by a technician setting up at his worksite. From the time of observation until the platform was shutdown and blowndown it is estimated that this would have been 15 mins. During this period the operating plant pressure would be decreasing at all times until reaching zero pressure.	A full investigation into the incident was undertaken and the booster pump to be removed from its location and sent onshore for detailed investigation. It is currently suspected that the thruster bearing failed.	No (probably immediate ignition)
2003-2004-60	152	30	Gas which had migrated ignited during welding of a new flange to an existing process system.	Crude vapour was ignited and all burnt.	This was not a release but a vapour from crude residue in pipework.	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
2002-2003-223	145	0	Electrical spark	None - contained within motor housing	BLANK	No (immediate ignition)
2002-2003-189	144	0	Unknown awaiting investigation, thoughts are friction	Unknown as condensate ignited but seems to have been confined to an area of 3 sq metres.UV detector came into alarm on AC cellar deck, followed by a second UV that initiated an ESD of the gas compression facilities. Platform general alarm sounded automatically.	BLANK	No (immediate ignition)
2003-2004-55	154	0	Turbine main start system. Explosion occurred due to rich gas mix during turbine start-up with all excess gas contained in turbine exhaust stack. Machine experienced heavy light-off during start sequence.	Gas had passed into turbine exhaust stack. No entry of gas into module. All hydrocarbons contained within turbine and exhaust stack	Machine experienced heavy light off due to excess gas during start sequence. It is considered that the "STAR" valve was passing during the start sequence resulting in a rich fuel mix. The power technician initiated a normal start on the turbine after warming through the fuel gas. He noted that all pre start parameters were normal and he initated a "No Load Start". The turbine speed picked up and the purge cycle was achieved at 450 rpm, which is normal for this machine. During the next	No (immediate ignition, fuel gas in hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
					part of the start sequence the machine accelerated towards "fuel on" speed but a "heavy light off" occurred, which resulted in damage to the exhaust ducting and exhaust gas entering the module. It is suspected that an earth fault on turbine control system allowed the "STAR" valve to open, or be open during the start sequence, resulting in over fuelling of the engine. It is difficult to predict the gas volumes in this case therefore we have estimated the maximum volume of gas which could pass through the STAR valve in 1 hour. The gas would be vented directly into the exhaust stack and would be vented into a safe location at all times. We therefore consider that this incident should be classified as "Significant", please contact Shell Expro for any further clarification.	

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for λ_i
2003-2004-207	151	900	Under investigation by Petrofac and the HSE	Portable gas detection adjacent the valve indicated 4% LEL. the fixed CH4 gas detector approx. one metre from the valve did not indicate LEL. Liquid washed away to hazardous drains in the area using sea water.	Liquid condensate samples to be sent to the HSE and Petrofac Boroscope and portable gas detector required by HSE for inspection.	Marginal leak (quantity released 0.015 kg)
2006-2007-54	194	0	Unknown, still under investigation.	Contained within the module.	BLANK	No (immediate ignition)

A2-2.3 Observations

For process leaks as defined in PLOFAM, 44 of 3,001 leaks ignited (1.5%). Considering only leaks with rate > 0.1 kg/s, the fraction ignited is similar, 12 ignitions of 687 leaks (1.7%).

A2-3 Estimated gas cloud sizes for observed leaks

A2-3.1 Method

In principle, there is quite extensive information available as a basis for quantifying gas cloud sizes for the leaks in the HCR database. In practice, the data recorded is more difficult to use for the following reasons:

The GOR (Gas Oil Ratio) is reported in HCR, but the data does not seem reliable. The gas fraction is therefore assumed as follows:

- Gas, 100%
- 2-phase, 33%
- Condensate, 10%
- Oil, 2%

For the ventilation, or ACH reported, "NOT KNOWN" dominates. The average ACH for modules with forced ventilation is about 1,000, the range is from 0 to 28,800. It seems that the figure given in many cases is the volume flow in m^3/h instead of the actual number of air changes per hour. ACH is therefore not included in the simplified model for estimation of the gas cloud sizes.

With these limitations in the data set, the following simple model for modelling the gas cloud size is applied in this project:

1. The LEL volume inside the module is found from the leak rate in kg/s as follows

$$V_{LEL} = 225\ [m^3 \cdot s/kg] \cdot m\ [kg/s] \cdot \text{gas fraction } [-]$$
$$V_{fla} = 150\ [m^3 \cdot s/kg] \cdot m\ [kg/s] \cdot \text{gas fraction } [-]$$

2. Obviously, the gas quantity released sets limits for the size of the gas cloud. Gas cloud limitation for released quantity (kg) is.

$$V_{LEL} \leq 4\ [m^3/kg] \cdot \text{Quantity } [kg]$$
$$V_{fla} \leq 2.65\ [m^3/kg] \cdot \text{Quantity } [kg]$$

3. The flammable gas cloud inside a hazardous area is always assumed to be small if the leak is not automatically detected. It is assumed that leaks not automatically detected have a V_{LEL} and V_{fla} less than or equal to $10m^3$.

4. The exposed volume does not exceed the module volume. Where module volume is not given, the volume is assumed 5,000 m^3. In many cases it may be that module volume is not given because the leak takes place outside or at the edges of a module.

A2-3.2 Exposure due to PLOFAM leaks 2001-2017

The resulting exposures from PLOFAM leaks are shown in Table A2 3.1 to Table A2 3.3.

Table A2 3.1: UKCS $V_{LEL,max}$ gas cloud exposure, PLOFAM leaks 2001-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	-	-		12,000	-	12,000
D(10-100)	-	-	-	4,033	3,770	7,803
C(1-10)	41	617	3,758	577	5	4,998
B(0.1-1)	425	2,038	1,554	359	241	4,617
A(<0.1)	1,127	1,374	367	29	0	2,897
Total	**1,593**	**4,029**	**5,679**	**16,998**	**4,016**	**32,315**

**Module size manually corrected to 12000m^3.*

Table A2 3.2: UKCS $V_{LEL:UEL,\ avg}$ gas cloud exposure, PLOFAM leaks 2001-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	0	0	0	12,000	0	12,000
D(10-100)	0	0	0	2,699	2520	5,219
C(1-10)	31	421	2,430	375	3	3,260
B(0.1-1)	293	1,388	1,065	263	166	3,175
A(<0.1)	794	969	248	24	0	2,035
Total	**1,118**	**2,778**	**3,743**	**15,361**	**2,689**	**25,689**

**Module size manually corrected to 12000m^3.*

Table A2 3.3: UKCS $V_{LEL:UEL,\ avg}$ gas cloud exposure * exposure time (s), PLOFAM leaks 2001-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	0	0	0	12,0000	0	12,0000
D(10-100)	0	0	0	249,219	1,512,000	1,761,219
C(1-10)	1,025	24,766	742,869	219,911	1,860	990,431
B(0.1-1)	15,860	242,300	596,426	165,201	99,811	1,119,598
A(<0.1)	242,047	490,570	174,186	13,982	0	920,785
Total	**258,932**	**757,636**	**1,513,481**	**768,313**	**1,613,671**	**4,912,033**

**Module size manually corrected to 12000m^3, exposure time set to 10s*

A2-3.3 Exposure due to PLOFAM leaks 1992-2017

The resulting exposures from PLOFAM leaks are shown Table A2 3.4 to Table A2 3.6.

Table A2 3.4: UKCS $V_{LEL,max}$ gas cloud exposure, PLOFAM leaks 1992-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	-	-	10	12,000	-	12,010
D(10-100)	-	-	7,240	11,016	12,034	30,290
C(1-10)	52	2,150	12,042	2,586	5	16,835
B(0.1-1)	1,126	4,848	5,217	1,053	337	12,581
A(<0.1)	2,615	2,529	579	41	2	5,766
Total	**3,793**	**9,527**	**25,088**	**26,696**	**12,378**	**77,482**

**Module size manually corrected to 12000m^3.*

Table A2 3.5: UKCS $V_{LEL:UEL,\ avg}$ gas cloud exposure, PLOFAM leaks 1992-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	0	0	10	12,000	0	12,010
D(10-100)	0	0	4,800	7,354	8,043	20,197
C(1-10)	39	1,452	8,017	1,758	3	11,269
B(0.1-1)	782	3,353	3,662	729	233	8,759
A(<0.1)	1,812	1,783	412	31	0	4,038
Total	**2,633**	**6,588**	**16,901**	**21,872**	**8,279**	**56,273**

**Module size manually corrected to 12000m^3.*

Table A2 3.6: UKCS $V_{LEL:UEL,\ avg}$ gas cloud exposure * exposure time (s), PLOFAM leaks 1992-2017 , ignitions at time <=5 s removed

Leak rate (kg/s)	Quantity released (kg)					
	A (<10)	B (10-100)	C (100-1000)	D (1000-10000)	E (>10000)	Total
E(>100)	0	0	0	120,000	0	120,000
D(10-100)	0	0	268,458	1,309,449	4,643,217	6,221,124
C(1-10)	1,310	108,760	1,652,856	905,723	1,860	2,670,509
B(0.1-1)	44,328	590,352	1,903,825	485,275	140,017	3,163,797
A(<0.1)	500,743	894,566	272,190	18,512	0	1,686,011
Total	**546,381**	**1,593,678**	**4,097,329**	**2,838,959**	**4,785,094**	**13,861,441**

**Module size manually corrected to 12000m^3, exposure time set to 10s*

A2-4 References

[1] Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", report no: 107566/R1, Rev: Final, Date: December 2018

Attachment A3

Other ignition data

Table of contents

A3-1 Introduction

This attachment documents additional data not directly used in the ignition model, but which serves as background information.

A3-2 Complete list of ignited events in the HCR database

A complete list of ignitions with a short description of the event is available from UKOOA/HSE. As a basis for this study, a list including 226 records for the period March 31st 1992 – December 31st 2017 is applied.

In the previous study (OLF ignition model), there were 143 ignitions for the 10 years period 1992-2002. There is no reference between the ignitions database and the leak database, so it is a puzzle to match the two lists. In attempting to do so, it was concluded that two ignitions (number 120 and 121) were related to the same release incident[1], making the total number of ignited releases 225.

143 of the 225 records were reported as non-process. In addition, incident number 54 is a diesel leak (from the description) reported as an oil leak. The distribution on type of fuel for the 144 non-process incidents follows:

- 64 lube oil
- 55 diesel
- 2 fuel oil
- 1 helicopter fuel
- 7 hydraulic oil
- 2 methanol
- 2 bottled gas
- 4 heat transfer oil
- 7 glycol

The remaining 81 incidents [226 – 143 (non-process) – 1 (double count) – 1 (diesel)] are ignitions of process fluids, including fuel gas incidents.

Of these 81 ignitions, 9 were related to flaring and flare carry over (ignitions by flare). 8 incidents were ignitions of a vent as a consequence of lightning. 7 incidents were concluded not applicable release scenarios – these were typically turbine start-up incidents involving fuel gas in hood.

[1] Alternatively, the leak may not have been included in the HCR database, or there may be inconsistent information)

Of the 57 [81-9-8-7] remaining ignitions ignition sources were distributed as follows:

29 were ignited by activity related causes including hot work
8 were related to drivers for rotating machinery (exhaust stack, etc.)
6 were related to electrical equipment
4 were related to pumps (bearing)
5 were concluded as static
5 remain unknown

Since hot work and activity related ignitions are considered separately in the ignition model, a set of 28 incidents remain as candidates to be applied as the basis for the ignition probability modelling. One of these (no 184) is the major leak at Centrica B which was ignited by an external source (turbine), and one ignition took place inside an atmospheric tank (no 206). The majority of the remaining 26 incidents involved very small quantities of gas and oil, incidents normally not reflected in QRA work on major accident risks. Nevertheless, the 26 incidents are proposed applied as an indication for the distribution of ignition sources relevant for process leaks. The following sections look further into the leak database, focusing on the number of leaks and ignitions in different categories of process leaks.

A list of the 26 records including a reference to the leak database is shown in the next table. For 6 of the 26 incidents (23%), ignition is reported as delayed. For 7 leaks, leak rate (quantity/duration) exceeds 0.1 kg/s. 2 of the 7 (29%) are recorded as delayed ignitions.

Table A3 2-1: Subset of ignited process leaks

Leak ID	HCR ign ID[2]	YEAR	PROCESS	SEVERITY	QUANTITY (kg)	DURATION (min)	Quantity/ duration (kg/s)	Ignition source	Delay time [s]
79	1	1993	GAS	SIGN.	54	30	0.030	Turbine	-
93	7	1993	GAS	MINOR	0.03	0.25	0.002	Electrical	-
3	14	1993	GAS	SIGN.	153	17	0.150	Exhaust	-
265	15	1994	GAS	SIGN.	210	10	0.350	Exhaust	-
133	29	1993	COND.	MINOR	27	5	0.090	Static	-
206	32	1994	COND.	MINOR	6	0.5	0.200	Electrostatic	-
54	64	1996	COND.	MINOR	2.7	0.5	0.091	Unknown	-
163	83	1997	GAS	MINOR	0.1	0.1	0.017	Static	-
133	88	1997	GAS	SIGN.	121.9	300	0.007	Electrical	9999
163	94	1998	GAS	MINOR	0.90	0.5	0.030	Static	-
174	96	1999	GAS	SIGN.	5	2	0.042	Turbine	-
56	112	2000	GAS	MINOR	0.70	6	0.002	Motor	-
219	120	2001	GAS	MINOR	0.02	0.16	0.002	Hot surface (driver)	-
189	144	2003	COND.	MINOR	59.9	40	0.025	Unknown (pump)	-
223	145	2003	GAS	MINOR	0.05	1	0.001	Spark	-
9	149	2002	OIL	MINOR	15	15	0.017	Pump	120
47	150	2002	OIL	MINOR	1.66	60	0.000	Pump	-
207	151	2004	COND.	MINOR	0.015	15	0.000	Unknown	900
62	164	2003	OIL	MINOR	45	6	0.124	Motor (pump)	-
29	165	2004	COND.	MINOR	2	0.25	0.133	Electrical	10
150	185	2005	GAS	MINOR	0.99	0.5	0.033	Pump	-
194	186	2006	GAS	MINOR	97.75	1440	0.001	Unknown	-
54	194	2006	GAS	MINOR	1.00	1	0.017	Unknown	-
12	201	2008	GAS	MINOR	6.1	7	0.015	Spark	7
145	208	2010	2-PHASE	SIGN.	2250	120	0.313	Electrical	120
87	226	2013	Oil	Sign.	134	16	0.140	Pump	-

[2] Note that the numbering of the ignitions has been changed in the database since the previous report (2007)

A3-3 All ignited PLOFAM leaks

Descriptions and evaluations of all ignited PLOFAM leaks (as discussed in appendix A and attachment A2) are given in Table A3 3.1 and Table A3 3.2.

Table A3 3.1: PLOFAM leaks 1992-2017 with average rate > 0.1 kg/s (13 off) [HCRD]

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1992-1993-11	4	0	THE HP FLARE, WHICH WAS LIT AT THE TIME OF OIL CARRYOVER	BLANK	A QUANTITY OF OIL WASCARRIED OVER FROM THE TEST SEPARATOR TO THE FLARE SYSTEM DURING AN OPERATION TO PRESSURISE VO3 USING WELL TO ASSIST SAND DISPLACEMENT. A LARGE PERCENTAGE OF THE OIL CARRY OVER WAS COLLECTED IN THE HP KNOCK OUT DRUM & THIS RESULTED IN HI-LEVEL ALARM IN THE MOL CONTROL ROOM. THE REMAINDER OF THE OIL WAS CARRIED UP THE HP FLARE WHERE NOT ALL OF IT WAS BURNED BY THE MARDAIR, A SMALL AMOUNT FALLING AS OIL DROPLETS TO THE MAIN DECK (REPORT RECEIVED BY CONTROL ROOM TECHNICIAN & OTHER OIL OBSERVED AS BURNING ON THE FLARE ANTI-RADIATION PLATFORM DECK.	No (flare carryover)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1993-1994-3	14	0	HOT GASES IGNITED IN EXHAUST STACK	FIRE SELF EXTINGUISHED AS FUEL SUPPLY WAS CONSUMED.	A FUEL CHANGE OVER FROM DIESEL TO GAS WAS ATTEMPTED ON GT2 BUT THE TURBINE RESISTED THE CHANGE OVER AND TRIPPED, THE TURBINE WAS RESET AND RESTARTED ON GAS. THE MACHINE WAS MANUALLY SHUTDOWN ABOUT 15 SECONDS LATER AFTER ABNORMAL SPEEDS AND TEMPERATURE WERE OBSERVED. HIGH TEMPERATURES WERE NOTED ON THE EXHAUST STACK AND WHEN CHECKED, FLAMES WERE SEEN TO BE EMITTING FROM THE STACK. THE GENERAL ALARM WAS SOUNDED AND FIRE PARTIES SENT TO THE SEEN.	No (fuel gas ignited inside turbine hood)
1993-1994-265	15	0	HOT EXHAUST STACK.	N/A	WHILST LOADING THE COMPRESSORS PRIOR TO COMING ON LINE, UNIT AK-K-040 INDICATED HIGH GAS GENERATOR VIBRATION. AT THIS STAGE THE DISCHARGE	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
					PRESSURE FROM THE MACHINE WAS IN EXCESS OF 600 PSIG AND A SURGING OF SOME DESCRIPTION WAS EXPERIENCED IN THE CONTROL ROOM. UNIT AK-K-040 SHUTDOWN ON HIGH GAS GENERATOR VIBRATION. DURING THE INVESTIGATION INTO THE SHUTDOWN, IT WAS NOTICED THAT SOME FUEL GAS PRESSURE WAS STILL INDICATED ON THE 3 WAY VALVE PRESSURE GUAGE AND THAT THE NEWLY INSTALLED AUTOMATIC VENT VALVE WAS HALF OPEN. FUEL GAS BLOCK AND VENT VALVE OPERATED MANUALLY BY THE TECHNICIANS. EXHAUST STACK FIRE INDICATED IN THE CONTROL ROOM. FIRE EXTINGUISHED BY MANUAL OPERATION OF CO2 SNUFFING SYSTEM.	

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1993-1994-4	30	0	IGNITION SOURCE WAS FLARE SYSTEM WHICH WAS LIT AT THE TIME OF THE CARRYOVER.	DROPS OF UNBURNED OIL RESIDUE FELL ON TOP DECK - WASHED INTO DRAINS OR WIPED UP FROM STRUCTURE. OIL FROM FLARE PILOT SYSTEM AT BASE OF FLARE TOWER - TO DECK.	A QUANTITY OF CRUDE OIL WAS CARRIED OVER FROM THE PRODUCTION SEPARATOR (VO2) TO THE FLARE SYSTEM VIA THE PRODUCTION SCRUBBERS VO4/V05. PRODUCTION FROM THE SATTELITE PLATFORM FE WAS BEING ESTABLISHED AT THE ACCIDENT, A LARGE SLUG OF LIQUID WAS RECEIVED FROM THE FE PRODUCTION LINE, WHICH TRIPPED THE SEPARATOR. HOWEVER, LIQUID WAS CARRIED OUT THROUGH THE SEPARATOR GAS OFF TAKE INTO THE FLARE SYSTEM. SOME OF THE OIL WAS NOT BURNED IN THE HP FLARE AND FELL AS DROPLETS ON THE MAIN DECK (WEST). NO INJURY TO PERSONNEL. NO DAMAGE TO PLANT.	No (flare carryover)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
1994-1995-206	32	0	CONDENSATE IGNITED DUE TO ELECTROSTATIC SOURCE (UNSATISFACTORY EARTHING BOND)	N/A	BLANK	Marginal leak (quantity released 6 kg)
1997-1998-71	86	30	EXCESS GAS IGNITED BY BURNERS	OVERFUELLED GAS ACCUMULATED IN ENGINE.	EXPLOSION IN EXHAUST DUCTING RUPTURED A FLEXIBLE BELLOWS	No (fuel gas ignited inside turbine hood)
2003-2004-45	153	0	The welder struck his arc to commence welding	A satisfactory gas test had just been taken by portable gas monitors (MSA Passport 5 Triple detector & MSA Tankscope meter). Very short duration flash/jet fire exhausted finite hydrocarbon inventory.	The workparty had failed to fit by Method the Stopple Plug (required Statement) to maintain the inert atmosphere & segregate the residual hydrocarbon atmosphere within the pipework from the workpiece to be welded.	No (hot work)
2003-2004-62	164	0	High pressure spray probably ignited on hot surface (of turbine/motor) on pump	None	BLANK	Yes (Pim, pump)
2004-2005-29	165	10	Air mover was positioned at manway entrance; when the air mover was switched on a vapour flash occurred at entrance to manway. As a result of the vapour flash, hot exhaust	Lazy condensate gas within vessel migrated out of manway opening when door was opened. Condensate not under pressure therefore unable to determine amount of condensate gas dispersion or quantity.	BLANK	No (not relevant leak scenario)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
			gases were emitted from the manway opening	No detection activated due to this dispersion, therefore duration not applicable as condensate gas within vessel flashed off immediately when air mover started and the GPA activation followed due to flame detection.		
2005-2006-191	184	5	Gas ignited on ingestion into combustion chamber of Ruston Gas turbine C (power generation)	Enveloped BP jacket topsides. 3 Jackets bridge linked. BD accommodation, BP process, CD Wellheads	Catastrophic failure of train 3 production cooler (shell and tube). Resulted in the release of approx. 7000kg HC gas which ignited on ingestion into R6T 'c' combustion chamber	No (turbine ignition
2009-2010-146	208	120	Electrostatic spark from an insulated conductor, charged by the electrostatically charged mist created by primary release is thought to be the most likely source of ignition	Liquid condensate thought to have rained out from leak, accumulating upon flat surfaces and equipment and to run down vertical surfaces to collect wherever the conditions allowed. This is apparent on the deck level and around well W4/KA with wax deposition on all surfaces. There is also evidence of condensate deposition and run off on the East end of the solid deck by the HPU and significant deposition of wax on the 9 m level. It is not clear	Erskine is a Normally Unattended Installation and was unmanned at the time of the incident. Manual operation of export pipeline SSSV and blowdown of the export pipeline was carried out by BG Lomond OIM.	Yes (Pim or Pif)

My identifier	Ign ID	Delay [s]	Ignition description	Extent of dispersion	Additional comments	Relevance for Pim (pump), Pim or λ_i
				whether this is the initial deposition or the melting and spread of wax following the fire. Gas escaping from the leak dispersed away from the installation under natural windflow. Modelling suggests that the gas cloud produced was not significantly large enough to cause detection by the installation gas detectors.		
2013-2014-99	226	0	Frictional heat from the mechanical seal	N/A	No loss of hydrocarbons to sea	Yes (Pim, pump)

Table A3 3.2: PLOFAM leaks 1992-2017 with average rate < 0.1 kg/s (31 off)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
1993-1994-108	11	0	WELDERS SPARK FROM HOT WORK SITE ADJACENT TO (AND ABOVE) THE LEAK. THIS PRODUCED A "GAS RING" TYPE OF FLAME, - STEADY BLUE CIRCULAR FLAME, 2 OR 3 INCHES HIGH.	DISPERSION MUST HAVE BEEN VERY LOCAL TO THE CHOKE - IT WAS NOT DETECTED BY FIXED GAS HEADS ABOVE, OR BY THE WELDERS PORTABLE MONITOR.	THE LEAK WAS FROM THE COLLAR OF A "GRAYTOOLS" PBS 30 CHOKE VALVE (VIA THE GLAND).	No (hot work)
1993-1994-133	5	0	WELDER CUTTING INTO REDUNDANT PIPEWORK.	BLANK	BLANK	No (hot work)
1994-1995-189	33	0	INTERNAL COMBUSTION OF EXTRANEOUS MATERIAL/GAS IN EXHAUST DUCTING	N/A	DURING NORMAL START SEQUENCE ON THE GAS COMPRESSOR ON REACHING GAS GEN LIT, A LOUD BANG WAS HEARD. ON INVESTIGATION SOME DISTORTION WAS FOUND ON THE EXHAUST TRUNKING. AN EXPANSION JOINT WAS FOUND TO BE BADLY DAMAGED ALSO A FLANGE APPEARED TO	No (fuel leak inside turbine hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
					HAVE SPREAD ON THE PIPEWORK. AN INTERNAL INSPECTION WAS CARRIED OUT ON ACCESSABLE PARTS AND APART FROM THE DISTORTION NOTHING WAS FOUND.	
1993-1994-237	29	0	POSSIBLY STATIC ELECTRICITY FROM CONTAINER AND/OR FROM OPERATOR'S CLOTHING.	OIL CONTAINED IN OPEN TOP METAL CONTAINER HAVING BEEN DRAINED FROM BOOSTER PUMP SUMP.	SOME OF THIS INFORMATION TAKEN FROM AN OIR/12 FOR SUBSEQUENT GAS LEAK OCCURING FROM EXCESS FIREWATER IN THE OPEN DRAIN SYSTEM.	No (immediate ignition)
1995-1996-26	56	0	FLAME FROM BURNING TORCH (OXYACETYLENE)	FLAME CONFINED TO SMALL AREA. SMALL POCKET OF TRAPPED GAS WITHIN PIPEWORK CAUGHT FIRE WHEN BOLTS WERE CUT TO RELEASE FLANGE. ALL PIPEWORK HAD BEEN NITROGEN FOAM INERTED.	AS PART OF THE CONSTRUCTION ACTIVITY ON THE PLATFORM, A 2" VALVE ON THE CONDENSATE HEADER SYSTEM REQUIRED TO BE REMOVED. PRIOR TO THE VALVE REMOVAL WORK TAKING PLACE THE SYSTEM HAD BEEN NITROGEN FOAM INERTED. AFTER REMOVING 6 BOLTS FROM THE FLANGES BY USE OF A BURNING TORCH, A GAS	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
					CHECK WAS INITIATED. ONCE THIS WAS COMPLETED SATISFACTORILY THE JOB RECOMMENCED TO BURN THROUGH THE LAST REMAINING BOLTS. DURING THIS PROCESS FLAMES WERE SEEN TO EMANATE FROM BETWEEN THE FLANGE FACES. THE JOB WAS IMMEDIATELY STOPPED WITH THE FIRE QUICKLY EXTINGUISHED BY USING A COMBINATION OF FIRE HOSE AND DRY POWDER. NO INJURY TO PERSONNEL OR DAMAGE TO EQUIPMENT ENSUED. SUBSEQUENT INVESTIGATION CONCLUDED THAT A TRAPPED POCKET OF GAS WAS PROBABLY IGNITED IN THE PROCESS TO RELEASE THE FLANGES. HSE WERE INFORMED AT 00:42 HRS.	
1996-	69	0	WELDING	UNFLUSHABLE DEAD LEG OF	BLANK	No (hot

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
1997-52			OPERATIONS	PIPE		work)
1996-1997-38	65	0	WHILE REMOVING A CHECK VALVE FROM 12" FLOW LINE USING A 110 VOLT GRINDER TO REMOVE THE BOLTS.	APPROX. 1 LTR OF CONDENSATE RELEASED ONTO SCAFFOLD STAGING AND PASSED ON DOWN THROUGH THE OPEN DECK GRATING TO THE SEA.	PLATFORM WAS SHUT DOWN AND DE PRESSURISED - CAMELOT FREEFLOW LINE WAS FLUSHED WITH WATER TO REMOVE CHECK VALVE - DURING BOLT REMOVAL WITH HAND GRINDER THE FLANGE CRACKED OPEN - A SMALL AMOUNT OF LIQUID MAINLY WATER WITH SOME CONDENSATE SPILLED ONTO BOARDS AND IGNITED - IMMED EXTUING-UISHED WITH DRY POWER - NO INJURIES	No (hot work)
1997-1998-163	83	0	STATIC, CAUSED BY POOR ELECTRICAL CONTINUITY OF EARTH STRAP.	GAS DISPLACED FROM DRUM DURING SAMPLING OPERATION, DISPERSED LOCALLY TO THE DRUM OPENING.	GAS DISPLACED FROM DRUM DURING SAMPLING OPERATION (AS NORMAL), IGNITED AT SAMPLING DRUM OPENING BY STATIC CAUSED BY POOR ELECRICAL CONTINUITY OF EARTH STRAP.	No (immediate ignition)
1997-1998-67	87	0	ARC WELDING OF FLANGE TO PIPE STUB	N/A	BLANK	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
1997-1998-133	88	99999	SPARK FROM DAMAGED TRACE HEATING CABLE	PRIOR TO IGNITION THE WIND SPEED WAS SUFFICIENT TO PREVENT GAS BUILD UP FROM THIS MINOR LEAK SOURCE. (WHEN THE WIND SPEED DROPPED TO LESS THAN 4 KNOTS GAS BUILT UP UNTIL IGNITION FROM THE DAMAGED TRACE HEATING SOURCE OCCURED).	LEAKING FITTING WAS IDENTIFIED AT 14:00 HOURS. 2 DEC JOB CARD RAISED TO REPAIR AT TIME OF IDENTIFICATION. LEAK CONSIDERED MINOR.	No (leak rate < 0.01, detection by ignition)
1998-1999-65	93	0	AIR OPERATED GRINDER	3M SECTION OF 10in PIPE - OPEN AT BOTH ENDS - VERY SMALL AMOUNT OF GAS ASSUMED TO HAVE MIGRATED INTO AREA DURING/FOLLOWING NITROGEN PURGING	BLANK	No (hot work)
1998-1999-61	92	0	THERE WAS NO HYDROCARBON RELEASE. AFFECTED SYSTEM WAS COMPLETELY ISOLATED FROM HYDROCARBON SOURCE AND HAD BEEN ISOLATED, PURGED, FLUSHED. A SMALL RESIDUE	N/A	BLANK	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
			(IMMEASURABLE BUT SUGGESTS LESS THAN HALF A CUP FULL) WAS CONTAINED IN A SECTION OF PIPE BEING CUT UP FOR REMOVAL. IGNITED BY SPARK/ HEAT FROM GRINDER			
1999-2000-113	111	0	WELDING OPERATION (BEING UNDERTAKEN)	AREA APPROXIMATELY 18"SQUARE.	BLANK	No (hot work)
1999-2000-59	110	0	WELDERS ARC	1 METRE FROM PIPE STUB AND IMMEDIATE DISPERSAL.	HOT WORK IN AREA WAS STOPPED AND INVESTIGATION INTO SOURCE OF HYDROCARBON RELEASE COMMENCED. IP RECEIVED BURNS TO THE BACK OF HIS LEFT HAND AND LOWER ARMS - RECEIVED TREATMENT FROM MEDIC AND WAS THEN EVACUATED TO HOSPITAL.	No (hot work)
1999-2000-28	113	0	BURNING TORCH FROM ADJACENT RED HOT WORK.	SMALL QUANTITY OF GAS PERMEATING FROM 6in FLANGE AND PERSONNEL WORKING	PLATFORM ON ANNUAL SHUTDOWN:- INSPECTION OF WELL MANIFOLD	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
				NEARBY WERE UNAWARE. GAS DETECTOR AT THE SCENE.	"DOWNCOMERS" ONGOING. DOWNCOMER REMOVED AND THEN REINSTATED - PARTIALLY MADE UP. SMALL VOLUME OF GAS BUILT UP VIA PASSING VALVE (PREVIOUSLY UNNOTICED) AND BEGAN TO LEAK PAST THE PARTIALLY MADE UP FLANGE - IGNITION AS DESCRIBED.	
1998-1999-188	108	0	FILTER BASKET HAD BEEN REMOVED FROM PIEPLINE WHICH HAD ALREADY BEEN BROKEN INTO TO REMOVE DOWNSTREAM TURBINE METER WITH NO HYDROCARBON PRESENT. THE BASKET WAS REMOVED AND ALTHOUGH NO EVIDENCE OF	THERE WAS AN INSTANTANEOUS BLUE FLASH. BUT NOT ENOUGH HYDROCARBON PRESENT TO SUPPORT CONTINUOUS BURNING.	BLANK	No (not relevant leak scenario

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
			LIGHT END HYDROCARBONS A BLUE FLASH WAS APPARENT WHEN IT WAS FLUSHED WITH WATER FROM A HOSE STATION. IT IS THOUGHT THAT THE HOSE WAS NOT ANTI-STATIC AND WAS THE SOURCE OF IGNITION.			
2000-2001-136	131	0	SOURCE OF IGNITION WAS SPARK FROM GRINDING OF PIPE WITH DISC GRINDER.	VERY SMALL POOL ON SCAFFOLD BOARD. AREA APPROX. 1/22 DIAMETER.	BLANK	No (hot work)
2000-2001-133	122		ASSUMED TO BE AS A RESULT OF WELDING WORK ONGOING NEAR THE FLANGE IN A SPECIALLY CONSTRUCTED HABITAT. NO WITNESS STATEMENYS CAN	WITNESS STATEMENTS INDICATE A "SMALL, FLICKING FLAME 3 - 4 INCHES IN LENGTH.	INVESTIGATIONS ARE ON GOING TO DETERMINE EXACT CAUSE BUT NO WITNESS STATEMENTS INDICATE EXACTLY AND PRECISLEY HOW THIS OCCURRED NOR HOW A SPARK/ SLAG ESCAPED FROM THE PURPOSE BUILT HABITAT.	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
			CONFIRM OR DENY THIS.			
2000-2001-61	119	60	IGNITION OCCURRED WHEN SHELL WAS BEING PRE-HEATED BY MEANS OF NAKED FLAME. OXY-ACETYLENE WAS THE FLAME.	LOCAL TO OUTLET OF 8in PIPE. IR DETECTION FOR THE AREA WAS ACTIVATED. THE AUTOMATIC FUNCTION OF THESE DETECTORS HAD BEEN INHIBITED PRIOR TO CARRYING OUT THE REPAIR WORK.	KTO1 Gas Compressor Train Inspection, pitting repairs to 1st stage cooler shell. The train was purged 3 times with nitrogen & spaded . All 5 scrubbers had their access doors removed & the 3 coolers had the end covers removed. The train had been open for 24 hrs prior to the accident. Prior to EO2 repairs the area had been correctly checked out for the issuing of the Hot Work Permit. Two fire watchers were on station at the site. The welder, Mr Ali Scott had completed 15 min of grinding in the cooler. When he lit his torch to apply heat treatment to the shell the 8" inlet pipe above him must have had a pocket of residue gas in it which flashed. His firewatch went to put it out with his glove when his mate used a dry powder extinguisher. This 8" pipe had just been internally NDT& no gas was detected. As a	No (hot work)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
					precaution the 8" pipe was blanked & a further spade fitted on the start up gas line (which was locked off). On fitting of this spade no gas was detected. The welding repairs continued without further incident.	
2000-2001-56	120	0	HOT TUBING CASING	CONTAINED WITHIN HOOD AND DISSIPATED THROUGH EXTRACT VENTILATION DUCT.	BLANK	No (fuel gas in hood)
2000-2001-219	121	0	HOT SURFACE	N/A	Platform was on normal production when Turbine generator AGT#2 shutdown automatically and the turbine enclosure automatic fixed CO2 extinguishant fired off. Operators were in attendance at the machine within two minutes and on local alarm panel, alarm 400 "Fire in enclosure" was active. Operator checked through hood window and no flames could be seen. CO2 had automatically activated and extinguished fire. Internal inspection of turbine found a nut backed off half turn on the fuel gas inlet to burner #4 causing the Dowty seal to be loose. Further	No (fuel gas in hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
					investigation ongoing with equipment manufacturer (AGT).	
2002-2003-47	150	0	Heat source from pump bearings	Localised - contained within skid and closed drain system	BLANK	No (immediate ignition)
2002-2003-9	149	120	Crude oil Booster Pump - suspect thruster bearing failure i.e. heat from friction causing flash fire followed by jet fire	Flame alarm activated in MCR, and fire/smoke was observed by a technician setting up at his worksite. From the time of observation until the platform was shutdown and blowndown it is estimated that this would have been 15 mins. During this period the operating plant pressure would be decreasing at all times until reaching zero pressure.	A full investigation into the incident was undertaken and the booster pump to be removed from its location and sent onshore for detailed investigation. It is currently suspected that the thruster bearing failed.	No (probably immediate ignition)
2003-2004-60	152	30	Gas which had migrated ignited during welding of a new flange to an existing process system.	Crude vapour was ignited and all burnt.	This was not a release but a vapour from crude residue in pipework.	No (hot work)
2002-2003-223	145	0	Electrical spark	None - contained within motor housing	BLANK	No (immediate ignition)
2002-2003-189	144	0	Unknown awaiting investigation, thoughts are friction	Unknown as condensate ignited but seems to have been confined to an area of 3 sq metres. UV detector came into alarm on AC cellar deck, followed by a second UV that initiated	BLANK	No (immediate ignition)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
				an ESD of the gas compression facilities. Platform general alarm sounded automatically.		
2003-2004-55	154	0	Turbine main start system. Explosion occurred due to rich gas mix during turbine start-up with all excess gas contained in turbine exhaust stack. Machine experienced heavy light-off during start sequence.	Gas had passed into turbine exhaust stack. No entry of gas into module. All hydrocarbons contained within turbine and exhaust stack	Machine experienced heavy light off due to excess gas during start sequence. It is considered that the "STAR" valve was passing during the start sequence resulting in a rich fuel mix. The power technician initiated a normal start on the turbine after warming through the fuel gas. He noted that all pre start parameters were normal and he initated a "No Load Start". The turbine speed picked up and the purge cycle was achieved at 450 rpm, which is normal for this machine. During the next part of the start sequence the machine accelerated towards "fuel on" speed but a "heavy light off" occurred, which resulted in damage to the exhaust ducting and exhaust gas entering the module. It is suspected that an earth fault on turbine control system allowed the "STAR" valve to open, or be open during the	No (immediate ignition, fuel gas in hood)

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
					start sequence, resulting in over fuelling of the engine. It is difficult to predict the gas volumes in this case therefore we have estimated the maximum volume of gas which could pass through the STAR valve in 1 hour. The gas would be vented directly into the exhaust stack and would be vented into a safe location at all times. We therefore consider that this incident should be classified as "Significant", please contact Shell Expro for any further clarification.	
2003-2004-207	151	900	Under investigation by Petrofac and the HSE	Portable gas detection adjacent the valve indicated 4% LEL. the fixed CH4 gas detector approx. one metre from the valve did not indicate LEL. Liquid washed away to hazardous drains in the area using sea water.	Liquid condensate samples to be sent to the HSE and Petrofac Boroscope and portable gas detector required by HSE for inspection.	Marginal leak (quantity releases 0.015 kg)
2006-2007-54	194	0	Unknown, still under investigation.	Contained within the module.	BLANK	No (immediate ignition)
2015/2016-4690	NA	Unknown	Heat: Outer surface of turbine exhaust duct	One gas detector at 100% and one at 15% LEL at 6.5 metre via pipework.	NA	No
2015/2016-4680	NA	Unknown	Pump running dry resulting in overheating	1 x high gas alarm - 1 LELm (20% LEL equivalent) - indication on	NA	No

My identifier	Ign ID	Delay [s]	Ignition source	Extent of dispersion	Additional comments	Relevance for Pif
			of the mechanical seal.	control panel 30-40% LEL equivalent 1 x Low gas alarm - 0.5 LELm (10% LEL equivalent)		
Year: 2016 URN: 6646	-	-	CUTTING TORCH WAS IGNITION SOURCE WITH SPARKS OR HOT SLAG PROVIDING THE IGNITION	BLANK	Only the cutting activity ceased with the work party remove the damaged hose from service before resuming work (other normal activities on the installation continued as planned)	NO

A3-4 Observed causes for ignitions

A3-4.1 General

Massive gas leaks rarely occur in Norway, UK and Denmark. Nevertheless, two ignited events are experienced; at Gorm C in 2001 and at Centrica B in 2006. Coarsely this is one ignited large leak in 10 years (for NCS, UKCS and DCS). The overall number of large gas leaks is about 1 per year (rate > 10 kg/s and quantity > 1000kg), which means the ignition probability could be as high as 1/10 for such leaks.

The two large ignited events are both gas leaks. Centrica Rough B was reportedly ignited by a turbine, and Gorm C suspected being ignited by a turbine. An important task is therefore to evaluate importance of the presence of turbines for the ignition probability.

Then, restricting the evaluations to process leaks exceeding 0.1 kg/s, there are 11 incidents in addition to the Centrica Rough B accident.

Ignition of the leak 2009-2010-146 is reported to be as a result of a droplet spray, and ignition delay is set to 120 seconds. If this ignition mechanism is correct, this is an “event ignition”, except for a significant delay. In any case, the gas cloud for this case was insignificant; the gas content is low, leak rate is moderate, ventilation conditions good with quite high wind speed (13 m/s). The flame was automatically detected, resulting in automatic shutdown, manual blowdown, but for some reason no deluge.

A3-4.2 Hot work incidents

First of all, it seems hot work ignition has a falling trend. Before 1990, there were several incidents of small gas leaks being ignited at the NCS. For the last years, this has been an infrequent scenario also for the UKCS. Still, we observe some minor gas leaks being ignited by welding operations (URN 6646 in 2016 and HCR ignition number 152 and 153) gas from the drain system ignited by welding (HCR ignition 214) and one ignition due to grinding. In the latter, it seems the leak was caused by a valve being left open (no equipment or design cause), and it is likely that there was some connection between the cause of the leak and the hot work being performed.

Table A3 4-1: Ignited hot work accidents

HCR ign. ID	HCR leak ID	Calc. rate (kg/s)	Avg. rate (kg/s)	Fluid	Delay (s)	Reported consequence
152	2003-04-60	0.004	0.03	GAS	30	Flash fire
153	2003-04-45	0.019	0.18	GAS	-	Jet fire
166	2005-05-31	-	0.01	GAS	-	Flash fire, explosion
214	2010-11-130	0.000	0.00	GAS	10	Flash fire

A3-4.3 Turbines

Some incidents are turbine accidents involving fuel gas for the turbine (for example HCR ignition 1, 96 and 112 in Table A3 4-2). In addition, the two most severe accidents in the data set (the Centrica B and the Gorm C) are reported as being ignited upon gas exposure of turbines (for Centrica B, gas in air intake is reported at the source of ignition).

The Centrica B accident gives a very clear indication that exposing the air intake of a running turbine to flammable gas can result in ignition. For the Gorm C ignition, the ignition mechanism is less certain, but the fact that a running turbine was exposed to flammable gas is an argument for applying a high ignition probability when a running gas turbine is exposed to flammable gas. Further, turbines are in general not running in central parts of the process areas, and knowing the number of extensive gas releases is quite low, experience lead to the conclusion that a running turbine should be regarded as a very potent source of ignition.

Table A3 4-2: Leaks ignited by turbines

HCR ign. ID	HCR leak ID	Calc. rate (kg/s)	Avg. rate (kg/s)	Fluid	Delay (s)	Reported consequence
184	2005-06-191	249	467	Gas	5	Flash, explosion, jet, pool
1	1992-93-79	-	0.03	Gas	Immediate	Turbine fire
96	1998-99-174	-	0.04	Gas	Immediate	Flames from turbine exhaust
112	1999-00-128	-	-	Gas	Immediate	“Backfire”

A3-4.4 Diesel engines

There are a number of ignitions from diesel engines in engine rooms when oil is spilled on hot exhaust manifolds. These ignitions are of relatively little importance for the ignition of process leaks, since diesel engines will very rarely be exposed to process oil leaks.

For the combustion air intakes for diesel engines, the case is different. It is quite common practice to keep diesel engines running upon gas detection in the combustion air intake, but to prevent gas from entering the engine room. The rationale is that gas in the air intake could lead to engine over-speed, but that over-speed protection systems will stop the engine in time, preventing ignition of the external gas.

At the Deepwater Horizon blowout, flammable gas reached both the engine rooms and the engines. There is some uncertainty related to the ignition mechanisms, but it seems the investigation report considers ignition from the engine as very likely despite the protection systems installed to prevent it.

Reference /1/ describes the shallow gas blowout, explosion and fire at West Vanguard. The description of the sequence of events is very similar to the description found in the Deepwater Horizon investigation. For sure, there was an explosion in the engine room, and the gas air intake channel to the engine room exploded violently. The gas may also have been ignited close to the release point. A third possible source of ignition was the extract fan in the HVAC for the cementing unit, which was not certified for operating in hazardous area. For West Vanguard, sparks caused by sand in the gas flow is identified as a possible cause for ignition.

A3-4.5 Pumps as source for leaks and ignitions

There are some leaks from pumps ignited at the pump. These are the events 144, 149, 150 and 164 in the list of HCR ignitions. In addition, HCR ignition number 185 is reported being an ignition by an undetected hot bearing on a pump inside a closed drain tank (this is a tank explosion accident). Further, for all leaks from pumps that were ignited, the pump itself is believed to have caused the ignition.

The conclusion is that pumps should be considered potential sources of ignition. As a consequence, oil and condensate leaks from pumps appear to be more likely ignited than other oil and condensate leaks. Since oil leaks from other leak sources than pumps have not been ignited at a pump, and since pumps are frequently located in process areas, the conditional probability for ignition given exposure to process oil leaks appears to be relatively low.

Table A3 4-3: Leaks likely to have been ignited by pumps

HCR ign. ID	HCR leak ID	Calc. rate (kg/s)	Avg. rate (kg/s)	Fluid	Delay (s)	Reported consequence
144*	2002/03-189	0.020	0.025	COND	Immediate	Flash, jet, pool
149	2002/03-9	0.020	0.017	OIL	120	Flash, jet
150	2002/03-47	0.000	0.000	OIL	Immediate	Jet
164**	2003/04-62	0.120	0.124	OIL	Immediate	Flash
185	2005/06-150	0.030	0.033	GAS	Immediate	Explosion
226	2013-2014-99	0.004	0.140	Oil	Immediate	Pool

**ignition source is considered unknown in the ignition cause distribution*
***ignition by the driver (motor/turbine)*

None of these are considered relevant leaks for the ignition model, because none were classified as “significant” or “major”.

The pump population in the HCR database is given in Table A3 4-4.

Table A3 4-4: Rotating equipment population data from HCR

Equipment years per system 1992-2012	Rotating equipment		
System	Compressors	Pumps	Mud / Shale pumps
Drilling Equipment	58	9704	14492
Export	169	3856	-
Flowlines	-	78	-
Gas Compression	4373	442	-
Import	-	156	-
Manifold	-	60	-
Metering	60	1418	-
Processing	163	6302	-
Separation	83	1996	-
Utilities	215	279	-
Well Control	20	31	-
Sum	**5141**	**24323**	**14492**
Sum without drilling equipment and well control	**5062**	**14589**	**-**

Table A3 4-5: Leaks and ignitions: leaks from pumps

Leaks from pumps in process systems	Quantity released					
Average leak rate	A(<100)	B(100-1000)	C(1000-4000)	D(4000-10000)	E(>10000)	Sum
E(>100)						
D(10-100)						
C(1-10)	1	8	4			13
B(0.1-1)	21(1)	22	1			36(1)
A(<0.1)	89(3)	3				92(4)
Sum	**111(5)**	**33**	**5**			**149(5)**

Table A3 4-5 corresponds to Table A3 4-3 except for leak nr 2005/06-150 (HCR ign. 185), where the leak was not from the pump itself, but the leak was ignited by a pump.

Table A3 4-6: Installation types and process area volumes in HCR database

Installation type	Installation years 1992-2012	Assumed average process area volume per installation [m3]
Fixed, manned	3217	25000
Fixed, unmanned	2032	7500
Mobile, manned	1986	1000
Total process area-years (m^3 ·yrs)		97651000
Equipment years		
Compressors (equipment years)		5062
Pumps (equipment years)		14589
Total, pumps and compressors		19651
Average density of rotating machinery		
Process area volume per rotating machinery (m^3/rot.eq)		4969
Process area volume per pump (m^3/pump)		6693
Process area volume per compressor (m3/compressor)		19291

A3-4.6 Electrical equipment

There is one incident (HCR ignition 165) related to temporary electrical equipment ("air mover being switched on"). The presence of the gas and the temporary equipment has a connection in the operations performed.

Then there is HCR ignition 206, where an electric heater is found to be the source of ignition. This appears to be an oil leak from a drain tank, and it seems the heater was inside the tank. For HCR ign. 206, the deviation between the calculated initial rate and the average rate is significant. The released quantity is reported as 200 kg released in 1 minute, the hole diameter is ">100" and actual pressure is 0.3 bar. Our interpretation is that there was 200 kg oil inside the tank, but no leak.

From the previous OLF ignition report, we have the HCR ignition no. 88, caused by a damaged heat tracing cable.

Table A3 4-7: Leaks ignited by electrical equipment

HCR ign. ID	HCR leak ID	Calc. rate (kg/s)	Avg. rate (kg/s)	Fluid	Delay (s)	Reported consequence
88	1997/98-133	0.007	0.007	Gas	9999	Jet fire
165	2004/05-29	0.13	0.13	Con.	10	Flash fire
206	2008/09-28	81.8	3.33	Oil	Immediate	Explosion

Note that for HCR ignition 88 (ignition due to a damaged heat tracing cable), the ignition is reported as delayed, but it seems the start of the leak may not be known (9999 is not the delay in seconds). The average rate reported is based on 121.9 kg gas released over 5 minutes.

A3-4.7 Electrical sparks, static, etc.

Some leaks are reported to have ignited as a result of electrical sparks. These are the HCR ignitions 145, 168, 201 and 208.

The latter (no. 208) is a liquid leak, where droplets in the spray are concluded to have resulted in a static electric spark. The GOR for this leak is recorded as 0.3. If this is the case, the leak is a pure liquid leak for all practical purposes. Since the majority of 2-phase leaks are recorded with GOR less than one, it seems likely that for most cases the GOR is not a GOR (Sm^3/Sm^3) but rather a gas fraction (kg/kg). From the leak rate (0.6 kg/s) and the ventilation conditions (open area, 13 m/s wind) it is obvious there was no or only a very small flammable gas cloud in this case. Thus this incident may be considered an event ignition, but with a significant delay time (reported as 2 minutes).

It is likely that when the ignition mechanism is reported as “electrical spark”, “static” or similar, the actual cause of ignition is uncertain. These are probably cases where other potential sources of ignitions have not been present. Even if there may actually have been another type of ignition mechanism involved, it is reasonable to include these as some kind of event ignitions that may take place in absence of other sources in the ignition model. Doing this, it is important to look into ignition delay for these events.

Table A3 4-8: Leaks ignited by electrical sparks, static, etc.

HCR ign. ID	HCR leak ID	Calc. rate (kg/s)	Avg. rate (kg/s)	Fluid	Delay (s)	Reported consequence
145	2002/03-223	0.0008	0.0008	Gas	Immediate	Explosion
168*	2004/05-150	0.12	0.11	Gas	Immediate	Flash fire
201	2008/09-12	0.02	0.01	Gas	7	Flash fire
208	2009/10-145	0.54	0.31	Oil	120	Pool fire

* Leak from well and thus not categorized as a process leak

A3-5 Blowouts

Blowouts on offshore installations, at least when released topside on a platform (fixed or mobile) are of interest for an ignition model. Blowouts are typically relatively large releases leading to extensive exposure of ignition sources.

Blowouts and Ignited blowouts are listed in the SINTEF Offshore blowout database, ref./2/. Per 31.12.2011 the database contains 592 blowouts, where 139 ignited. For this project, blowouts released on a platform inside a process area or similar are of interest for ignition probabilities.

The database is considered most complete for the "western world" and after 1980. Hence, the following filters are applied:

- Only in the following areas (field: CountryName)
  - US/GOM OCS
  - Denmark
  - Norway
  - Netherlands
  - UK
  - Canada East
- After 31.12.1979 (field: BlowoutDate)
- No blowouts with only underground flow, (field MainCategory value "Blowout (underground flow)")

This leaves 244 blowouts and well releases where 29 are recorded as ignited. Furthermore, releases subsea and diverted releases are filtered out:

- No subsea release points (field ReleasePoint, containing "subsea")
- No diverted well releases (field MainCategory "Diverted well release")

This leaves 159 blowouts, 26 ignitied. In the following table, these 159 (26) blowouts and well releases are shown by installation type (field InstallationType).

- Jack-up for fields containing "JACKUP"
- Floating for fields containing "SUBM", "DRILLSHIP" or "BARGE"
- Fixed for fields containing "TENSION", "JACKET" or "SATELITTE"

The ignited blowouts are shown in the following tables.

Table A3 5.1: Ignited blowouts – topside HC release

Ignitied blowouts	Installation type				
Category	FIXED	FLOATING	Jack-Up	Unknown	Total
Blowout (surface flow)	**11**	**5**	**7**		**23**
Totally uncontrolled flow, from a deep zone	7	4	5		16
Totally uncontrolled flow, from a shallow zone	4	1	2		7
Well release	**2**	**1**			**3**
Unknown					
Total	**13**	**6**	**7**		**26**

Table A3 5.2: Blowouts– topside HC release

Blowouts	Installation type				
Category	FIXED	FLOATING	Jack-Up	Unknown	Total
Blowout (surface flow)	**48**	**9**	**41**	**2**	**100**
Totally uncontrolled flow, from a deep zone	40	6	23	1	70
Totally uncontrolled flow, from a shallow zone	8	3	18	1	30
Well release	**32**	**14**	**10**	**2**	**58**
Unknown			**1**		**1**
Total	**80**	**23**	**52**	**4**	**159**

Table A3 5.3 Fractions of blowouts ignited– topside HC release

Ignited fractions of blowouts	Installation type				
Category	FIXED	FLOATING	Jack-Up	Unknown	Total
Blowout (surface flow)	**23 %**	**56 %**	**17 %**		**23 %**
Totally uncontrolled flow, from a deep zone	18 %	67 %	22 %		23 %
Totally uncontrolled flow, from a shallow zone	50 %	33 %	11 %		23 %
Well release	**6 %**	**7 %**			**5 %**
Unknown					0 %
Total	**16 %**	**26 %**	**13 %**		**16 %**

In the following the ignited blowouts are tabulated for installation type and time to ignition.

Table A3 5.4 Ignited blowouts – topside HC release

Ignited blowouts and well releases	Installation type				
Category / time to ignition	FIXED	FLOATING	Jack-Up	Unknown	Total
Blowout (surface flow)	**11**	**5**	**7**	**0**	**23**
Totally uncontrolled flow, from a deep zone	**7**	**4**	**5**	**0**	**16**
< 5min	3	1	3	0	7
5-60min	0	0	0	0	0
>60min	4	3	2	0	9
Totally uncontrolled flow, from a shallow zone	**4**	**1**	**2**	**0**	**7**
< 5min	2	0	0	**0**	2
5-60min	1	1	1	**0**	3
>60min	1	0	1	**0**	2
Well release	**2**	**1**	**0**	**0**	**3**
< 5min	2	1	0	0	3
5-60min	0	0	0	0	0
>60min	0	0	0	0	0
Total	**13**	**6**	**7**	**0**	**26**

Table A3 5.5 Ignited fractions– topside HC release

Ignited blowouts and well releases	Installation type				
Category / time to ignition	FIXED	FLOATING	Jack-Up	Unknown	Total
Blowout (surface flow)	**23 %**	**56 %**	**17 %**	**0 %**	**23 %**
Totally uncontrolled flow, from a deep zone	**18 %**	**67 %**	**22 %**	**0 %**	**23 %**
< 5min	8 %	17 %	13 %	0 %	10 %
5-60min	0 %	0 %	0 %	0 %	0 %
>60min	10 %	50 %	9 %	0 %	13 %
Totally uncontrolled flow, from a shallow zone	**50 %**	**33 %**	**11 %**	**0 %**	**23 %**
< 5min	25 %	0 %	0 %	0 %	7 %
5-60min	13 %	33 %	6 %	0 %	10 %
>60min	13 %	0 %	6 %	0 %	7 %
Well release	**6 %**	**7 %**	**0 %**	**0 %**	**5 %**
< 5min	6 %	7 %	0 %	0 %	5 %
5-60min	0 %	0 %	0 %	0 %	0 %
>60min	0 %	0 %	0 %	0 %	0 %
Total	**16 %**	**26 %**	**13 %**	**0 %**	**16 %**

All the ignited blowouts are described in the following. The column “ignition description” is an extract from the “Remark” field in the database where the fire or explosion is described. “Ign source” is our interpretation of the previous field about what is said about the ignition source.

Table A3 5.6 Ignited blowouts, part 1

ID	Date	Main Category	Sub Category	Country	Field
183	24.03.1980	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	US/GOM OCS	HIGH ISLAND A-368(W. 3)
191	24.08.1980	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	VERMILION 348,Well A1
192	29.08.1980	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	MATAGORDA ISLAND 669-1
199	12.01.1981	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	HIGH ISLAND 38, well 1
225	15.05.1982	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	SOUTH MARSH ISLAND 155,A-4
227	14.07.1982	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	WEST CAMERON 65(W.JA-3)
231	21.10.1982	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	US/GOM OCS	EUGENE ISLAND 361, W. A-10
249	01.08.1983	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	UK	FORTIES
254	12.10.1983	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	US/GOM OCS	EAST BREAKS 160, W. A-28
255	21.10.1983	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	<
265	14.09.1984	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	GREEN CANYON 69
278	06.10.1985	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	NORWAY	6407/6-2,HALTENBANKEN
281	04.12.1985	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	WEST CAMERON 648 W-A1
286	10.11.1986	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	WEST CAMERON 71, w 12
359	09.10.1990	Well release	Limited surface flow before the secondary barrier was activated	US/GOM OCS	SOUTH PASS 60 D, Well D10
360	23.10.1990	Well release	Other	US/GOM OCS	SHIP SHOAL 356(wellA-4)
399	24.01.1996	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	EUGENE ISLAND 380A
420	01.04.1997	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	EAST CAMERON 328, w A-6
434	27.11.1996	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	WEST DELTA 58, w.4
453	09.09.1999	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	Ship Shoal Block 354 (G15312) well A2
459	02.01.2000	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	SM Block 261, Lease G16337, Well N0. 2
476	01.03.2001	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	US/GOM OCS	Eugene Island 284

ID	Date	Main Category	Sub Category	Country	Field
507	09.08.2002	Blowout (surface flow)	Totally uncontrolled flow, from a shallow zone	US/GOM OCS	Grand Isle Block 93
524	09.02.2004	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	Eugene Island 277 (G10744) Well A-3 BP
571	18.12.2004	Well release	Limited surface flow before the secondary barrier was activated	UK	Unknown
611	20.04.2010	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	Mississippi Canyon Block 252, Macando, lease G32306

Table A3 5.7 Ignited blowouts, part 2

BO-ID	Platform Name	Installation type	GOR	igntime	Ign.type	Consequence	Ignition description	Ign. source
183	PLATFORM A	FIXED	0	< 5min	EXPLOSION	TOTAL LOSS	“When removing the locking bars the 8" diverter valve suddenly opened allowing gas pressure into a flexible hose which bursted. The gas immediately ignited.”	Unknown
191	PLATFORM A	FIXED	160300	>60min	EXPLOSION	SEVERE	“caught fire after 12 hours”	Unknown
192	OCEAN KING	Jack-Up	222639	>60min	EXPLOSION	TOTAL LOSS	“gas and mud were spurting through the rotary. Closed annular 5.5 hrs later the csg ruptured just below BOP. In seconds the gas exploded.”	Perhaps rupture
199	PENROD 50	FLOATING	0	>60min	FIRE	SEVERE	“Well blew out through the swivel neck. Well bridged,- started to flow again 3 hrs later, ignited. 2 hrs later bridged.» “Rig Penrod 50 (built 1957). No wells have ever produced from this block”	Unknown
225	PLATF. A/MAYRONNE162	FIXED	127	< 5min	EXPLOSION	SMALL	“explosion occurred near the shale shaker area. Two men had slight burns and a third man suffered bruises”	Unknown
227	PLATF.JA/POOL RIG 52	Jack-Up	33485	>60min	FIRE	TOTAL LOSS	“The next day the well caught fire. After 3 days the fire was put out.”	Unknown

BO-ID	Platform Name	Installation type	GOR	igntime	Ign.type	Consequence	Ignition description	Ign. source
231	PLATF.A/NOBLE RIG 24	FIXED		>60min	FIRE	SEVERE	"the annular preventer leaked and then cracked. SD and abandoned platform. Fire started 10 hr later."	Unknown
249	PLATFORM D	FIXED		< 5min	EXPLOSION	SEVERE	"The explosion occurred in a wellhead compartment after a production well drilled into a shallow gas zone. BOP was not installed, indicating that 30" casing was in hole. Diverter system likely either failed to activate or failed after activation."	Unknown
254	CERVEZA	FIXED	0	5-60min	EXPLOSION	SEVERE	"After diverting for 35 minutes, one of the diverter lines ruptured near the flange downstream of the valve (8" line). The gas ignited immediately."	Perhaps rupture
255	SATELLITE 3/PORTAL40	FLOATING	1053	>60min	FIRE	DAMAGE	"During displacement of mud to low density packer fluid the well began to flow because the plug lost integrity. The operator started to circulate heavy mud. After a while the TIW valve started to leak at the stem.-caught fire."	Unknown
265	ZAPATA LEXINGTON	FLOATING	0	>60min	EXPLOSION	SEVERE	"Gas was directed to shale shaker. Gas ignited immediately."	Unknown
278	WEST VANGUARD	FLOATING		5-60min	FIRE	SEVERE	"After few mins the diverter lines eroded. Also gas leak in the telescopic joint. Disconnected riser. Explosion. Disconnected 4 anchors."	Unknown
281	PLATFORM A	FIXED	7398	>60min	FIRE	SEVERE	"Att. to kill w/fluid 4 days later. Travelling block fell and ignited gas"	Dropped object
286	PLATFORM NO.12	FIXED	143498	< 5min	EXPLOSION	SMALL	"The 1" pipe was blown out of the hole, and the gas ignited by abrasive action as 1" pipe was blown out"	Abrasive action

BO-ID	Platform Name	Installation type	GOR	igntime	Ign.type	Consequence	Ignition description	Ign. source
359	PLATFORM D	FIXED	322	< 5min	FIRE	UNKNOWN	"Pulled tubing out of down hole hanger and prep. to circulate well when well began to flow. Stabbed a tubing safety valve. An explosion and fire followed (ignition source unknown"	Unknown
360	PLATFORM A	FIXED		< 5min	FIRE	NO	"Gas migrating up the 16" x 20" annulus was ignited by a torch being used to drill hole in the casing to drain above the wellhead."	Hot work
399	Sundowner XV/ Plat.A	Jack-Up	1424888	< 5min	EXPLOSION	SEVERE	"The gas flowing out of the workstring ignited"	Unknown
420	1001E/PRIDE	FIXED	0	>60min	EXPLOSION	TOTAL LOSS	"Within an hour and a half of evacuation, the gas flowing from the well ignited"- "On April 9, 1997 the well was accidentally re-ignited by a cutting torch."	1: Unknown 2: Hot work
434	MARINE XV	Jack-Up	1770	< 5min	EXPLOSION	SEVERE	"After the SSSV was open, the pressure was bled down into the mud pit room and an explosion occurred. The SSSV was not closed thereby allowing the continuous feeding of the fire."	Unknown
453	Platform A	FIXED	765	>60min	EXPLOSION	DAMAGE	"The platform emergency shutdown system was then activated, and all personnel evacuated the platform. The well ignited on September 12, 1999, and burned intermittently until September 17, 1999."	Unknown
459	Cliff's Drilling 153	Jack-Up	0	< 5min	FIRE	UNKNOWN	"The 10 ¾ inch casing head by 16 inch casing head spool began leaking, and caught fire."	Unknown
476	Ensco 51/Platform A	Jack-Up		>60min	EXPLOSION	SEVERE	"The well experienced annular flow from shallow sands (700 and 1200 ft) after the crew set and cemented casing. On March 2, 2001, the well caught fire. The derrick	Unknown

BO-ID	Platform Name	Installation type	GOR	igntime	Ign.type	Consequence	Ignition description	Ign. source
							and substructure of the rig (Ensco 51) collapsed onto the platform."	
507	Diamond Ocean King Platform C	Jack-Up	0	5-60min	EXPLOSION	DAMAGE	"After 30 minutes of diverting the diverter failed (port side line blew off diverter flange) and the gas flowed uncontrolled. The uncontrolled flow subsequently caught fire after approximately 5 minutes, resulting in abandonment of the rig and platform"	Unknown, delayed
524	Platform A/Ensco 60	FIXED	0	< 5min	EXPLOSION	SMALL	"While waiting on cement, pressure built up on the 9-5/8 inch by 13-3/8 inch intermediate by surface casing annulus. With the driller's gauges reading 0 psi, 3,000 psi pressure was observed on a secondary gauge monitoring the same annulus pressure. Shortly thereafter, an explosion occurred"	Unknown
571	Ocean Guardian	FLOATING	0	< 5min	FIRE	SMALL	"Whilst pumping up, at 400 psi, the seal assy prematurely released and unexpected gas behind the seal assy evacuated the sea water in the riser on to the drillfloor. There was a fire at the riser/rotary table interface which lasted for between 2 and 5 minutes."	Unknown
611	Deepwater Horizon	FLOATING	0	< 5min	EXPLOSION	TOTAL LOSS	"The flow of gas into the engine rooms through the ventilation system created a potential for ignition which the rig's fire and gas system did not prevent"	Probably diesel engines

Table A3 5.8 Ignited subsea blowouts, part 1

BlowoutID	BlowoutDate	MainCategory	SubCategory	CountryName	Field
296	22.09.1988	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	UK	BLOCK 22/30B - 3
316	08.01.1989	Blowout (surface flow)	Totally uncontrolled flow, from a deep zone	US/GOM OCS	MAIN PASS 299, WELL 11

Table A3 5.9: Ignited subsea blowouts, part 2

BO-ID	Platform Name	Installation type	GOR	igntime	Ign.type	Consequence	Ignition description	Ign source
296	OCEAN ODYSSEY	FLOATING		< 5min	EXPLOSION	UNKNOWN	"At around 1255 hours, the first explosion occurred when the gas reaching the sea level"	Unknown
316	TELEDYNE MOVBILE 16	Jack-Up	0	>60min	EXPLOSION	TOTAL LOSS	"On January 8th, fireboats were mobilized to the area and began spraying water onto Teledyne Movible 16 at approx 1.30pm. At 2.30pm the gas flow ignited. The fire died January 27th"	Unknown

A3-6 Review of the UKOOA ignition probability model

The Energy Institute reviewed the HCR data (which they refer to as OIR12 data) and proposed an ignition probability model, ref. /3/. The data analysed was for the period 1992 to 2000 (inclusive).

This report concluded that most, if not all ignitions during that period would be of little relevance to major accident hazards risk analysis.

Following the review of ignited events, ref. /3/ concludes that an ignition probability model needs to be derived from the data on events that did not ignite. For initial leak rate in the categories 1 to 50 kg/s and > 50 kg/s the report concluded that an ignition probability of 0.02 would be applicable. It is worth looking into the counting of leaks in somewhat more detail:

The study identified 294 process leaks with severity “major” or “significant” with an average leak rate exceeding 0.2 kg/s and calculated maximum leak rate exceeding 0.5 kg/s (1992-2000 UKCS). 6 of these leaks ignited, but, as the report concludes, none of these “were related to the ignition of process fluids from the main process” and “it is likely that many of these were reportable because they ignited”.

Table B 6-1: UKOOA ignition model basis

Release type	Rate	No of events, average release rate	No of events, maximum release rate
Gas	>50 kg/s	3	21
	1-50 kg/s	54	130
	<1 kg/s	94	0
Oil	>50 kg/s	1	14
	1-50 kg/s	26	56
	<1 kg/s	51	0
Condensate	>50 kg/s	0	6
	1-50 kg/s	11	17
	<1 kg/s	15	0
2-phase	>50 kg/s	0	4
	1-50 kg/s	13	24
	<1 kg/s	26	0

If understood correctly, the ignition probability for leaks exceeding 50 kg/s is then quantified as $P = 0.5/(21+1) \approx 0.02$ based on the maximum release rate estimate. It is worth noticing that very few leaks have an average rate exceeding 50 kg/s, and based on three large leaks, the generic ignition probability would be $0.5/4 = 1/8$. With more recent data included, the Centrica B ignition would fall into this category.

Trying to reproduce this calculation, we found 5 process gas leaks with average leak rate exceeding 50 kg/s for the period 1992 – 2000. It seems that two of the 5 leaks (possibly the two related to well operations) were discarded in ref. /3/. Since year 2000, there has only been one leak in this category (Centrica B), so the fraction ignited for an updated data set would be one in four, or 25%.

The maximum rate is calculated based on fluid density, pressure and hole size, while the average rate is based on the reported quantity released and the leak duration. It is likely that there are inconsistencies in the dataset that contribute to the large differences in the number of large leaks depending on the definition of leak rate.

For leaks 1 – 50 kg/s a generic ignition probability of approximately 0.01 for gas leaks and 0.02 for liquids is concluded, but the calculation is not shown in the report.

Due to the way this data set was selected, there are relatively few leaks in the smallest leak rate category.

On this basis, ref. /3/ proceeds to develop ignition probability look-up tables for different types of process modules, installations and releases.

OGP risk assessment data directory, ref. /4/ refers to the UKOOA ignition model and summarises the results in Figure B 6.1.

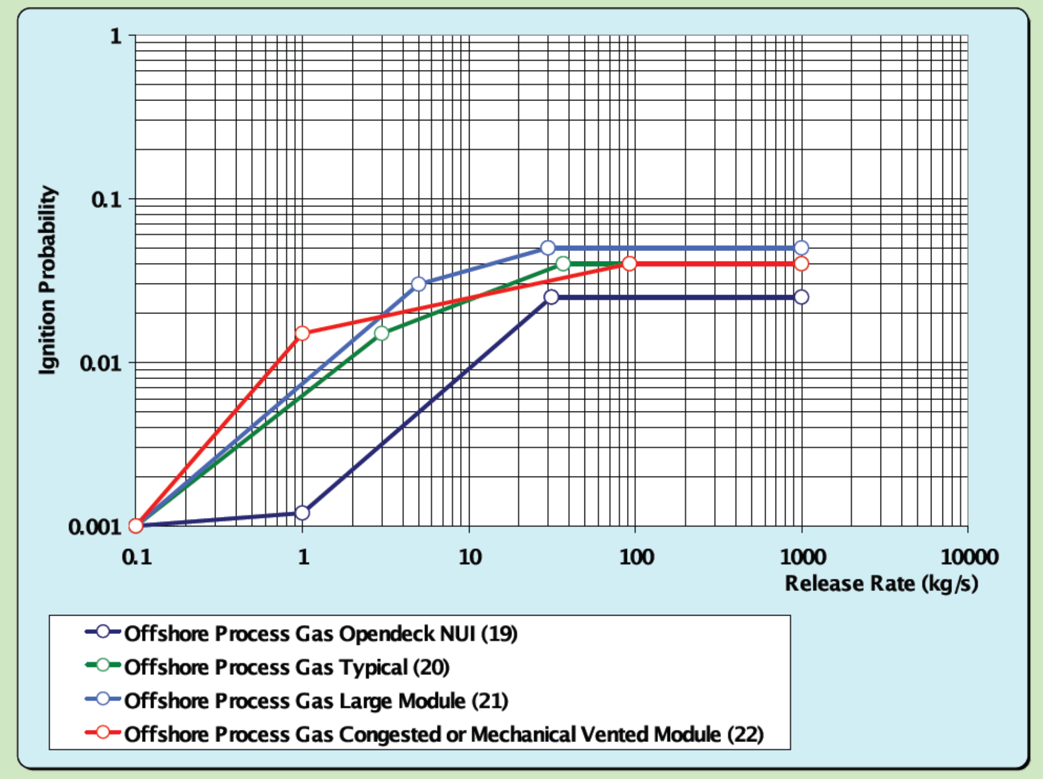


Figure B 6.1 UKOOA ignition model results

A3-7 References

/1/ STF25 A85013: Årsaksforhold ved utvikling av brann og eksplosjon om bord i boreriggen «West Vanguard» natt til den 7. oktober 1985, SINTEF desember 1985

/2/ blowout.exprosoft.net

/3/ Ignition probability review, model development and look-up correlations. Published by the Energy Institute, January 2006.

/4/ Risk Assessment Data Directory; International Association of Oil and Gas Producers (OGP); report no. 434-6.1 March 2010.

Appendix B

Efficiency of isolation of electrical ignition sources

Efficiency of isolation of electrical ignition sources

Report no 100027/R1
Date 28 September 2012
Client Statoil ASA

Øystein Spangelo

From: Jens Kristian Holen [jkhol@statoil.com]
Sent: 28. september 2012 08:24
To: Øystein Spangelo
Cc: Ingar Fossan
Subject: RE: Annonymisert rapport: "Efficiency of isolation of electrical ignition sources"

Hei,
Ja, det er helt greit for bruk i dette prosjektet.
Eventuelt annet bruk bør avklares med oss.
Mvh Jens

From: Øystein Spangelo [mailto:osp@scandpower.com]
Sent: 26. september 2012 13:26
To: Jens Kristian Holen
Cc: Ingar Fossan
Subject: Annonymisert rapport: "Efficiency of isolation of electrical ignition sources"

Hei Jens!

Ref. møtereferatet fra statusmøte for oppdatering av OLF tennmodellen 28. august; se vedlagt Scandpower rapport der plattformene er anonymisert som plattform A, B og C.

Kan du verifisere om den anonymiserte rapporten kan distribueres til de andre deltagerne?

hilsen Øystein

Best regards,
Øystein Spangelo
Dr. Ing., Principal Consultant

Scandpower AS
P.O.Box 1252 Sluppen, N-7462 Trondheim, Norway

T +47 73 54 63 60
M +47 930 08 164
E osp@scandpower.com
W www.scandpower.com www.riskspectrum.com www.lr.org

Scandpower AS
P.O. Box 1252 Pirsenteret
N-7462 TRONDHEIM, NORWAY
www.scandpower.com
www.riskspectrum.com
Tel. +47 73 54 63 60
Fax +47 73 54 63 61

Report no: 100027/R1	**Date:** 28 September 2012
Rev no.: Final	☐ Open Distribution ☒ Distribution only after client's acceptance

Title:

EFFICIENCY OF ISOLATION OF ELECTRICAL IGNITION SOURCES

Client: Statoil ASA

Client specification:

The aim of the project is to establish a model for determination of the degree of electrical isolation on gas detection. The model shall be able to incorporate in the OLF and JIP ignition models without major modifications to these models.

Summary:

A model for establishing the degree of electrical isolation taking into account the ignition potential of electrical equipment with different Ex protection has been developed. Detailed counts of the number of electrical equipment being live before and after gas detection have been performed on Platform A, Platform B and Platform C. The ignition potential of equipment as function of their Ex class has been established by GexCon. This has been combined with the equipment count into electrical isolation efficiencies for the 3 installations. Recommended values for the isolation efficiency for an installation to be used in the OLF and JIP models in case no specific equipment count is performed are given for different degrees of equipment isolation. The established degree of equipment isolation is significantly lower than assumed in the OLF ignition model

	Platform type
Platform A	Jacket
Platform B	Concrete
Platform C	Jacket

Key words		**Name**	**Signature**
	Prepared by:	Jan A. Pappas Morten Nilstad Pettersen Kees van Wingeerden, GexCon	
	Reviewed by:	Jan K. Lund	
	Approved by:	Ingar Fossan	

TABLE OF CONTENTS

1. INTRODUCTION

On offshore installations part of electrical ignition sources are isolated on gas detection in order to reduce the probability of ignition. This is accounted for in the ignition probability models commonly used in QRA on the Norwegian Shelf. Both in the OLF model (Ignition Modeling in Risk Analysis, Scandpower report 89.390.008/R1) and the previous JIP/ TDIIM model (JIP Ignition Modeling, Time Dependent Ignition Probability Model, DNV 96-3629, rev 04 og Guidelines for use of JIP Ignition Model, DNV 99-3193, rev 01) the fraction of ignition sources being isolated shall given as input to the model.

In the OLF model a value of 75% isolation is suggested based on an average of the values used by several Norwegian operators. The values used by the former Statoil and Hydro operators differ significantly, hence the intention of this work is to establish a model for the fraction of ignition sources being isolated on gas detection that can be integrated into the OLF and JIP ignition probability models without major modifications of these.

The aim of project is to find recommended values for the degree of electrical isolation based on:

- Establish a model for establishing the degree of electrical isolation to be used in the OLF and JIP/TDIIM ignition models
- Counts of electrical equipment live before and after electrical isolation on gas detection on Platform A, Platform B and Platform C. These represent both old installations (Platform B and Platform C), a new installation (Platform A) and previous Statoil installations (Platform A and Platform B) and a previous Hydro installation (Platform C)
- Characterization of the ignition potential of the electrical equipment according to their Ex class. This has been performed by GexCon as a subcontract to the project, and their full report is presented in Appendix B.
- The counts of live equipment are then weighted by these potentials to obtain a recommended degree of electrical isolation.

2. ABBREVIATIONS

AC	-	Alternating Current
AIT	-	Autoignition Temperature
DC	-	Direct Current
ESD	-	Emergency Shutdown
JIP	-	Joint Industry Project
MIE	-	Minimum Ignition Energy
OLF	-	Oljeindustriens Landsforening
PCS	-	Process Control System
PSD	-	Process Shutdown

3. THE OLF IGNITION MODEL

The OLF ignition model, Ref /1/ is a basic model for calculation of ignition probability given a gas release in a classified area (typically zone 2). The model is based on generic data and from 10 years (1992-2002) experience related to gas leaks and ignitions on offshore installations on the Norwegian and UK continental shelves.

- The model gives a contribution to immediate ignition (leak rate dependent), i.e. before generation of a gas cloud
- The model reflects ignition as a function of gas cloud growth for continuous ignition sources which will be exposed to the periphery of the expanding cloud
- The model reflects ignition as a function of the size of the ignitable gas cloud for discrete ignition sources which may be exposed to any part of the cloud
- The model reflects isolation of ignition sources due to gas detection.

3.1 Input to the Model

Input to the model is description of the gas cloud, i.e. size/volume of flammable mixture at a given time step and the increase in the gas cloud during the time step. Also the point in time for gas detection and subsequent degree of ignition source isolation has to be entered into the model. A model for predicting the degree of this isolation is the subject of the present report.

3.2 Model Parameters

3.2.1 Definition of the Parameters

Event Ignition, P_{event}

Some leaks represent a potential source of ignition. The leak may be due to equipment break-down, impacts or operator intervention, e.g. hot work. The term "event ignition" is used for ignitions that occur immediately and are typically related to the cause of the leak in some way. In the proposed model for ignition probability, P_{event} may vary with the leak rate and medium. For the different leak categories, P_{event} describes the fraction of all the leaks in the particular category that have a cause that also leads to ignition of the leak.

The event ignitions are not electrically related and will not be further considered in this study.

Ignition Sources in the Area, P_{if}

The potential ignition sources that are distributed in the considered area are described by the parameter P_{if}. The P_{if} parameter is defined such that it is comprised of both continuous and discrete ignition sources. It is related to an area of 1,500 m^2 * 10 m exposed for 3 minutes without isolation of ignition sources.

P_{if} will have contributions from both electrical and non-electrical sources within the hazardous area. Note, however, that ignition due to hot work and sources outside of the hazardous area like turbine intakes, hot exhaust ducts etc are not included in P_{if} but are treated separately in the model.

For the purpose of this study, P_{if} will be used to denote the base ignition probability in the hazardous area from electrical sources (irrespectively of the physical ignition being by spark or hot surface.)

Continuous vs. Discrete Ignition Sources, i_a and i_b

The ignition source can be of a continuous type, i.e. the gas will ignite immediately on contact with the gas (expect for a temperature dependent ignition delay for hot surfaces, see Section 6.2.2) or it may be of a discrete or sporadic nature, i.e. the time of ignition is random. The relative contributions to ignition probability for discrete ignition sources are described by i_b and i_a. i_b is applied before isolation, and i_a after isolation. Technically this parameter is related to 3 minutes exposure duration in order to make it a more comprehensible parameter. Some continuous ignition sources may also have a time delay from gas exposure till ignition occurs as the gas need some time to penetrate a damaged Ex protection. This is accounted for by giving i_a an increased value.

The Effect of Ignition Source Isolation, P_{iso}

The effect of ignition source isolation on ignition probability is quantified using the parameter P_{iso}. P_{iso} = 0 means that ignition source isolation has no effect with respect to ignition probability. P_{iso} = 1 means that ignition source isolation effectively stops all ignition sources in the area. In this study we will primarily use the opposite value, i.e. the factor F (hereafter denoted the isolation factor) representing the ignition probability after isolation relative to that prior to isolation, i.e.

$$F = 1 - P_{iso}$$

F is thus a measure of the fraction of ignition sources live after electrical isolation. The purpose of this study is to find a model to predict F based on information of the type and number of electrical equipment on an installation as well as suggesting a generic value that can be used in lack of installation specific data.

The effect of isolation on continuous ignition sources (that may be hot surfaces) is not immediate. This is taken into account by the parameter P_{hot}.

Time Delay, Ignition by Hot Surfaces after Isolation, P_{hot}

For continuous sources there is an additional delay related to the cooling time of hot surfaces. The probability that the continuous source is still a potential source of ignition has been modelled exponentially decreasing. A new fraction, P_{hot}, is the fraction of the isolated ignition sources that can still ignite a flammable gas cloud. P_{hot} must be calculated from the transient detection probability and the time constant applied for ignition probability reduction for continuous ignition sources. P_{hot} is, thus, a time-dependent factor. This will not be addressed further in this study.

4. MODEL FOR THE EFFECT OF ELECTRICAL ISOLATION ON IGNITION PROBABILITIES

4.1 General model

Any electrical equipment located in a hazardous area is considered to be a potential ignition source although the equipment has the required Ex protection, the reason being that Ex protection can fail. Depending on the zone category the Ex protection is approved for, one or more barriers will have to fail in order for the equipment to act as an ignition source, hence the probability of Ex failure will be strongly dependent on the Ex class. This is further outlined in Section 6.

Let P_{if}^{b} be the intrinsic ignition probability in the area (i.e. assuming the ignition source is exposed to explosive gas) due to electrical equipment before gas detection and electrical isolation. In principle, P_{if}^{b} is the sum of the ignition probabilities associated with each electrical equipment in the area. Assuming for simplicity that the electrical equipment can be of two categories 1 and 2 with corresponding equipment ignition probabilities P_1 and P_2 , then

$$P_{if}^{b} = N_1 P_1 + N_2 P_2 \qquad \text{4-1}$$

where N_1 and N_2 are the numbers of equipment of each category. Assume further that the ignition probability of the two categories are related , i.e.

$$P_2 = k\, P_1 \qquad \text{4-2}$$

where the ignition potential k is a function of Ex category, equipment type, voltage level etc. After electrical isolation the ignition probability P_{if}^{a} is given by

$$P_{if}^{a} = f_1 N_1 P_1 + f_2 N_2 P_2 = F\, P_{if}^{b} \qquad \text{4-3}$$

where f_1 and f_2 is the fraction of equipment 1 and 2 being live after isolation.
The factor F represents the relative ignition probability after electrical isolation and is the fraction of electrical equipment being live after isolation weighted by the equipment ignition probabilities, i.e.

$$F = \frac{P_{if}^{a}}{P_{if}^{b}} = 1 - P_{iso} = \frac{f_1 N_1 P_1 + f_2 N_2 P_2}{N_1 P_1 + N_2 P_2} \qquad \text{4-4}$$

By using Equation 3-2 F is given by

$$F = 1 - P_{iso} = \frac{f_1 N_1 + k f_2 N_2}{N_1 + k N_2} \qquad \text{4-5}$$

In this formula for F the equipment ignition probabilities have been eliminated and replaced by the relative ignition probability k.
In the general case if n categories of electrical equipment with n different equipment ignition probabilities, F is given by

$$F = \frac{\sum k_i f_i N_i}{\sum k_i N_i} \ , \ \ k_1 = 1 \qquad \text{4-6}$$

where the category 1 is chosen as the equipment type with the lowest ignition probability so that all $k_i > 1$ for $i > 1$.
In general a type of equipment, say a motor, can be of different Ex types. For an equipment type i there can be Ex types j so the one can define

$k_{i,j}$ = the relative igntnion intensity for equipment i with Ex type j
$f_{i,j}$ = the fraction of equipment of type (i, j) being live after isolation
$N_{i,j}$ = the total number of equipment of type (i,j) in the area

Then *F* is given by

$$F = \frac{\sum k_{i,j} f_{i,j} N_{i,j}}{\sum k_{i,j} N_{i,j}} \quad , \quad k_{1,1} = 1 \qquad \text{4-7}$$

4.2 Continuous and discrete ignition sources

Continuous and discrete ignition sources have different effect in the total ignition probability in a scenario, i.e. when including the probability of gas exposing an ignition source. Continuous sources will ignite gas when the source is exposed to the gas while a discrete source may ignite at any time after it has been exposed. Hence discrete sources tend to dominate the ignition probability during the later phases of a scenario where the gas cloud increases in size. The probabilistic explosion pressure (e.g. the pressure exceedance curve) may thus be quite sensitive to the amount of continuous versus discrete ignition sources. If the distribution of continuous and discrete sources is significantly changed after electrical isolation, this is reflected in the ignition probability model by i_b and i_a. The shutdown will typically isolate more equipment of some categories than other – and it is reasonable to expect a different distribution of discrete and continuous sources before and after isolation. In that case, the effect on the ignition probability can be modelled by calculating i_b and i_a by

$$i = \frac{\sum i_{p,q}\, k_{p,q} N_{p,q}}{\sum k_{p,q} N_{p,q}} \qquad \text{4-8}$$

where

$i_{p,q}$ = fraction of discrete ignition sources of equipment p with Ex class q
$N_{p,q}$ = number of equipment of type p with Ex class q

By counting $N_{p,q}$ and calculate $i_{p,q}$ before and after electrical isolation and inserting in Equation 3-8, i_b and i_a is found.

4.3 Time of electrical isolation

The isolation of ignition sources on gas detection will take place in different steps at different points in time depending on the extension and location of the gas. The shutdown is governed by the ESD shutdown logics for which the basic requirements are given in NORSOK S-001 item 10.4.3. The overall ESD shutdown logic diagram is shown in Figure 4.1. The main items of relevance to electrical isolation are given in Table 4.1.

Table 4.1: Main levels of isolation of ignition sources

Cause	ESD level	Main effect on isolation
Single gas detection	Alarm only	Isolate all sockets and external non-essential consumers
Confirmed gas detection in hazardous areas	ESD 2	Stop process. Different degree of isolating consumers in hazardous areas except safety critical
Confirmed gas detection in safe area of the installation (air intakes)	ESD 1	Trip main generators, start emergency generator

The different levels of electrical isolation will occur at different times depending on the dispersion of the gas. At each consecutive level of isolation more consumers are isolated, so in general there will be 3 different isolation factors F occurring at different times as illustrated in Table 4.2.

Table 4.2: Isolation factors and corresponding times for electrical isolation

Shutdown level	Isolation factor	Time
Single Detection (SD)	F_{SD}	t_{SD}
ESD 2	F_{ESD2}	t_{ESD2}
ESD 1	F_{ESD1}	t_{ESD1}

In practice, the time difference between single gas detection and ESD 2 will be short in all scenarios except quite small leaks, in which case F_{ESD2} and t_{ESD2} will be sufficient. ESD1 will normally presuppose a large leak in combination with unfavourable wind condition which may be a relevant scenario in some cases. The process of calculating a representative value of t_{ESD1} is more complex and should be given special consideration if ESD1 is relevant. Note also that F_{ESD1} will be the smallest F, often significantly smaller than F_{ESD2} as illustrated in Section 5 and 7.

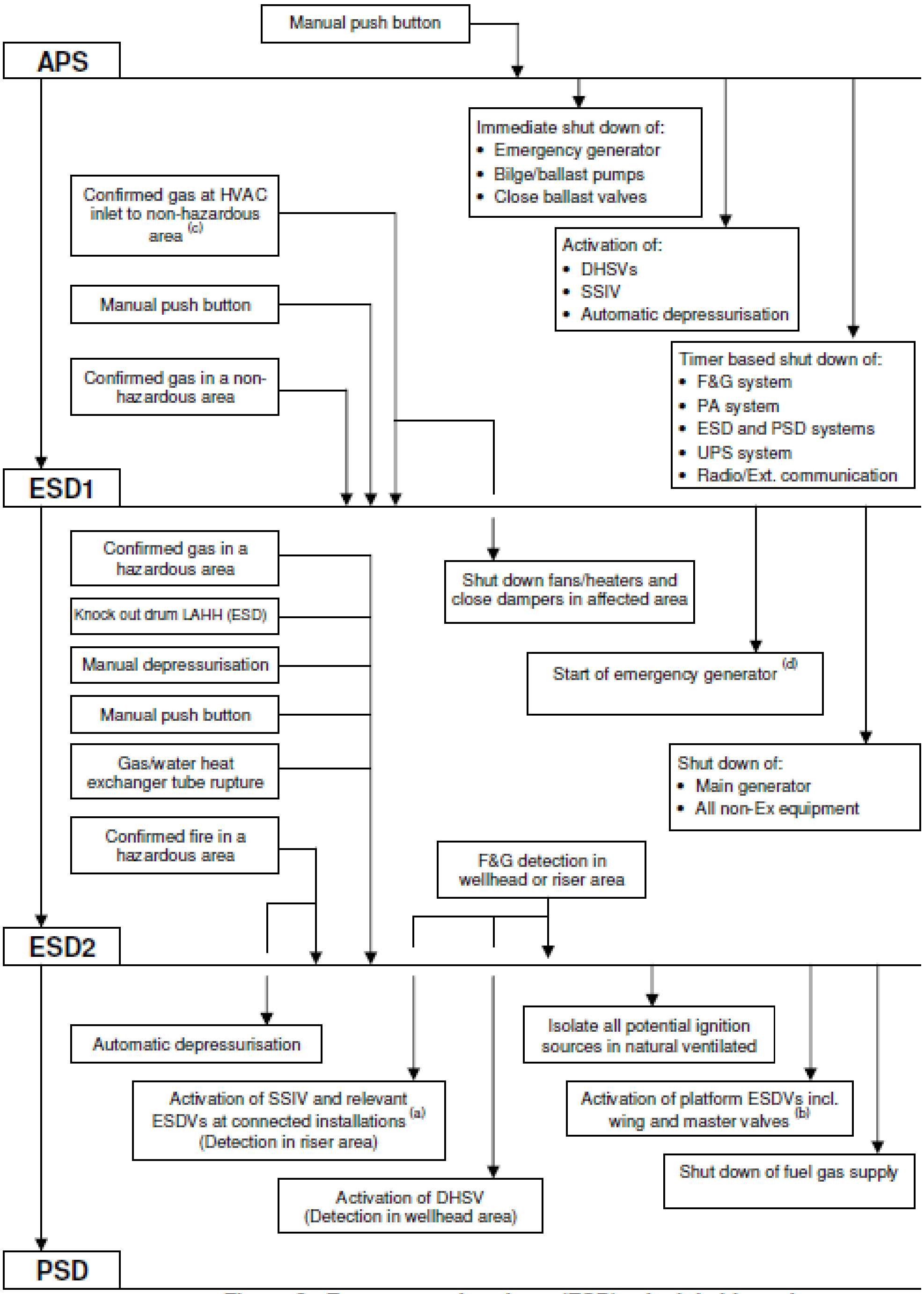


Figure 2 - Emergency shut down (ESD) principle hierarchy

(a) Can be sub-sea well template, wellhead platform, compressor platform, onshore plant.
(b) Local shut down of flow from subsea templates and upstream platforms by ESD or PSD.
(c) Alternative to ESD1 can be ESD2 and selective electrical isolation depending on location, see Table 2.
(d) Alternatively inhibit start of emergency generator may be considered due to ISC.

Figure 4.1: Overall ESD shutdown logic according to NORSOK S-001

4.4 Limitations to the model

The use of the model for F has its limitations related to the distribution of electrical equipment of different Ex classes.

The way the model works is that the isolation factor F is applied to the initial ignition probability P_{if}^{b} which is a generic value corrected for the size of the module. The model will thus not distinguish between installations with very different philosophies for use of Ex classified equipment. This is illustrated in Figure 4.2.

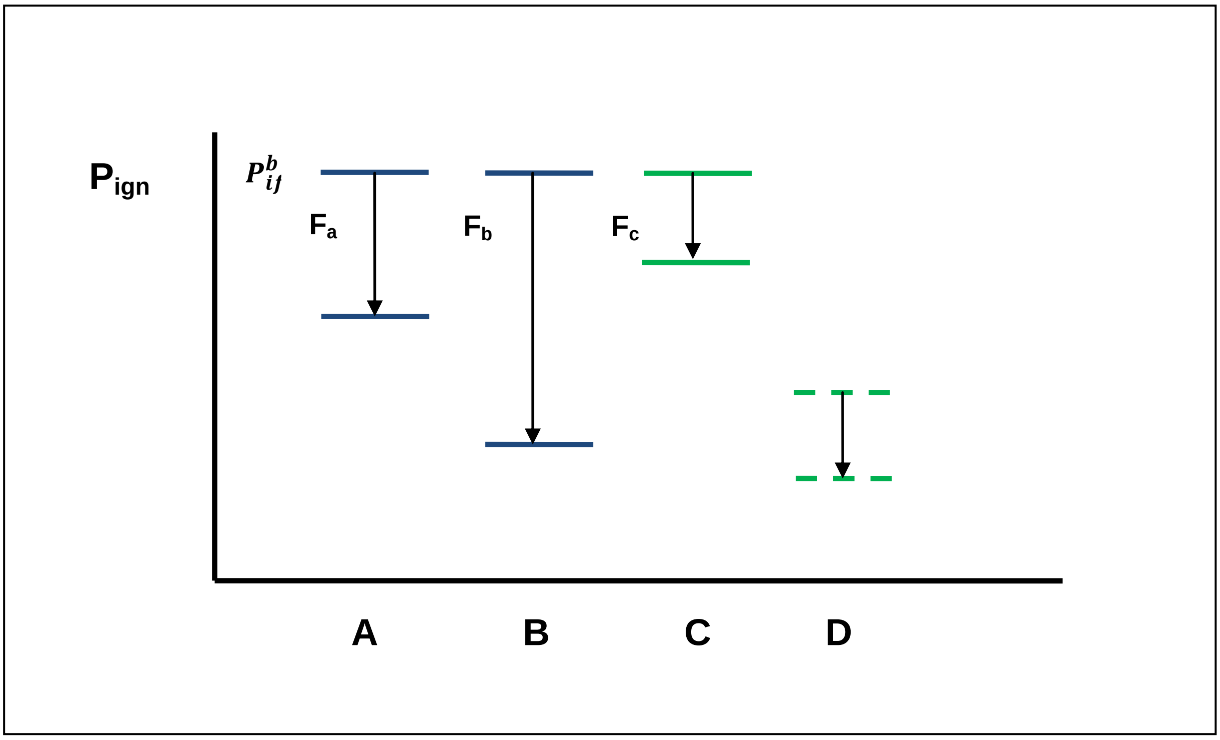


Figure 4.2: Illustration of the effect of different Ex philosophies

For the sake of illustration, Module A is Zone 2 and has only Zone 2 certified equipment. It has a certain P_{if}^{b} only determined by the module size and with an isolation philosophy resulting in the isolation factor F_a .Module B is the same but with a different shutdown philosophy with more extensive isolation giving an increased isolation factor to F_b . Alternative C is as alternative A but with all Zone 2 equipment replaced by Zone 1 equipment. The ignition probability prior to isolation will in reality decrease (as illustrated in case D) but this is not reflected in the model as P_{if}^{b} is independent on the type of Ex equipment used. The effect of isolation would be smaller than for case A as there is no Zone 2 equipment (with greater ignition potential k) to isolate, the resulting F_c is thus the smallest. So in reality this design would give the lowest ignition probability after isolation as illustrated in case D but the model nevertheless predicts the design to give the highest ignition probability after isolation as shown by case C.

The reason for this artefact of the model is that P_{if}^{b} is generic (apart from the size correction). Platforms with different Ex philosophies will all appear identical with the same P_{if}^{b} . This property is inherent in the OLF ignition model where the P_{if} parameter represents the “average” North Sea platform with regard to the use of different Ex classes on equipment. The obvious solution would be to find a way to modify P_{if}^{b} according to the distribution of types of Ex equipment. However, this is not straightforward as one would have to establish that distribution for the “average” platform. If it was possible to establish the modified P_{if}^{M} can be found as

$$P_{if}^{M} = \frac{\sum n_i k_i}{\sum n_i^{av} k_i} P_{if}$$

where n_i is the relative number of equipment of Eex class i on the actual installation and n_i^{a} is the corresponding value for the “average” installation as basis for P_{if} in the OLF model. Such an extension of the OLF model is, however, outside the scope of the present study and should be left to the OLF developers.

In conclusion, the present model based on establishing a F factor to modify P_{if} should be used with care on installations where the use of Ex equipment differs significantly from what is average practice in the UK and Norwegian sectors of the North Sea.

5. DEGREE OF ELECTRICAL ISOLATION

5.1 Main Methodology

The aim of the analysis was to count all ignition sources in the process and drilling areas for the chosen platforms. Further, the shutdown philosophy is used to make a count of ignition sources available after various levels of ESD and PSD.

Information about ignition sources and shutdown philosophy was not easily available. Hence, several assumptions were needed in order to calculate the ignition source shutdown philosophy. The assumptions were developed in cooperation with technical safety and the electro discipline for the installations.

The detailed results of the counts for Platform A, Platform B and Platform C are given in Appendix A.

5.2 Main Assumptions

Below are the main assumptions developed in this project. Installation specific assumptions and counting rules for each installation are presented in Appendix A

- The electrical consumer groups identified in this analysis are motors, other main equipment, heat trace, lights, push buttons, junction boxes, socket outlets, telecom, instruments and instrument junction boxes
- All equipment with EX classification in the classified areas of the process and drilling modules are assumed to be electrical consumers. Equipment without EX classification are not considered
- All electrical consumers are assumed operating continuously. With reference to the electrical load factor, this is a conservative simplification since not all electrical consumers are running continuously
- Spare tag numbers and equipment are not assumed to be live electrical consumers
- All electrical consumers belonging to the electro discipline are assumed to be high voltage, i.e. > 220 V
- Electrical consumers under the instrument discipline are assumed low voltage , i.e. ≤ 220 V
- It is assumed that switchboards and breakers are located in safe areas or locally in rooms safe by pressurization. Hence, the switchboards are not included as ignition sources. In cases with local breakers in field, these have double Ex protection (both on breaker and cabinet) and are hence not considered as potential ignition sources
- All electrical equipment within a package have distinct tag numbers in the databases. The exceptions are junction boxes and pushbuttons for main equipment.

5.3 Types of electrical equipment

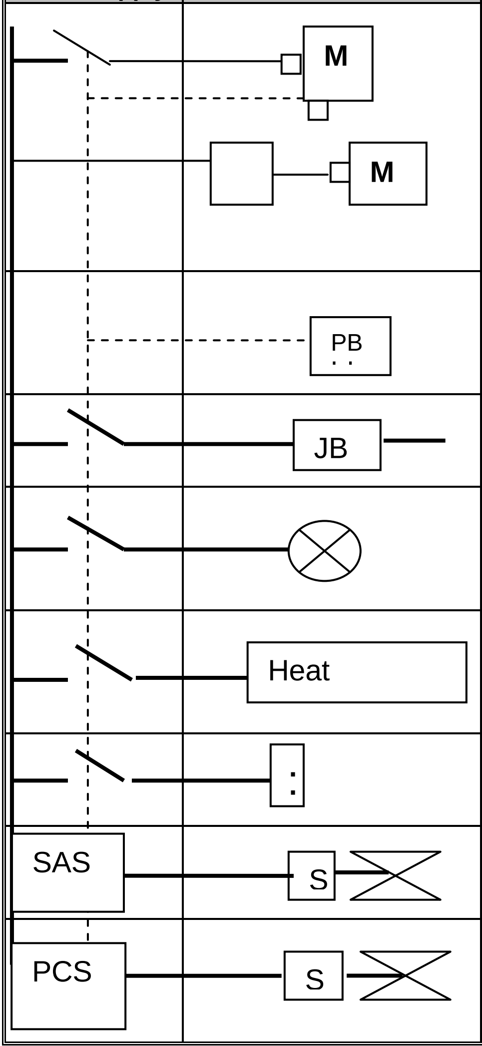
The types of electrical equipment considered are:

- Motors
- Junction boxes
- Push buttons
- Lighting
- Heat tracing and heaters
- Socket outlets
- Other main equipment (all main equipment that is not one of the above classes)
- Instruments, solenoids.

The isolation of these equipment types is determined by the electrical isolation philosophy as manifested in the ESD shutdown hierarchy and Cause and Effect diagrams. This will differ somewhat between installations, but the typical principles are illustrated in Figure 5.1. The equipment is also sorted according to the voltage level - lower or higher than 220 V although the effect of voltage level on the ignition potential of the equipment is limited except for Low Voltage AC equipment as further discussed in Section 6.2.1 and 6.3. The number of AC equipment < 150 V is so low, however, that the effect of voltage level on the isolation efficiency in most cases can be neglected. Details of this are given in Appendix A.

One important NORSOK requirement is that isolation of electrical equipment shall be performed on the power supply source, i.e. by disconnection of the power feed cable from the distribution board in the switchboard room. A potential gas release in a hazardous area will thus not be exposed to potential sparks or hot surfaces from tripping the breakers as these potential ignition sources are separated from the gas release.

The isolation efficiencies for the installations have been corrected for the ignition potentials of the different equipment types according to their Ex protection as given in Table 6.1.



LER/CER Power supply	Field Equipment	Unit	Ex type (typical)	Single gas detection	ESD 2	ESD 1	Assumptions/comments
		Motor	Ex e (n)	Active	Trip	Trip	When A/B/C units, only one active.
		Motor, drilling emergency	Ex e (n)	Active	Active	Active	All motors running in normal operation (conservative, ref load factor)
		JB	Ex de	Active	Trip	Trip	Follow motor (incl drilling)
		PB	Ex md	Active	Active	Active if control voltage on emergency	Follows control voltage
		PB	Ex m	Active	Active	Status following the function	Emergency PB active
		Junction	Ex d	Active	Active		
		JB	Ex de				Some instrument JB are tagged as E
		Normal light	Ex de	Active	Active	Trip	Trip of light follows trip of supply switchboard
		Emer. light	Ex de	Active	Active	Active	
		Heater or heat trace	Ex de	Active	Variable	Trip	
		Socket outlets	Ex de	Trip	Trip	Trip	
		Solenoids on ESD/PSD valves	Ex ia	Active	Trip	Trip	Signal normally energized, close by trip.
		Solenoids on control valves	Ex ia	Active but not energised	Active but not energised	Active but not energised	PCS is normally deenergised and is usually kept in position on gas detection. Control current from 4-20 mA.

Table 5.1 Types of electrical equipment, Ex type and isolation principles

5.4 Result from equipment counts.

5.4.1 Platform A

The fractions F of equipment being live after isolation based on the equipment count on Platform A are given in Table 5.2 and Figure 5.1. The main conclusions to be seen are:

- The amount of equipment live is significantly larger in drilling than in process areas
- A significant amount of equipment is isolated already on single gas detection
- The remaining equipment on ESD 1 is significantly lower than on ESD 2
- The effect of the Ex scaling factor for ignition potential is significant for process but moderate for drilling.

Table 5.2 Isolation factor F for Platform A with and without correction for ignition potential according to Ex protection.

	Without scale factor for Ex protection				With scale factor for Ex protection			
	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
Process	100%	62%	55%	39%	100%	53%	38%	23%
Drilling	100%	89%	89%	73%	100%	84%	83%	66%
Total	100%	77%	73%	57%	100%	68%	60%	44%

The relatively strong effect of ignition source isolation on Platform A is mainly due to isolation of heat tracing already on single gas detection. The reason for the low fraction of equipment live on ESD 1 is that main power is tripped.

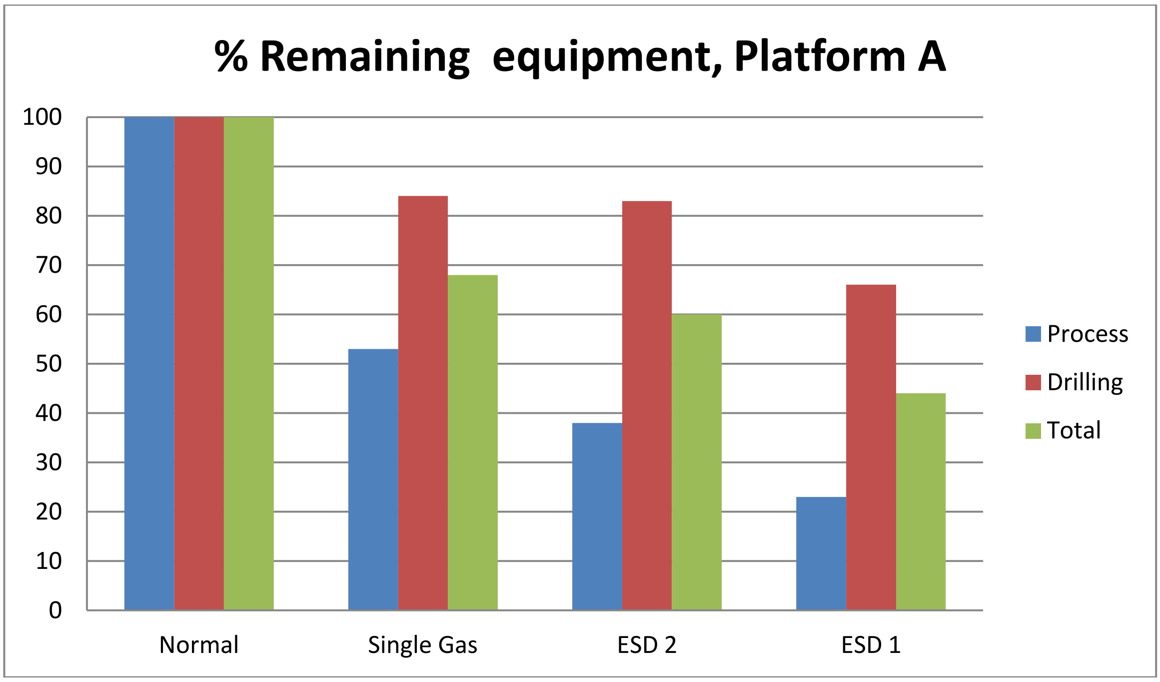


Figure 5.1: Isolation factor F for equipment on Platform A, scaled for Ex protection.

5.4.2 Platform B

The fractions F of equipment being live after isolation based on the equipment count on Platform B are given in Table 5.3 and Figure 5.2. The main conclusion to be seen are:

- A very low fraction of equipment is actually isolated except on ESD 1
- There are only minor differences between process and drilling
- The reduction due to the Ex scaling factor for ignition potential is moderate for process. For drilling there is actually a very small increase.

Table 5.3: Isolation factor F for Platform B with and without correction for ignition potential according to Ex protection.

	Without scale factor for Ex protection				With scale factor for Ex protection			
	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
Process	100%	97%	90%	40%	100%	97%	82%	27%
Drilling	100%	93%	93%	40%	100%	94%	94%	32%
Total	100%	96%	91%	40%	100%	96%	86%	28%

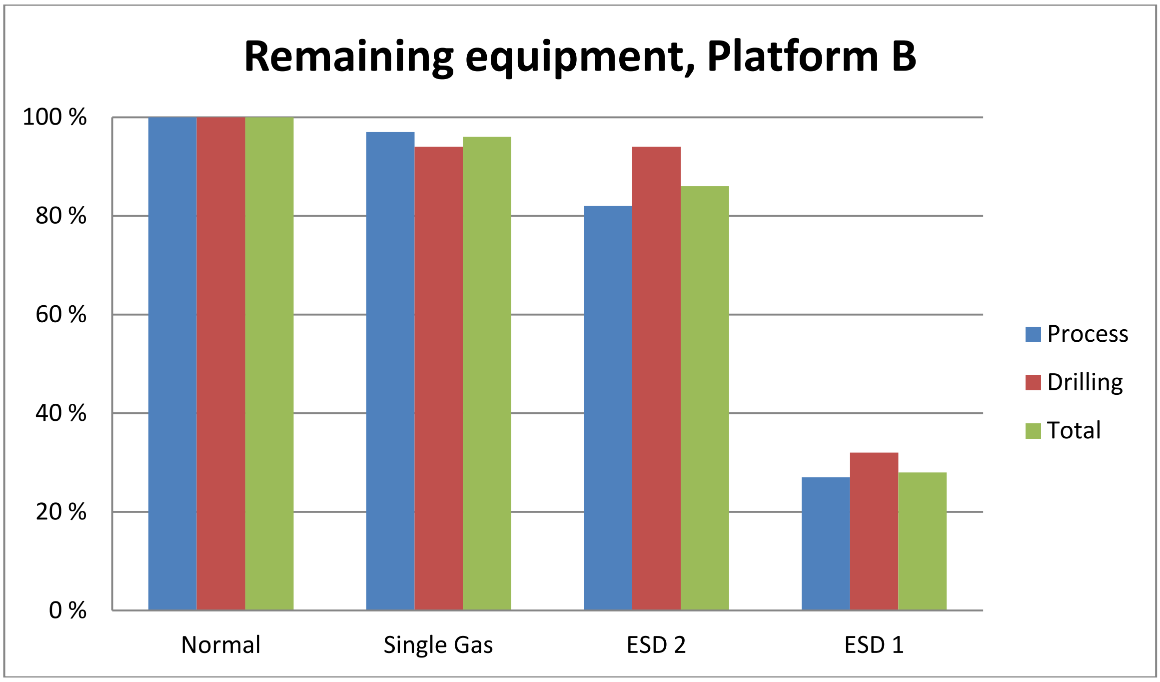


Figure 5.2: Isolation factor F for equipment on Platform B, scaled for Ex protection

The reason for the very limited effect of electrical isolation on ESD 2 is basically that there is no additional equipment isolation on ESD 2 compared to single gas except that motors related to the process are stopped, but they constitute a low number and has a correspondingly little effect on the ignition probability. The reason for the low fraction of equipment live on ESD 1 is that main power is tripped.

5.4.3 Platform C

The fractions F of equipment being live after isolation based on the equipment count on Platform C are given in Table 5.4 and Figure 5.3. However, the data for Platform C are more uncertain due to limitations in equipment data bases and the results should accordingly be used with care. The general picture is nevertheless very similar to Platform B, i.e.

- A very low fraction of equipment is actually isolated except on ESD 1
- There are only minor differences between process and drilling (even smaller than for Platform B)
- The remaining fraction of equipment on ESD 1 is higher than for Platform A and Platform B, i.e. there appears to be more emergency consumers on Platform C than on the other two installations. The number of emergency consumers on Platform C was found by counting emergency consumers in the equipment list as no emergency consumer list was available.

Table 5.4: Isolation factor F for Platform C with and without correction for ignition potential according to Ex protection.

	Without scale factor				With scale factor			
	Normal	**Single gas**	**ESD 2**	**ESD 1**	**Normal**	**Single gas**	**ESD 2**	**ESD 1**
Process %	100%	100%	93%	60%	100%	100%	97%	52%
Drilling %	100%	99%	97%	64%	100%	100%	99%	60%
Total %	100%	100%	95%	62%	100%	100%	98%	56%

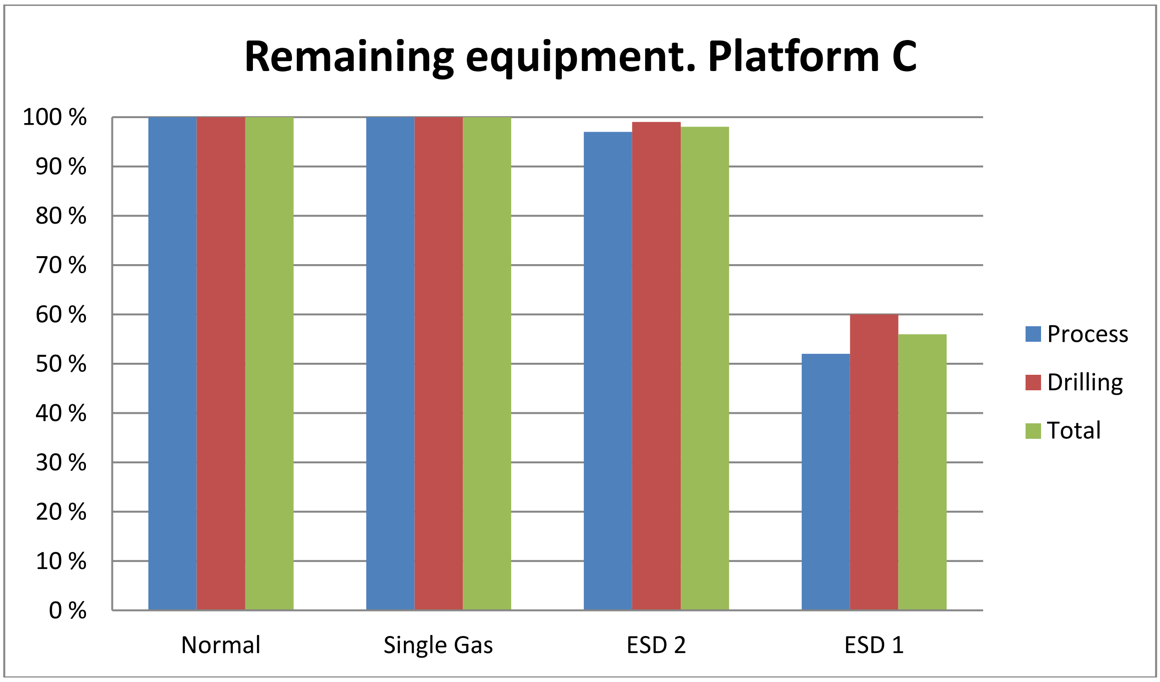


Figure 5.3: Isolation factor F for equipment on Platform C, scaled for Ex protection

The effect of the Ex correction factor appears to be to increase the ignition probability for single gas and ESD 2, as opposed to Platform A and Platform B. This may, however, be an artefact from difficulties in establishing the precise Ex category for a number of equipment due to limited information in the equipment databases.

As the data quality on Platform C was poor compared to Platform A and Platform B, the quantitave results should used with care. However, as the general trend on Platform C is similar to Platform B, the quantitative results for Platform B will be used for representing the results for platforms with limited electrical isolation, i.e. trip of sockets on single gas detection and process shutdown on conformed gas detection (ESD 2).

5.4.4 Summary

The average isolation factor F has been calculated by weighting the number of equipment on each platform. However, as the data for Platform C is less reliable than for the other platforms, Platform C has not been included in the average values given in Table 5.4. For the most common use which is for ESD 2, confirmed gas detection in hazardous area, the average values (with Ex scaling factor) for F is about 65% in process areas and 90% in drilling areas.

Table 5.5: Average isolation factor F for Platform A and Platform B with and without correction for ignition potential according to Ex protection.

Platform A Platform B	Without scaling factor				With scaling factor k, ref Table 7.1			
	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
Process	100 %	83 %	76 %	39 %	100 %	81 %	66 %	25 %
Drilling	100 %	90 %	90 %	65 %	100 %	88 %	88 %	53 %
Total	100 %	86 %	81 %	49 %	100 %	84 %	74 %	35 %

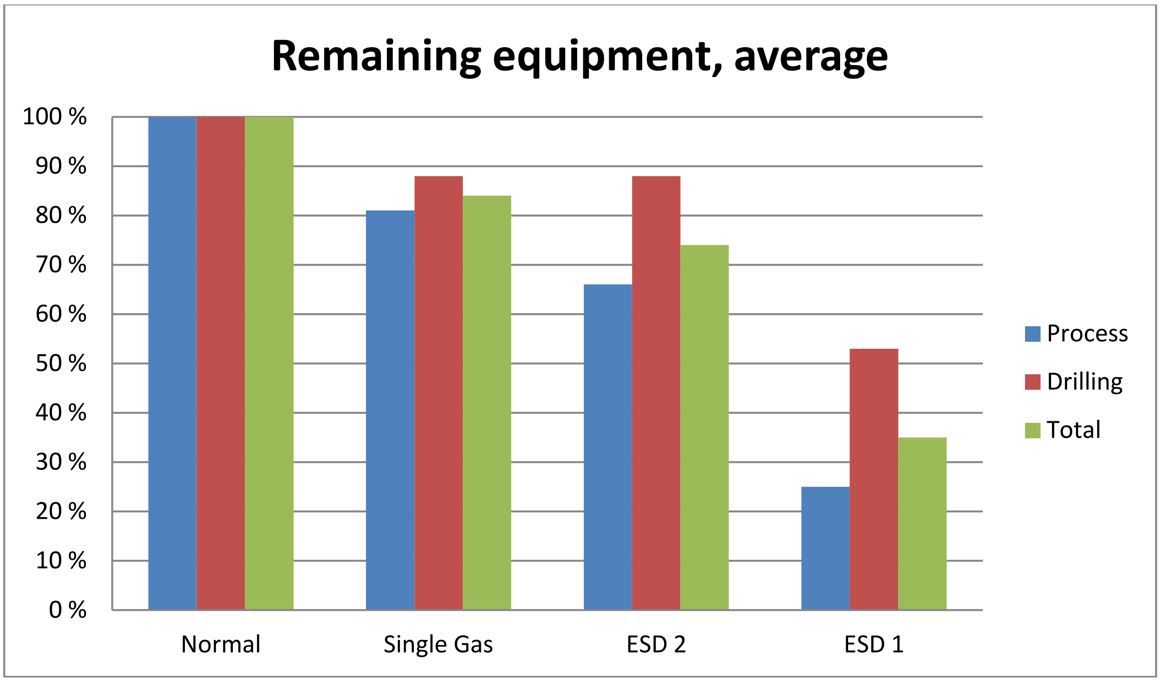


Figure 5.4: Average isolation factor F for Platform A and Platform B, scaled for Ex protection.

To illustrate the effect of including Platform C, the corresponding values of F for all installations would be about 80% and 95% (ref Table 5.6).

Table 5.6: Average isolation factor F for all platforms with and without correction for ignition potential according to Ex protection.

All platforms	Without scaling factor				With scaling factor k, ref Table 7.1			
	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
Process	100 %	88 %	81 %	46 %	100 %	91 %	83 %	40 %
Drilling	100 %	94 %	93 %	64 %	100 %	97 %	96 %	58 %
Total	100 %	91 %	87 %	54 %	100 %	94 %	90 %	49 %

The value for F of 66% in the process areas is an average between to installations with very different electrical isolation philosophies. On Platform A all heat tracing is isolated already on single gas detection whereas it is only isolated on ESD 1 on Platform B. This illustrates that the F factor depends strongly on the shutdown and isolation philosophy and which should be taken into account when establishing values for F for a specific installation. This is further elaborated in Chapter 7.
In drilling in general, much less equipment is isolated on gas detection hence the values for process areas are not applicable. An F factor of about 90% is more relevant.

The reason F is not smaller than about 80% (Platform B) if the only effect of gas detection is to stop the process, is that the type of equipment that mainly is isolated are motors and associated junction boxes. This constitutes only a small fraction of the total amount of live electrical equipment as illustrated in Table 5.7.

The data in Table 5.7 provides an interesting summary of distribution of electrical ignition sources on the installations. Instruments constitute about 40% of the total and can not be isolated, lighting constitutes about 20% and is generally kept live. What is always isolated are sockets (about 2%) on single gas detection and motors in process area (about 2%) that stops as the process is shut down. In addition comes the corresponding junction boxes, and assuming one per motor (i.e. 2%) this means that only about 6 % of the ignition sources in process areas are always isolated on gas detection. Motors in drilling are on the other hand generally kept live. What happens to the remaining sources is to a large degree determined by the ignition source control philosophy on the installation. In most cases these ignition sources are kept live, in some cases parts of the sources are shut down like on Platform A where heat tracing is isolated.

So the really effective ignition source control first occurs at ESD 1 where the main power is tripped and only emergency consumers are kept live.

Table 5.7: Isolation factor F for each class of equipment in hazardous areas, average over all installations.

			Single gas		ESD2		ESD1	
	Total	% of total	#	%	#	%	#	%
Motor	619	2.2 %	619	100.0 %	422	68.2 %	113	18.3 %
Other main eq	498	1.8 %	474	95.2 %	350	70.3 %	11	2.2 %
Heating	3779	13.7 %	2790	73.8 %	2788	73.8 %	86	2.3 %
Lighting	5580	20.2 %	5580	100.0 %	5580	100.0 %	2402	43.0 %
Push Buttons	746	2.7 %	746	100.0 %	536	71.8 %	122	16.4 %
Junction Boxes	3467	12.6 %	2478	71.5 %	2279	65.7 %	230	6.6 %
Sockets	517	1.9 %	12	2.3 %	12	2.3 %	11	2.1 %
Telecom	659	2.4 %	659	100.0 %	659	100.0 %	623	94.5 %
Instrument	10724	38.9 %	10724	100.0 %	10196	95.1 %	10196	95.1 %
Instrument JB	997	3.6 %	997	100.0 %	997	100.0 %	997	100.0 %

6. CHARACTERIZATION OF IGNITION SOURCES

6.1 General

The ignition potential of an Ex-certified electrical equipment is determined by the probability of the Ex protection failing in a mode so the equipment becomes an ignition source. The level of protection and number of barriers vary for the different Ex classes and critical failure rates will vary accordingly.

The following methods of protection are most commonly used offshore:

- Flameproof equipment , Ex d, approved for Zone 1
- Equipment protected by “increased safety”, Ex e, approved for Zone 1
- Equipment of type Ex n, approved for Zone 2
- Equipment protected by encapsulation, Ex m, approved for Zone 1
- Intrinsically safe, Ex i. Ex ia is approved for Zone 0, Ex ib for zone 1
- Equipment protected by pressurization, Ex p, approved for Zone 1.

A more detailed description of the protection mechanisms is given in Appendix B. Any equipment approved for a zone category is automatically approved for all higher zones, e.g. a Zone 1 equipment can also be used in Zone 2.

6.2 Characterization of electrical ignition

Ignition due to electrical effects can be of two different mechanisms:

- Ignition from sparks produced by the equipment itself or failures in the equipment
- Ignition from surfaces heated by the electrical energy in the system.

In this section the main characteristics and properties of these ignition types will be described. A very extensive review of electrical (and other types of) ignition sources is found in Ref /2/.

6.2.1 Ignition by sparks

Ignition by sparks or an arc between two electrodes can be caused in two ways:

- By applying a sufficient high voltage across electrodes held at a fixed distance, or

- Opening or closing of an electrical contact (“break” or “make”, short circuits etc)

The first method lends itself more easily to investigation and has been subject of research for more than a century. Although significant research has been done for contacts in many types of geometries, it is more difficult to draw clear cut conclusions due to the effects of the “real world”. The challenge is that the conditions established for ignition by arc between surfaces at a fixed distance are not conservative with regard to contact arcs.

In order to produce a spark between electrodes at a fixed distance the electrical field strength (i.e. voltage over the gap divided by the gap separation) has to be above a minimum limit determined by the material between the electrodes. For air this is about 3.0 MV/m or 3 kV/mm (the dielectric strength of air). However, there is a minimum voltage of about 340 V irrespective of the electrode distance, the so called Paschen limit. In other words, it is not possible to generate a spark between to electrodes at a fixed distance in air for voltages below about 340 V.

For contact arcs (opening or closing the electrode gap like in switches or shortcircuits between leads) the situation is, however, very different in that arcs can be produced at much lower voltages. For copper wires the minimum voltage and current to sustain an arc in air is about 13 V and 0.45 A (Ref Appendix B) in a resistive circuit.

When closing a gap (like closing a switch) in a capacitive circuit, the energy stored in the capacitor is released as the contacts close.

When opening a gap in a circuit (like opening a switch), the inductive energy stored is released as opening the contacts interrupts the current in the circuit. If the circuit has a high impedance (i.e. the capacity to store electromagnetic energy as in a solenoid or in parallel leads of long distance) an arc can be initiated with only 1 V drop over the gap as much higher voltages can be generated by the rapid change in current due to the make or break. This occurs even if 10 – 15 V is needed for a steady arc. Statistically AC circuits are less likely to produce arcs than DC circuits due to the reversal of the electric field in the gap at least for AC voltages < 150 V. Equipment with AC voltage < 150 V will thus have smaller ignition potential than other equipment.

As most breakers and switches are opened on the switchboard in a safe area, one would not expect break arcs (release of inductive energy) to be so relevant as ignition sources. The exception will be normally energized push buttons like emergency stop buttons, but very few of these if any are likely to be used in a gas scenario. In other words, sparks generated by tripping of equipment mainly occur in a safe area and will not contribute significantly to the ignition probability

For a spark to ignite an explosive gas mixture, the spark energy has to be above the minimum ignition energy (MIE) of the mixture which for stoichiometric methane-air mixtures is 0.37 mJ. Once the minimum ignition requirements have been exceeded (voltage for a given resistance, capacitance and inductance in the circuit) the ignition probability quickly becomes 100% both for low and high power electrical circuits. Generally speaking, however, considering all equipment the likelihood of high voltage equipment becoming an ignition source after failure of the safety barrier is higher than for low voltage equipment suffering from failure of the safety barrier.

6.2.2 Ignition by hot surfaces

Electrical equipment will be heated due to the resistance in the circuit. The heat can be produced for several reasons:

- Heat produced by normal resistance in the circuit like in a motor
- Heat produced by failures leading to increased resistance in a circuit like reduced cross section in faulty wiring
- Heat produced by failures leading to reduced resistance between leads like in faulty insulation between leads.

For an explosive gas mixture to be ignited by a hot surface, the surface temperature has to be above the autoignition temperature (AIT) for the gas. Methane has the highest AIT of all hydrocarbons of 540 C while molecules with longer chains (like octane) have AIT of about 200 C. The ignition temperature is also dependent on the surface area, the smaller the area the larger the temperature as illustrated in

Figure 6.1 and discussed in Appendix B.

There is, however, one additional aspect of ignition by hot surfaces that has an important effect of the probability of ignition. A gas mixture suddenly exposed to a surface above AIT will not ignite immediately but after a time delay. The closer the surface temperature is to AIT the longer time delay as illustrated for methane in

Figure 6.2. This may have significant practical consequences. It is seen that for a surface temperature even as high as 700 C, i.e. 160 C above AIT, the gas will need a retention time of at least 15 sec. So if the gas is passing over the surface due to the flow set up by the leak, buoyancy or ventilation, it will not ignite unless the gas uses more than 15 sec to pass the surface. For lower temperatures it takes even longer time.

This extra safety that in reality will be present for gas leaks is not taken into account in the EX certification wrt maximum allowable surface temperature and is thus an additional safety factor in the Ex barrier system. However, this safety factor cannot be considered to be present in case of ignition of liquids as liquids will usually stick to the hot surface for longer than the retention time (which furthermore is shorter for liquids than for gases at the same temperature).

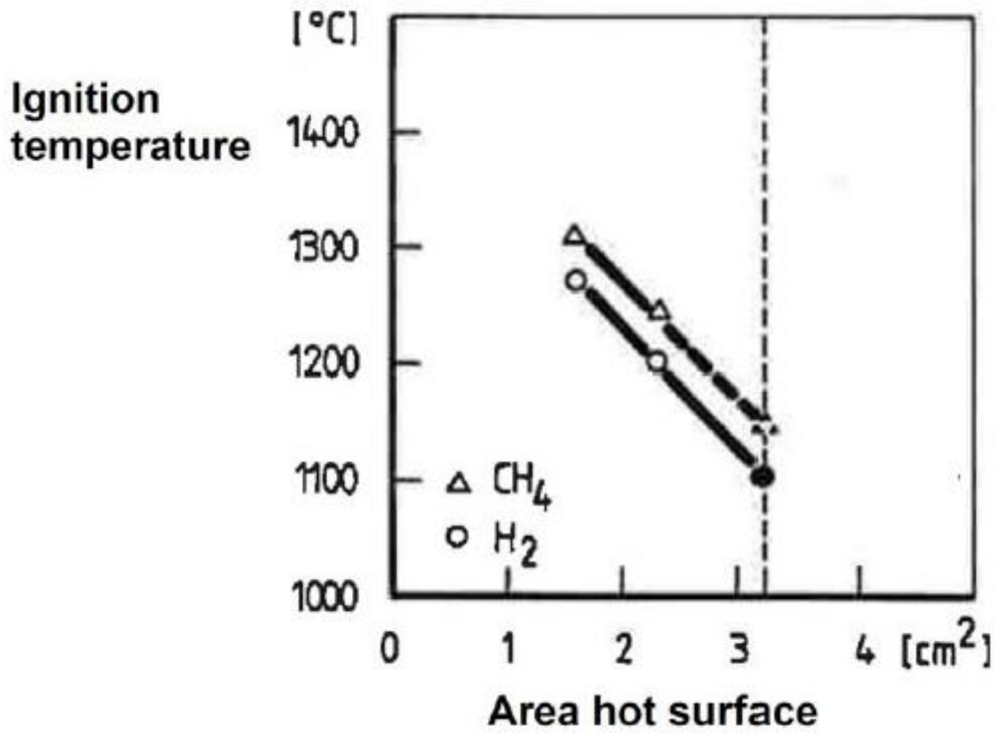


Figure 6.1: Ignition temperature as function of surface area, taken from Appendix B

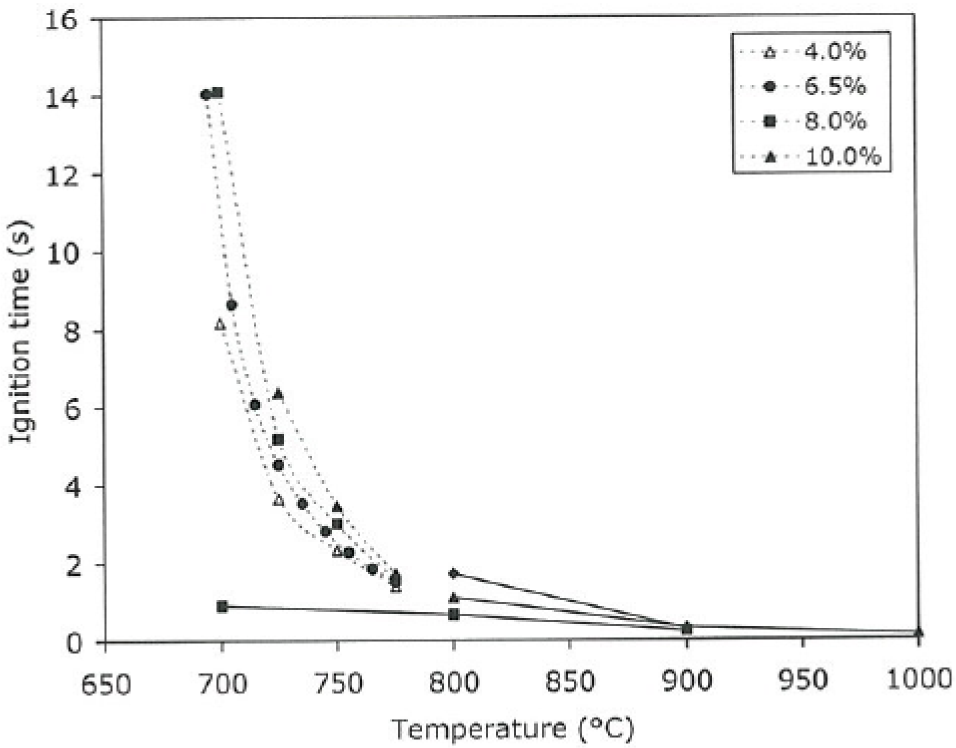


Figure 6.2: Ignition delay time for methane, taken from Ref /2/

In conclusion, this all implies that ignition of natural gas-air mixtures at hot surfaces will only be possible if temperatures exceed the auto-ignition temperature of the gas considerably.

6.3 Ignition potential of electrical ignition sources.

Scandpower has commissioned GexCon to make a review of the risk of ignition for electrical equipment. This Section summarizes their findings, reference is given to their full report in Appendix B for further details.

The failure rate of Ex protection is very difficult to estimate. Formally, the European Directive 94/9/EC demands that all companies introducing Ex equipment onto the European Union market shall determine the risk for the equipment to become an ignition source where the influence of environmental factors and maintenance procedures shall be taken into account. However, this is generally not performed by the suppliers.

Accident statistics could be consulted, but there appears to be no records revealing statistics on how often Ex equipment have been ignition sources for accidental explosions. Health and Safety Laboratory has published a report in 2005, Ref /3/ showing that of the ignited releases in the UK offshore sector, the probability of ignition in zone 2 areas was between 1.3 and 3.3 times that in zone 1 depending on released fluid. This may appear less than expected, but as there is usually a rather large fraction zone 1 equipment also in zone 2 (note that of all the main Ex classes listed above, Ex n is the only class that is only approved for zone 2), the difference will be smaller than the difference between the failure probability for zone 1 and zone 2.

The best source for failure data for Ex equipment identified by GexCon is the EU sponsored project SAFEC, Ref 13 in Appendix B, which was concerned with the specification of reliability, fault tolerances and integrity requirements related to safety categories in electrical devices in terms of probability of demand and/or failure frequencies. Based on the SAFEC data and communication with the German PTB institute that approves Ex certification and perform test of Ex ia equipment, GexCon recommends to use the failure data given in Table 6.1. As the environmental conditions as well as quality of maintenance will have a significant effect on the failure rates, these are given for two different conditions:

- "Normal" failure rates for controlled environmental conditions and high quality of maintenance
- "Harsh" failure rates for use in environments with possibility of ingress of seawater, salt and other chemicals. For practical purposes a naturally ventilated process module is considered as "normal" unless there are extensive exposure to degrading chemicals while an open process area in e.g. an FPSO is considered as "harsh" due to more extensive exposure to seawater.

Table 6.1: Failure data and ignition potential for different types of Ex protections

Type of protection	Use in zone	Normal failure rate (hr^{-1})	Failure rate harsh environment	Normal ignition potential k	Extra factor to k due harsh environment
Ex ia	0	$3.3 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	1	3
Ex ma	0	$3.3 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	1	3
Ex ib	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex mb	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex d, only sparking	1	$1 \cdot 10^{-7}$	$1 \cdot 10^{-7}$	3	1
Ex d, sparking and hot surfaces	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex e	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex p	1	$3.3 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	10	3
Ex n	2	$3.3 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	100	3
Ex s*	0-2	$3.3 \cdot 10^{-6}$	$1 \cdot 10^{-5}$	100	3

* Assumed equal to zone 2 equipment (Ex n) by ScP unless zone category is given.

An aspect of the electrical design that might be considered to be of importance to the ignition potential is the voltage level (and thereby the power) of the equipment. Instrument systems are normally operated on 24 V DC while most process equipment are operated on 400V AC or higher. GexCon concludes as discussed in Section 6.2.1 ,however, that the voltage has no effect on the ignition potential in the sense of the ignition probability given a critical failure of the Ex protection (except for AC systems < 150 V.) The reason for this is basically that if the energy in the system is sufficient for ignition, increasing the effect energy orders of magnitude will not influence the resulting explosion. In practice there is, however, so low number of AC equipment < 150 V that the ignition potential can be considered independent of the voltage level.

6.4 Intermittent and continuous ignition sources

The time of ignition during a gas leak has a significant effect on the probabilistic explosion pressure.

A source that is continuously present will ignite as soon as the gas exposes the ignition source which usually will be during the first phase of the cloud development, although there will be a time delay if the source is a surface with high temperature as discussed in Section 6.2.2. The location of the ignition point will be peripherally in the cloud.

For an intermittent source the time of ignition will be random. Hence it may occur at any time during the development of the gas cloud and anywhere in the cloud.

Sources that are sparks produced by make/breaks of switches or pushbuttons will only be active at the instant of the use of the switch or pushbutton.

Typical ignition mechanisms for different electrical equipment are presented in Table 6.2. In the standard version of the OLF model it is assumed 50% continuous and 50% intermittent sources before electrical isolation. After electrical isolation the model assumes an increased fraction of intermittent sources i.e 75%.

If the ignition sources can be sorted according to the 3 categories above, a more realistic ignition probability can be achieved.

In Appendix B different conditions for generating an arc are discussed, and it is concluded that a spark over an electrode gap is either continuous or a single event like e.g. on making or braking of a switch. Intermittent sparks are considered very unlikely given a fixed gap distance. The only realistic way of producing an intermittent spark or arc over a gap would be if the gap distance itself was intermittent due to mechanical movement of the wires.

A characterization of electrical ignition sources is given in Table 6.2.

Type	**Typical Ex prot**	**Ignition mechanism**	**Failure type**	**Ignition type: Continuous, intermittent, only on breake/make**
Motor	Ex d Ex n	Spark, hot surface	Spark in motor, High T on rotor/stator, fire.	Continuous
Junction box	Ex de	Hot surface	Creep currents, last strand failure	Continuous when equipment is active
Switch/breaker	Ex md	Spark	Not relevant for motor breakers (in LER), only for field switches	Single event on make/break
Pushbutton	Ex md	Spark	Spark	Single event on make/break
Lighting	Ex de	Spark, temperature	Hot surface, spark (igniter) depending on type of lighting	Igniter only on make, intermittent when flickering. Continuous
Heat tracing/ Heaters	Ex de	Hot surface,spark	Hot surface due to cable failure Spark from damage to power feed cable from insulation maintenance	Continuous Intermittently from insulation surface
Sockets	Ex de	Spark Hot surface	From use of equipment (mostly welding)	Continuous
Solenoids	Ex ia	Spark Hot surface	Failure in Zener barrier + Internal shortcircuit, spark or hot surface Bonding failure – current to earth	Continuous, intermittent on tripping.
Instruments	Ex ia	Spark	Failure in Zener barrier + Internal shortcircuit, spark or hot surface Bonding failure – current to earth	Continuous, intermittent on tripping

Table 6.2: Ignition source characterization for different types of electrical equipment, based on Table 4 in Appendix B (somewhat extended by ScP).

7. DISCUSSION AND CONCLUSIONS

The isolation efficiency is dominated by several factors:

- The degree of isolation by electrical equipment ≥ 220V, i.e. equipment normally provided by the electro discipline. The isolation is determined by the ESD philosophy and can differ between installations. Many installations only isolate external ignition sources and stop the process without isolating other equipment in hazardous areas while some groups of equipment not needed in an ESD scenario is isolated on some installations. This factor can thus be influenced by design and operation of the installation

- In drilling, only a very limited shutdown of ignition sources is usually performed so that most ignition sources remain live in a gas scenario

- The number of instruments. Neither ESD, PSD nor PCS are tripped on gas detection. The only instrument equipment type that is isolated are solenoids on fail-safe valves and other fail safe units as these units are closed or started by tripping the signal. The resulting total number of live instruments is usually larger than the number of electro equipment ≥ 220V

- The Ex protection philosophy, i.e. basically the use of zone 1 versus zone 2 equipment in zone 2 areas as well as use of zone 0 (Ex ia) instruments. In general the failure rate increases by a factor 10 from zone 0 to zone 1 and a factor 10 from zone 1 to zone 2. For equipment exposed to seawater (and other aggressive fluids) like on an open deck on FPSO, the failure rates increase by a factor of 3

- The voltage level of the equipment has no significant effect on the ignition potential of electrical equipment with the possible exception that the ignition potential of AC systems with voltage < 150 V may be lower than for other systems.

There are some aspects of ignition source characteristics that also should be considered when counting and characterizing ignition sources:

- Sources that are sparks produced by make/breaks of switches or pushbuttons will only be active at the instant of the use of the switch or pushbutton which in a gas scenario will be the time of electrical isolation. These are accordingly discrete sources that do not occur randomly in time. However, all power breakers to main equipment are located in safe electrical switchboard rooms and will not be exposed to gas in the hazardous areas

- Intermittent sparks, i.e. sparks occurring on and off randomly in time, are considered very unlikely given a fixed gap distance. The only realistic way of producing an intermittent spark or arc over a gap would be if the gap distance itself was intermittent due to mechanical movement of the wires.

As the data quality on Platform C was poor compared to Platform A and Platform B, the quantitave results for Platform C should used with care. However, the general trend on Platform C is similar to Platform B hence the quantitative results for Platform B will be used for representing the results for platforms with limited electrical isolation, i.e. trip of sockets, external non-critical consumers and non Ex equipment (if any) on single gas detection and process shutdown on conformed gas detection (ESD 2).
For a typical platform in the Norwegian sector of the North Sea designed according to NORSOK S-001 with regard to ESD philosophy and ignition source control, the ignition source isolation efficiency will depend on the degree of ignition source isolation in addition to isolation of sockets on single gas detection and process shutdown on confirmed gas detection in hazardous areas. If a detailed count of ignition sources is available platform specific values can be obtained by using the method in Chapter 4 combined with the data in Table 6.1.

If an equipment count is not available, recommended values for F or P_{iso} are given in Table 7.1 based on Platform A and Platform B. If there is no other equipment isolation than sockets and process shutdown the values for Platform B may be used. If the ignition source isolation is more or less extensive than on Platform A (i.e. isolation of all heat tracing) the values for F or P_{iso} can be scaled accordingly. The equipment distribution in Table 5.7 in combination with Table 6.1 can be used as a guide for estimating the contribution from a given type of equipment.

Table 7.1: Recommended values for ignition source isolation efficiency

Ignition source contrl philosophy	Process		Drilling	
	F	P_{iso} = 1 - F	F	P_{iso} = 1 - F
Isolate sockets and process shutdown (typical Platform B)	0.8	0.2	0.95	0.05
Partial isolation of other equipment (typical Platform A)	0.4	0.6	0.8	0.2
Trip main power, ESD 1	0.25	0.75	0.5	0.5

The value of P_{iso} = 0.75 as suggested in the OLF ignition model actually corresponds to the values found for ESD 1 (trip of main power) and is thus too optimistic for use in a regular gas scenario in a process module. Some installations trip main power on ESD 2, for those the suggested OLF value of P_{iso} = 0.75 is representative.

The calibration of the OLF model was based on P_{iso} = 0.75 and it is recommended to evaluate if a recalibration of the model parameters should be performed. A recalibration should also consider the fraction of continuous versus intermittent ignition sources as this study indicates that continuous sources may be more dominating than presently suggested by the OLF model.

The model for using the F should be used with care for platforms having a distribution of Ex type equipment very different from the typical North Sea platform. In that case the base area ignition probability P_{if} should somehow be corrected. This is, however, outside the scope of this study and should be discussed within the OLF ignition model.

8. REFERENCES

/1/ “Ignition Modeling in Risk Analysis”. Scandpower Report 89.390.008/R1 19 March 2007.

/2/ V. Babrauskas. “Ignition Handbook”, Society of Fire Protection Engineers and Fire Science Publishers, 2003

/3/ Thyer, A.M., ”Offshore ignition probability arguments” ;Health and Safety Laboratory Report HSL/2005/50, 2005

APPENDIX A

IGNITION SOURCES AT PLATFORM A, PLATFORM B AND PLATFORM C

TABLE OF CONTENTS

The following attacments are not included in this anonymised version of the report:

Attachment 1: Excel Work Book with results for Platform A!
Attachment 2: Excel Work Book with results for Platform B
Attachment 3: Excel Work Book with results for Platform C

A1. INTRODUCTION

This appendix presents the methods and the results for the counting of ignition sources at Platform A (PLA), Platform B (PLB) and Platform C (PLC). Platform B was chosen as it represents a original and old Statoil platform. Platform A represents a new Statoil platform and Platform C is originally a Hydro platform.

Data material for this analysis is collected from STID (PLB and PLA) and SAP (PLC).

A1.1 List of Abbreviations

ESD	-	Emergency Shutdown
JB	-	Junction Box
PB	-	Push Button
PLA	-	Platform A
PLB	-	Platform B
PLC	-	Platform C
PSD	-	Process Shutdown
SAS	-	Safety and Automation System
SO	-	Socket Outlet
UPS	-	Uninterruptable Power Supply

A2. METHODOLOGY

A2.1 General

The background information for this study is collected from TEARK, STIDele, SAP and from dialogues with technical safety and the electro discipline. Relevant documents used are ESD/PSD logic documents, area safety charts, single line diagrams, ignition source manuals where available, el trip groups, electro consumer lists, emergency power lists and instruments consumer lists.

A2.2 Main Methodology

The aim of the analysis was to count all ignition sources in the process and drilling areas for the chosen platforms. Further, the shutdown philosophy is used to make an overview of ignition sources available after various levels of ESD and PSD.

Information about ignition sources and shutdown philosophy was not easily available. Hence, several assumptions were needed in order to map the ignition source shutdown philosophy. The assumptions were developed in cooperation with technical safety and the electro discipline for the installations.

A2.3 Main Assumptions

Below are the main assumptions developed in this project. Installation specific assumptions and counting rules are presented for each installation:

- The electrical consumer groups identified in this analysis are motors, other main equipment, heat trace, lights, push buttons, junction boxes, socket outlets, telecom, instruments and instrument junction boxes
- All equipment with EX classification in the classified areas of the process and drilling modules are assumed to be electrical consumers. Hence, equipment without EX classification are not considered
- All electrical consumers are assumed operating continuously. With reference to the electrical load factor, this is a conservative simplification since not all electrical consumers are running continuously
- Spare tag numbers and equipment are not assumed to be live electrical consumers
- All electrical consumers belonging to the electro discipline are assumed to be high voltage, i.e. > 220 V
- Electrical consumers under the instrument discipline are assumed low voltage , i.e. ≤ 220 V
- It is assumed that switchboards and and breakers are located in safe areas or locally on rooms safe by pressurization. Hence, the switchboards are not included as ignition sources. In cases with local breakers in field, these have double Ex protection (both on breaker and cabinet) and are hence not considered as potential ignition sources
- All electrical equipment within a package have distinct tag numbers in the databases. The exception are junction boxes and pushbuttons for main equipment.

- The results are summarized for each EX level with and without scale factors showed in Table A 1. The scale factors to be used are as presented in the main report. With scale factors, the remaining electrical consumers after a given shutdown level are:

$$M = \#_{EXn} \cdot 100 + \#_{EXs} \cdot 100 + \#_{EXd} \cdot 10 + \#_{EXe} \cdot 10 + \#_{EXde} \cdot 10 + \#_{EXp} \cdot 10 + \#_{EXm} \cdot 10 + \#_{EX_{ib}} \cdot 10 + \#_{EXia} \cdot 1$$

Table A 1: Scale factors for reliability of each EX level

Ex-n	EX s	Ex-d	Ex-e	Ex-de	Ex-p	Ex m	Ex ib	Ex ia
100	100	10	10	10	10	10	10	1

A3. PLATFORM A

The Platform A platform was installed on the North sea field on XXXX and the production drilling began in XXXX. The platform is located in XXX meters of water and the platform is a fully-integrated fixed steel platform with drilling, process facilities and living quarters.

A3.1 Areas for Analysis

The areas that are analyzed are shown in Table A 2

Table A 2: Modules at Platform A incldued in the analysis

Module	Description
P10N/S,11, P12	Lower Process
P21, P22, P23, P24A	Upper Process
D11, D12, D13, D14, D21, D22, D23, D24, D31, D32, D33, D34	Drilling Area

A3.2 Ignition Source Shutdown Philosophy

A simplified overview of the ignition source shutdown philosophy at Platform A is shown in Figure A 1. According to SAP AO XXXXXXXX-XXXX all Heat Trace cables shall be isolated upon single gas detection anywhere on the platform.

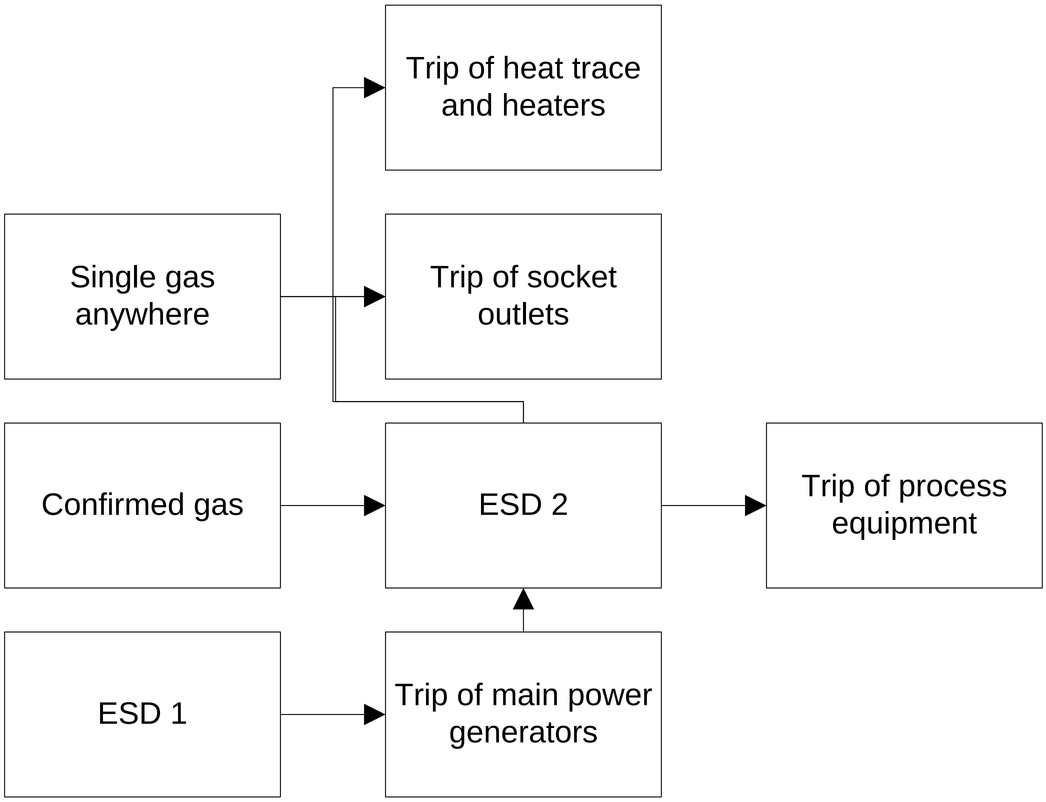


Figure A 1: Overview of ignition source shutdown philosophy at Platform A

The ignition sources tripped at ESD 2 are not described in any documents. The lists with main equipment are examined to identify which consumers that are assumed to trip after initiation of PSD on the basis that equipment not needed to maintain production will be live..

A3.3 Rules for Counting of Electrical Ignition Source

The data for Platform A were collected from STID. The following AD HOC reports were collected from IngReg:

- Electro Field Equipment
- Heat Trace
- Instrument Junction Box
- Instruments
- Main Equipment
- Telecom.

The reports form the foundation for further analyses. The Platform A specific counting rules for identification of electrical consumers are explained in the following sections.

A3.3.1 Assumptions relevant for all datasets

- Only tag numbers with status “A” (As built) are kept
- Equipment that are denoted with “Spare” in “Description” is removed
- For equipment that are denoted “A”, “B”, etc., only the “A”-equipment is counted. The B, C, etc. equipment is assumed spare

- Breakers are placed in safe switchboard rooms. Breakers located locally in the modules are located in Exe cabinets and the breaker itself are Exd These are assumed not to be ignition sources due to double Ex protection
- All SAS system cabinets are connected to the UPS system and electrical isolation occurs 30 minutes after ESD 0. Hence, all instruments are assumed live until ESD 0 except ESD and PSD valves that are deenergised on ESD 2 and normally deenergised valves (control valves). The tag numbers that are not associated with an EX class are removed. The EX class is shown in the column “EX_Class”. However, if a tag number is associated with a Gas_Group, but not an EX class it is kept because it is assumed that the EX class should have been included
- A review is made of the production shutdown philosophy. Equipment that is assumed not tripped by the PSD is identified, e.g. winches, fire water equipment, etc.
- All electrical equipment except spares are assumed in operation. This is a conservative approach with respect to load factor.

A3.3.2 Main Equipment

Each motor is assumed to have one junction box (JB) and one push button (PB). The JB and PB is assumed to follow the shutdown philosophy of the main equipment.

By ESD 2, process main equipment is shut down. A manual analysis is performed to sort out the equipment that is assumed not to be tripped at ESD 2, i.e. equipment not needed to maintain production..

A3.3.3 Lights

The lights are tripped when the supply electrical switchboard is tripped. Hence, electrical switchboards connected to the 82 system is assumed tripped by ESD 1. Electrical switchboards connected to the 84 system are fed by emergency power and tripped upon ESD 0.

A3.3.4 Emergency Consumers

The emergency consumers are obtained from electrical consumer lists. The lists are found from STIDele and shows consumers from the various emergency switch boards.

A3.3.5 Heat Trace

In accordance with SAP AO XXXXXXXX-XXXX, every heat trace cable shall be isolated upon single gas alarm. Heat tracing is identified from the heat trace database. All tags with EX classification in the Heat Trace report are assumed to be heat trace.

Heaters are not assumed to trip upon single gas.

A3.3.6 Socket Outlets

Socket outlets are identified from the ”Electro Field Equipment” database. The socket outlets are identified by sorting out only the equipment with tag type ”W”. All socket outlets fed by main power are tripped on single gas. The socket outlets connect to emergency power are not tripped and are identified from the emergency consumer lists.

A3.3.7 Instruments

All instruments are assumed "live" until ESD 0 except for normally energized solenoids for ESD and PSD valves. These solenoids are tripped upon ESD 2. Motor operated control valves are assumed not to be operated during ESD or PSD and are accordingly not live.

A3.4 Results

The overall results for Platform A is presented in Table A 2. The table shows the distribution of the ignition sources for the various shutdown levels. Further, the results are illustrated in Figure A 2 and Figure A 3. The two figures show the trip of high and low voltage respectively for the shutdown levels. The detailed results for Platform A are shown in Appendix A. The appendix does also include results sorted on EX classification.

Table A 3 shows the remaining ignition sources of high and low voltage at each shutdown level.

Table A 3: Presentation of ignition sources for each level of ignition source shutdown at Platform A. Includes both Electro and Instrument sources.

Voltage	Area	Normal		Single gas		ESD 2		ESD 1	
		#	%	#	%	#	%	#	%
High voltage	Process	2754	100	1178	45	968	40	296	14
	Drilling	1807	100	1264	72	1264	72	500	29
Low voltage	Process	1425	100	1425	100	1326	91	1326	91
	Drilling	3122	100	3122	100	3113	100	3113	100
Total	All	9094	**100**	6989	**77**	6671	**73**	5235	**58**

Table A 4: Results for remaining ignition sources at high and low voltage with and without scale factor.

	Without scale factor				With scale factor			
Area	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
D11	833	725	724	565	5969	4882	4882	3537
D12	851	768	767	718	5235	4522	4522	3988
D13	537	479	479	368	4188	3512	3512	2692
D14	57	49	49	37	466	343	343	220
D21	348	277	276	230	3000	2409	2409	2066
D22	257	231	230	127	2165	1766	1766	1134
D23	72	70	70	34	434	373	373	244
D24	279	273	273	207	2290	2213	2213	1859
D31	719	656	654	602	3660	3121	3101	2717
D32	433	383	382	344	2262	1846	1846	1541
D33	409	367	366	309	2074	1643	1633	1213
D34	134	108	107	72	997	728	728	530
P10N	74	47	42	27	457	203	145	55
P10S	50	14	14	5	401	102	93	21

	Without scale factor				With scale factor			
Area	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
P11	829	576	489	390	7105	4594	2709	1786
P12	485	314	271	200	3764	2064	1384	834
P21	1160	693	612	457	8940	4370	3148	1823
P22	910	520	466	296	7450	3481	2877	1716
P23	463	258	226	126	3530	1528	1042	462
P24	208	181	174	121	1838	1413	1199	886
Process	4179	2603	2294	1622	33485	17754	12597	7581
Drilling	4929	4386	4377	3613	32740	27357	27327	21741
Total	9108	6989	6671	5235	66225	45110	39923	29323
Process %	**100%**	**62%**	**55%**	**39%**	**100%**	**53%**	**38%**	**23%**
Drilling %	**100%**	**89%**	**89%**	**73%**	**100%**	**84%**	**83%**	**66%**
Total %	**100%**	**77%**	**73%**	**57%**	**100%**	**68%**	**60%**	**44%**

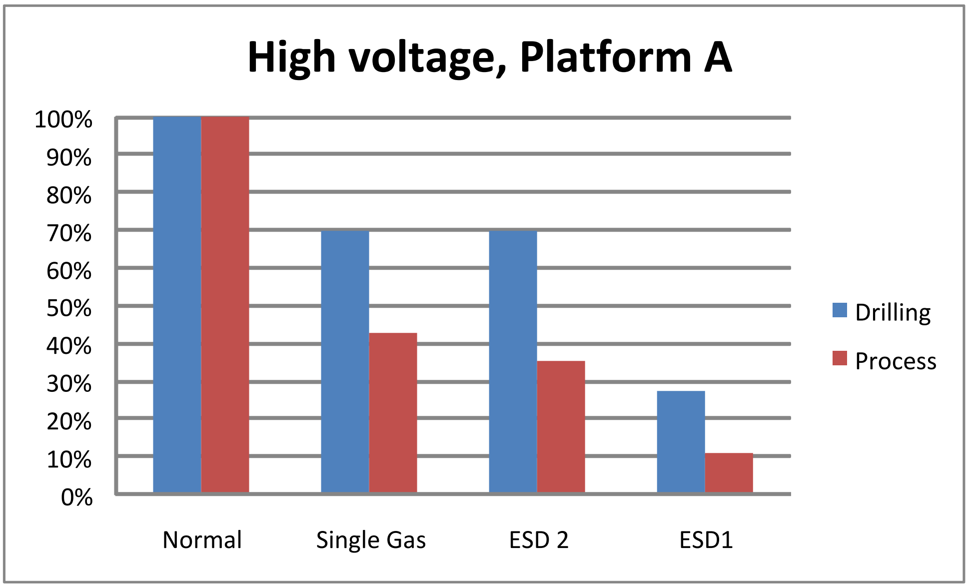


Figure A 2: Illustration of high voltage shutdown at Platform A

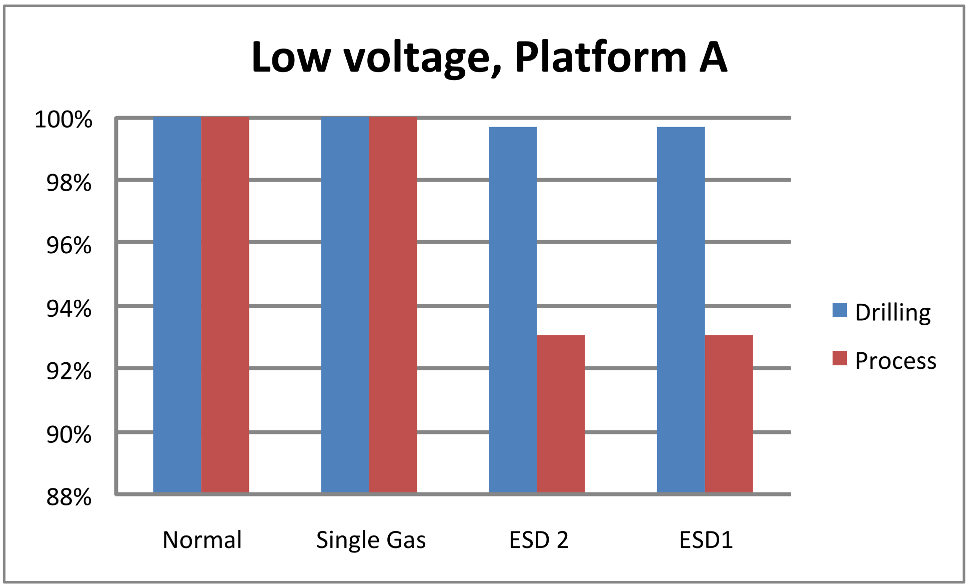


Figure A 3: Illustration of low voltage shutdown at Platform A

A4. PLATFORM B

Platform B is an integrated drilling, accommodation and production platform that started production in XXXX. Since XXXX, Platform B has received and processed oil from the XXXX field..

The platform was chosen as it represents original Statoil installations that are relatively old.

A4.1 Areas for Analysis

The modules that are chosen for this analysis is shown in Table A 5

Table A 5: Areas chosen for the analysis

Module	Description
M10	Process: Gas Treatment Module
M14	Process: Gas Treatment Module
M15	Process: Separator Module
M16	Process: Wellhead Area
M17	Process: Wellhead Area
M19	Process: Manifold module
M24	Process: Gas Compression module
M25	Process: Separator module
D11	Drilling: Substructure
D21	Drilling module

A4.2 Ignition Source Shutdown Philosophy

A simplified overview of the ignition source shutdown philosophy is shown in Figure A 4. In contrast to Platform A, heat trace is not tripped before ESD 1.

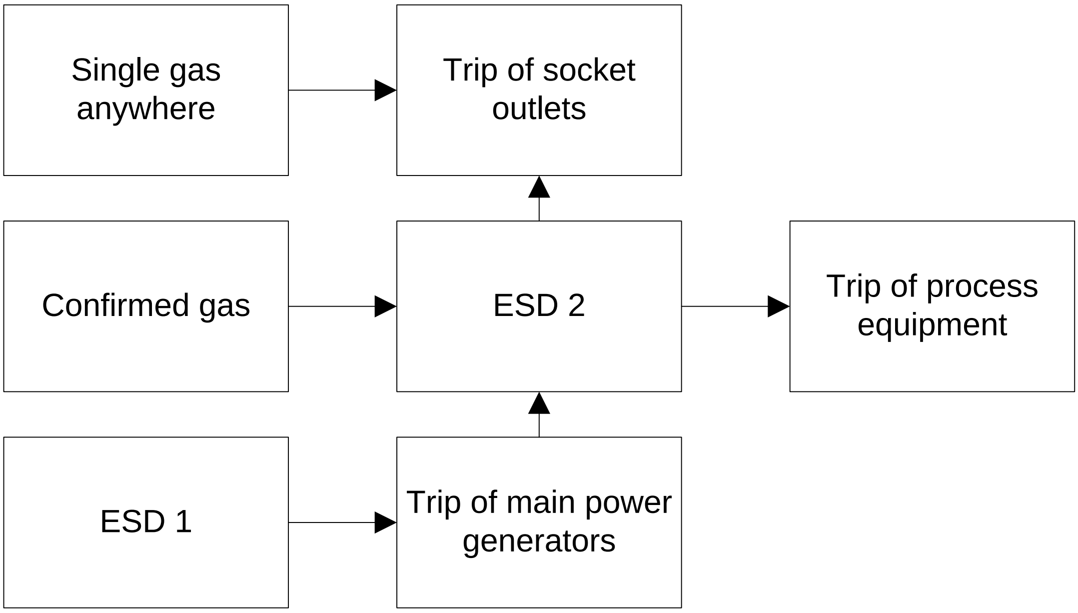


Figure A 4: Overview of ignition source shutdown philosophy

The ignition sources tripped at ESD 2 are not described in any documents. The lists with main equipment are examined to identify which consumers that are assumed to trip after initiation of PSD.

A4.3 Rules for Counting of Electrical Ignition Source

A4.3.1 Emergency Consumers

The data for Platform B were collected from STID, i.e. same data sources as Platform A. The following AD HOC reports were collected from IngReg

- Electro Field Equipment
- Heat Trace
- Instrument Junction Box
- Instruments
- Main Equipment
- Telecom.

The reports form the foundation for further analyses. The Platform B specific counting rules for identification of electrical consumers are explained in the following sections.

A4.3.2 Assumptions relevant for all datasets

- Only tag numbers with status “A” (As built) are kept
- Equipment that are denoted with “Spare” in “Description” is removed
- For equipment that are denoted “A”, “B”, etc., only the “A”-equipment is counted. The B, C, etc. equipment is assumed spare
- All SAS system cabinets are connected to the UPS system and electrical isolation occurs 30 minutes after ESD 0. Hence, all instruments are assumed live until ESD 0 except ESD and PSD valves that are deenergised on ESD 2 and normally deenergised valves (control valves)

- The tag numbers that are not associated with an EX class are removed. The EX class is shown in the column “EX_Class”. However, if a tag number is associated with a Gas_Group, but not an EX class it is kept because it is assumed that the EX class should have been included
- A review is made of the production shutdown philosophy. Equipment that is assumed not tripped by the PSD is identified, e.g. winches, fire water equipment, etc.
- All electrical equipment except spares are assumed in operation. This is a conservative approach with respect to load factor.

A4.3.3 Main Equipment

Each motor is assumed to have one junction box (JB) and one push button (PB). The JB and PB is assumed to follow the shutdown philosophy of the main equipment.

By ESD 2, process main equipment is shut down. A manual analysis is performed to sort out the equipment that is assumed not to be tripped at ESD 2.

A4.3.4 Lights

The lights are tripped when the supply electrical switchboard is tripped. Hence, electrical switchboards connected to the 82 system is assumed tripped by ESD 1. Electrical switchboards connected to the 84 system are fed by emergency power and tripped upon ESD 0.

A4.3.5 Emergency Consumers

The emergency consumers are obtained from electrical consumer lists. The lists are found from STIDele and shows consumers from the various emergency switch boards.

A4.3.6 Heat Trace

In contrast to Platform A, heat trace and heaters are not tripped upon single gas.

A4.3.7 Socket Outlets

Socket outlets are identified from the ”Electro Field Equipment” database. The socket outlets are identified by sorting out only the equipment with tag type ”W”. All socket outlets fed by main power are tripped on single gas. The socket outlets connect to emergency power are identified from the emergency consumer lists and are assumed live.

A4.3.8 Instruments

All instruments are assumed “live” until ESD 0 except for normally energized solenoids for ESD and PSD valves. These solenoids are tripped upon ESD 2. Motor operated control valves are assumed not to be operated during ESD or PSD and are accordingly not live.

It was not possible to obtain PSD valves directly. Hence, tag numbers with the text “PSD” in the description field was assumed to be PSD and hence tripped at ESD 2. Tag numbers with function code “EY” were assumed to be ESD valve solenoids.

A4.4 Results

The overall results for Platform B is presented in Table A 6. The table shows the distribution of the ignition sources for the various shutdown levels. Further, the results are illustrated in Figure A 5 and Figure A 6 . The figures illustrate the development of the ignition source shutdown for respectively high and low voltage. The detailed results for Platform B are shown in Appendix B. The appendix does also include results sorted on EX classification. Table A 7shows the remaining ignition sources of high and low voltage at each shutdown level.

Table A 6: Presentation of ignition sources for each level of ignition source shutdown at Platform B.

Voltage	Area	Normal		Single gas		ESD 2		ESD 1	
		#	%	#	%	#	%	#	%
High voltage	Process	4311	100	4138	96	3865	90	856	21
	Drilling	1504	100	1372	91	1372	91	444	29
Low voltage	Process	1502	100	1502	100	1379	92	1379	92
	Drilling	275	100	275	100	275	100	275	100
Total	All	7592	**100**	7287	**96**	6891	**91**	2954	**39**

Table A 7: Results for remaining ignition sources at high and low voltage with and without scale factor.

	Without scale factor				With scale factor			
Area	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
M10	425	411	370	136	3919	3779	3374	1055
M14	1124	1098	1038	413	12444	12184	10223	3158
M15	686	670	622	289	8325	8175	6356	2043
M16	642	614	588	279	5932	5652	5239	2108
M17	716	686	636	340	5948	5648	5098	2032
M19	639	625	566	197	5649	5509	5076	1487
M24	1164	1128	1043	472	13665	13345	10168	2999
M25	540	531	504	232	4396	4306	4100	1282
D11	892	846	846	356	11604	11144	11136	3663

D21	887	801	801	363	10767	9907	9906	3599
Process	5936	5763	5367	2358	60278	58598	49635	16163
Drilling	1779	1647	1647	719	22371	21051	21042	7262
Total	7715	7410	7014	3077	82649	79649	70677	23425
Process %	**100%**	**97%**	**90%**	**40%**	**100%**	**97%**	**82%**	**27%**
Drilling %	**100%**	**93%**	**93%**	**40%**	**100%**	**94%**	**94%**	**32%**
Total %	**100%**	**96%**	**91%**	**40%**	**100%**	**96%**	**86%**	**28%**

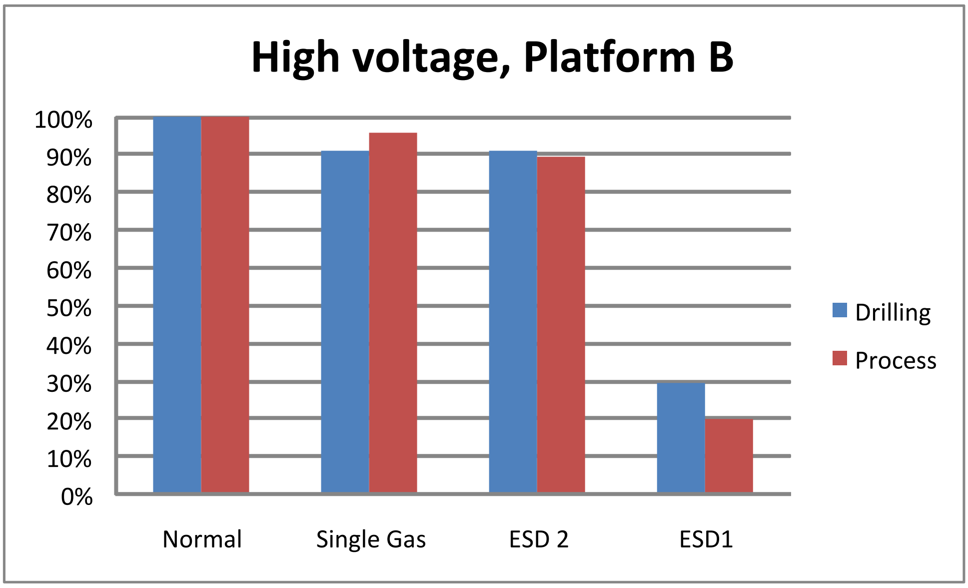


Figure A 5: Illustration of high voltage shutdown at Platform B

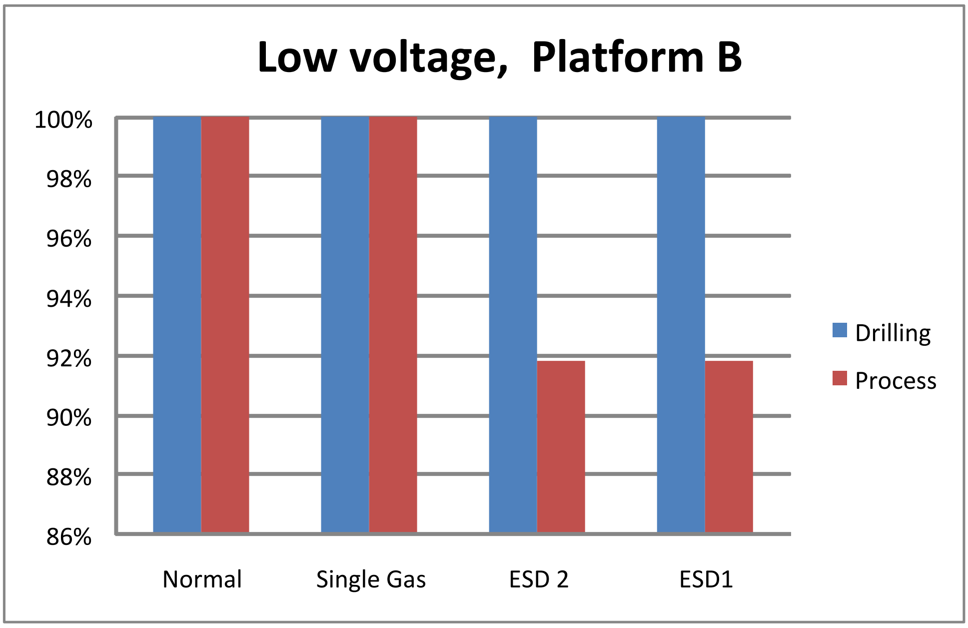


Figure A 6: Illustration of low voltage shutdown at Platform B

A5. PLATFORM C

Platform C is an integrated drilling, accommodation and production platform with a steel jacket. The production started in XXXX and oil is produced from XX wells.

The platform is chosen for this analysis as it represents original Hydro installations.

A5.1 Areas for Analysis

The modules chosen for counting of electrical ignition sources are shown in Table A 8

Table A 8: List of modules chosen for the analysis

Module	Description
M21	Process level 1 and mezzanine
M22	Process area
M23	Process area and LER
M30/31/32	Wellhead module
M40	Skidding module
M51	Drilling level 1 and mezzanine; BOP Area and mud log. unit
M52	Drilling level 2; mud treatment area
M53	Drill floor and drill floor upper level
M60	Drilling derrick general
M70	Cementer module general

A5.2 Ignition Source Shutdown Philosophy

The basis of the ignition source shutdown philosophy is shown in Figure A 7. Except for socket outlets, there are no dedicated ignition source shutdown. However, an initiation of an ESD 2 will trip a significant amount of electrical consumers in the process areas. It is assumed that none of the electrical consumers in the drilling areas will be affected by an ESD 2. After ESD 1 only electrical consumers connected to the emergency power supply will be live.

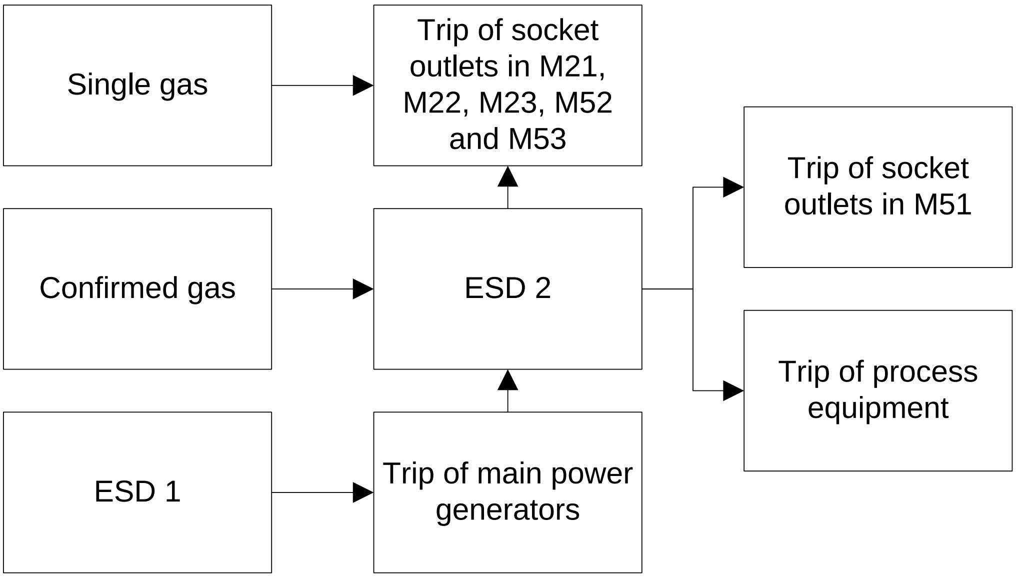


Figure A 7: Summary of ignition source shutdown philosophy for Platform C

The ignition sources tripped at ESD 2 are not described in any documents. The lists with main equipment are examined to identify which consumers that are assumed to trip after initiation of PSD.

A5.3 Rules for Counting of Electrical Ignition Source

A5.3.1 Emergency Consumers

The data for Platform C were collected from SAP. The method for identifying electrical consumers at Platform C is different than for Platform A and Platform B. It is not possible to obtain consumer lists from SAP, neither electrical consumers nor emergency consumer lists.

To obtain an overview of electrical consumers, search for equipment groups are performed in SAP. Identified groups of equipment are motors, other main equipment, heat trace, lights, push buttons, junction boxes, socket outlets, telecom, instruments and instrument junction boxes.

EX categorization is not described in the data sets as in STID: However, in X-Hydro there were a survey that mapped the EX categorization of all equipment. Equipment marked as EX during this survey are assumed to be electrical consumers. Other tag numbers are not considered.

A5.3.2 Assumptions relevant for all datasets

- Only tag numbers with status “As built” are kept
- Equipment that are denoted with “Spare” in “Description” is removed
- For equipment that are denoted “A”, “B”, etc., only the “A”-equipment is counted. The B, C, etc. equipment is assumed spare

- All SAS system cabinets are connected to the UPS system and electrical isolation occurs 30 minutes after ESD 0. Hence, all instruments are assumed live until ESD 0. except ESD and PSD valves that are deenergised on ESD 2 and normally deenergised valves (control valves) The tag numbers that are not associated with an EX class are removed. The EX class is shown in the column “EX_Class”. However, if a tag number is associated with a Gas_Group, but not an EX class it is kept because it is assumed that the EX class should have been included
- A review is made of the production shutdown philosophy. Equipment that is assumed not tripped by the PSD is identified, e.g. winches, fire water equipment, etc.
- All electrical equipment except spares are assumed in operation. This is a conservative approach with respect to load factor.

A5.3.3 Main Equipment

Each motor is assumed to have one junction box (JB) and one push button (PB). The JB and PB is assumed to follow the shutdown philosophy of the main equipment.

By ESD 2, process main equipment is shut down. A manual analysis is performed to sort out the equipment that is assumed not to be tripped at ESD 2.

A5.3.4 Lights

The lights are tripped when the associated electrical switchboard is tripped. Hence, electrical switchboards connected to the 82 system is assumed tripped by ESD 1. Electrical switchboards connected to the 84 system is fed by emergency power and tripped upon ESD 0.

A5.3.5 Emergency Consumers

It was not possible to obtain datasets of emergency consumers. Hence, a manual inspection of the main equipment lists were necessary to assume which equipment that are emergency consumers.

A5.3.6 Heat Trace

Heat trace and heaters are not tripped upon single gas.

A5.3.7 Socket Outlets

Socket outlets are identified from the ”Electro Field Equipment” database. The socket outlets are identified by sorting out only the equipment with tag type ”W”. All socket outlets supplied by main power are tripped on single gas. The socket outlets connect to emergency power are identified from the emergency consumer lists, these are not tripped.

A5.3.8 Instruments

All instruments are assumed “live” until ESD 0 except for normally energized solenoids for ESD and PSD valves. These solenoids are tripped upon ESD 2.

Tag numbers with defined equipment group as “NAS magnetventil” or “PAS magnetventil” are identified as ESD or PSD valves. These are assumed tripped at ESD 2.

A5.4 Results

The overall results for Platform C is presented in Table A 9. The table shows the ignition sources live at various shutdown levels. Further, the results are illustrated in Figure A 8 and Figure A 9 . The figures illustrate the development of the ignition source shutdown for respectively high and low voltage. The detailed results for Platform C are shown in Appendix C. The appendix does also include results sorted on EX classification.

Table A 10 shows the remaining ignition sources of high and low voltage at each shutdown level.

Table A 9: Presentation of ignition sources for each level of ignition source shutdown at Platform C

Voltage	Area	Normal		Single gas		ESD 2		ESD 1	
		#	%	#	%	#	%	#	%
High voltage	Process	2362	100	2352	99	2198	93	625	29
	Drilling	2741	100	2696	98	2696	98	819	39
Low voltage	Process	2333	100	2333	100	2188	94	2188	94
	Drilling	2941	100	2941	100	2788	95	2788	95
Total	All	10370	**100**	10322	**100**	9861	**95**	6420	**62**

Table A 10: Results for remaining ignition sources at high and low voltage with and without scale factor.

	Without scale factor				With scale factor			
Area	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
M20	2389	2389	2236	2172	28600	28526	27265	26699
M21	803	801	720	207	26820	26776	26062	9001
M22	614	613	556	94	18000	17927	17485	5683
M23	694	693	676	220	27060	27021	26779	10743
M24	195	189	190	121	8260	8196	8115	4250
M30	2107	2113	1960	1475	31660	31608	30931	26275
M31	797	786	786	335	42650	42569	42565	15370
M32	62	60	60	44	2140	2118	2114	1509
M40	119	117	117	44	9080	9058	9057	3568
M50	1249	1248	1248	1036	27150	27082	26682	23205
M51	185	183	183	67	8140	8122	8122	3918
M52	209	209	209	80	10060	10051	10051	4106
M53	262	258	258	116	13180	13139	13139	6173
M60	264	257	257	139	7490	7445	7410	6235

M70	404	389	389	254	4000	3928	3822	2404
M71	17	17	17	17	160	160	160	160
Process	4695	4685	4378	2814	108740	108445	105707	56375
Drilling	5675	5637	5484	3607	155710	155279	154053	92923
Total	10370	10322	9862	6421	264450	263724	259760	149298
Process %	**100%**	**100%**	**93%**	**60%**	**100%**	**100%**	**97%**	**52%**
Drilling %	**100%**	**99%**	**97%**	**64%**	**100%**	**100%**	**99%**	**60%**
Total %	**100%**	**100%**	**95%**	**62%**	**100%**	**100%**	**98%**	**56%**

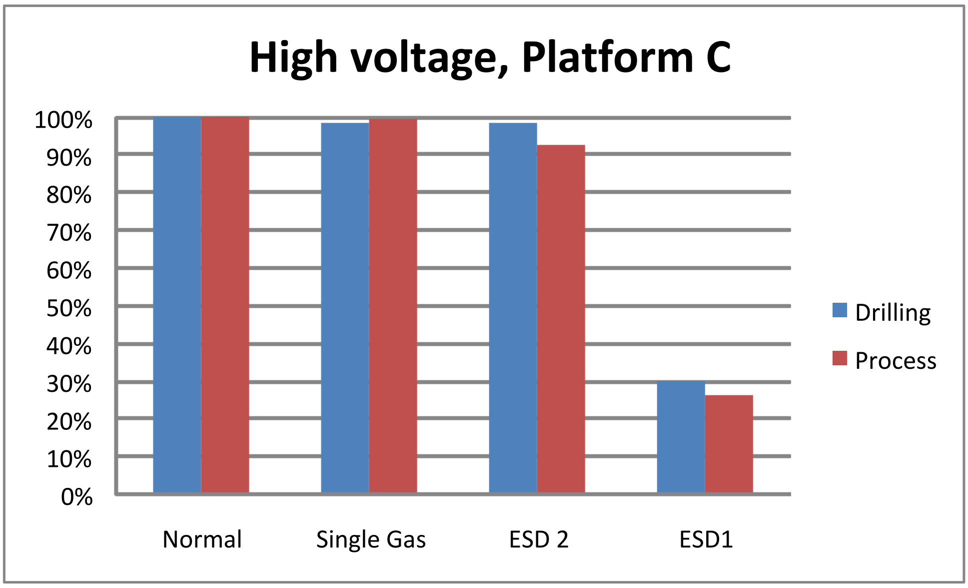


Figure A 8: Illustration of high voltage shutdown at Platform C

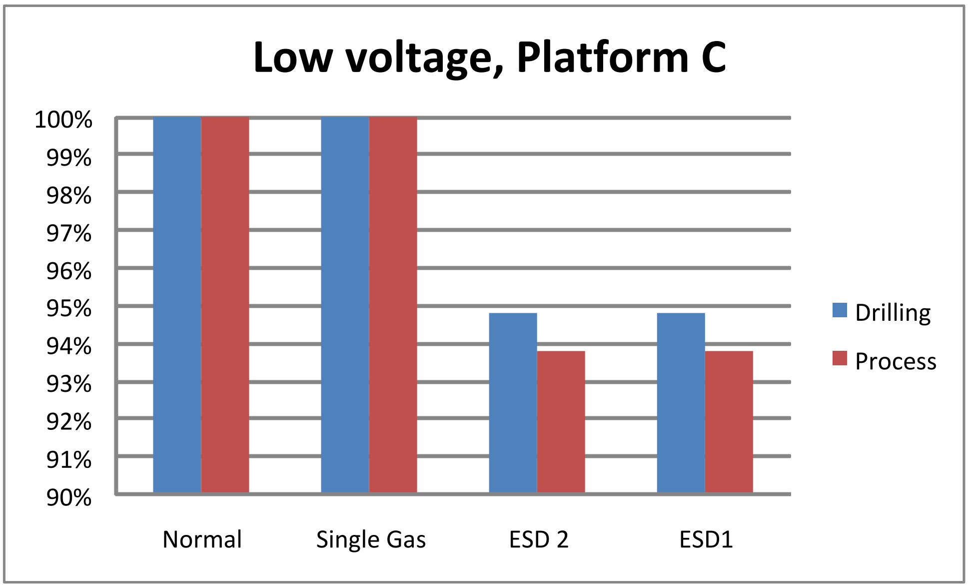


Figure A 9: Illustration of low voltage shutdown at Platform C

A6. RESULT SUMMARY

The overall ignition source shutdown for both high/low voltage and process/drilling is shown in Figure A 10. It shows that about 50-60 % of all ignition sources are shut down when there is only emergency power available. The high fraction of live shutdown sources is due to the high number of instruments on low voltage that is available until ESD 0.

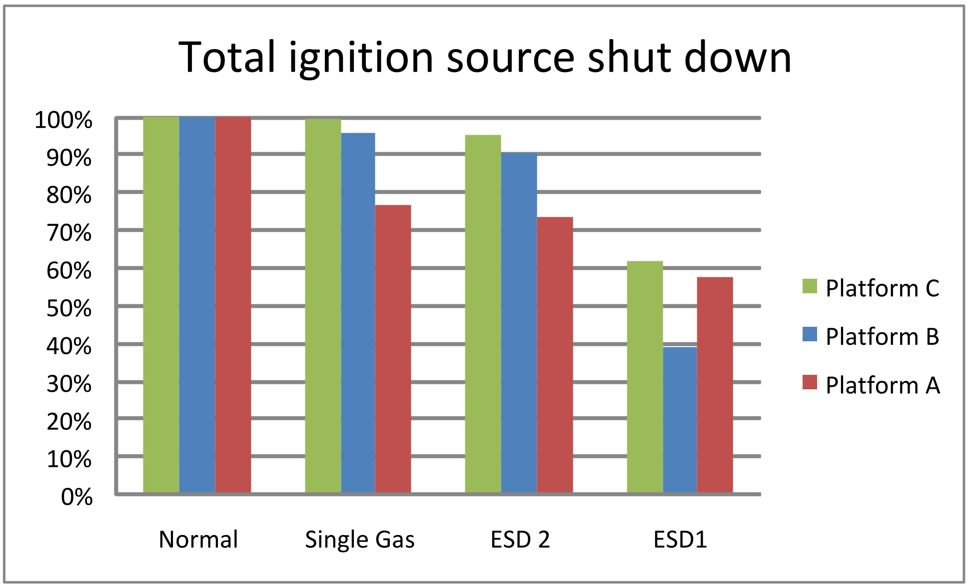


Figure A 10: Overall ignition source shutdown without scale factor for Platform A, Platform B and Platform C

shows the distribution of high voltage shutdown for the three installations. The major difference is that Platform A has a higher fraction of tripped equipment after single gas and ESD 2. That is due to the shutdown of heat trace at single gas.

The total results for low voltage is shown in Figure A 12 . The results shows that instruments are usually not tripped until ESD 0.

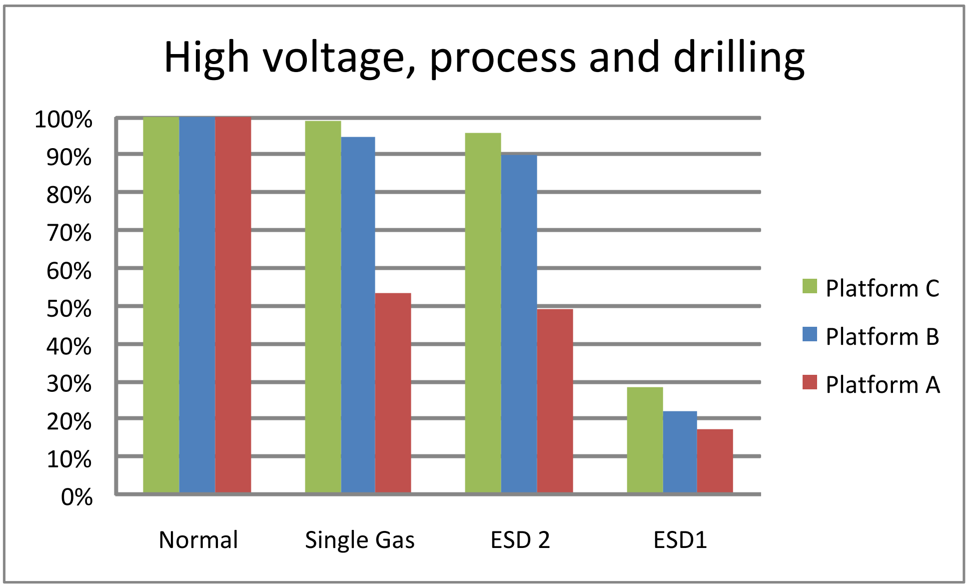


Figure A 11: Illustration of shutdown of high voltage ignition sources without scale factor for all three installations

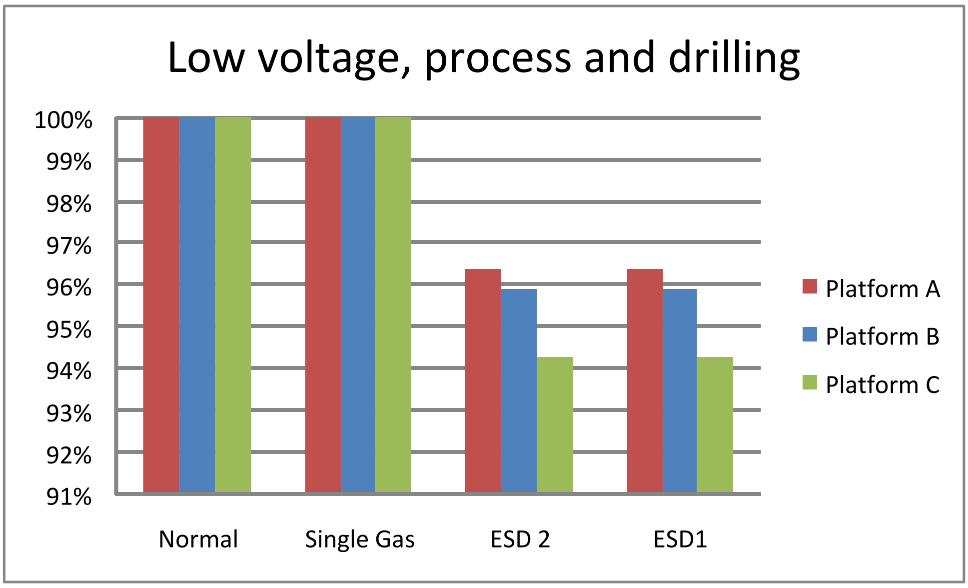


Figure A 12: Illustration of shutdown of low voltage ignition sources without scale factor for all three installations

Table A 11: Overall results for the three platforms. The results show the shutdown fraction with and without scale factor for each shutdown level.

	Without scale factor				With scale factor			
All platforms	Normal	Single gas	ESD 2	ESD 1	Normal	Single gas	ESD 2	ESD 1
Process	100%	88%	81%	46%	100%	91%	83%	40%
Drilling	100%	94%	93%	64%	100%	97%	96%	58%
Total	100%	91%	87%	54%	100%	94%	90%	49%

APPENDIX B

ELECTRICAL EQUIPMENT ON OFFSHORE FACILITIES: RESIDUAL RISK FOR IGNITION. CEXCON REPORT 10-F44162-RA-1 REV 01, OCTOBER 2010

APPENDIX B

BERGEN - 07.12.2010
Ref. No.: GexCon-10-F44162-RA-1
Rev.: 02

REPORT

Electrical equipment on offshore facilities: residual risk for ignition

Client
Scandpower AS

Author(s)
Kees van Wingerden

Document Info

Author(s)

Kees van Wingerden

Classification

Confidential (F)

Title

Electrical equipment on offshore facilities: residual risk for ignition

Extract

A need to upgrade the existing ignition models used in QRA studies for offshore facilities has been identified. In this connection GexCon was approached by Scandpower to address especially the residual risk for ignition due to electrical equipment present on offshore facilities. The residual risk is estimated both before and after isolation.

Project Info

Client

Scandpower AS

Clients ref.

Dr. Jan Pappas

GexCon Project No.

44162

GexCon Project Name

Ignition modelling

Revision

Rev.	Date	Author	Checked by	Approved by	Reason for revision
00	01.10.2010	Kees van Wingerden	Geir Pedersen	Brian Wilkins	First draft issued to client
01	17.10.2010	Kees van Wingerden	Geir Pedersen	Brian Wilkins	Revised report after including comments client
02	07.12.2010	Kees van Wingerden	Geir Pedersen	Brian Wilkins	Revised report after including additional comments client

Disclaimer

GexCon shall not be liable for damages, which the assignor, or assignor's clients, vendors, consultants or other third party, suffers when applying or using the results of GexCon's work, unless there is misconduct or gross negligence on the part of GexCon or on the part of the persons used by GexCon to carry out the work.

Table of Contents

1 Introduction

Norwegian regulations demand the performance of QRA based studies regarding the risks of explosions on offshore installations. In this connection also the risk of ignition needs to be addressed implying estimating the probability of ignition for each potential ignition source present in the area considered. Ignition models have been developed to take this into account. The models also consider ignition probability in dependency of actions taken upon a release such as de-activation of potential ignition sources after gas detection (implying varying probability in time), ignition source type (continuous or intermittent) and number of potential ignition sources engulfed by the released gas cloud.

A need to upgrade the existing ignition models has been identified and Scandpower was granted a project by Statoil to improve the ignition models considering electrical ignition sources only. GexCon was approached by Scandpower to address especially the residual risk for ignition due to electrical equipment present on offshore facilities. The residual risk is estimated both before and after isolation.

2 Types of protection used for electrical equipment on offshore facilities

As part of the project Scandpower performed a study aiming at determining among other things the methods of protection used for electrical equipment used on offshore facilities.

From the study it evolved that the following methods of protection are used offshore:
- Flame proof equipment (Ex d) [1],
- Equipment protected by “increased safety” (Ex e) [2],
- Equipment with type of protection “n” (Ex n) [3],
- Encapsulated equipment (Ex m) [4],
- Intrinsic safe equipment (Ex i; Ex ia and Ex ib) [5].

According to European standards these methods of protection are only allowed for use in areas classified as zones 1 and 2 (hazardous area classification). Exceptions are: equipment with type of protection “n” (Ex n) which is only allowed for use in zone 2, encapsulated equipment type Ex ma and intrinsic safe equipment protection type Ex ia which also are allowed for use in zone 0 (EN 60079-14).

Electric equipment on offshore facilities is mainly consisting of the following items:
- Motors (protected by Ex d or Ex n)
- Junction boxes (protected by Ex d or Ex e)
- Push buttons (protected by Ex m or Ex d)
- Lighting (protected by Ex d or Ex e)
- Heat tracing and heaters (protected by Ex d or Ex e)
- Socket outlets (protected by Ex d or Ex e)
- Solenoids (protected by Ex i)
- Instrumentation (protected by Ex i).

Of these electric equipment items motors have non-electric moving parts which due to friction or generation of mechanical sparks may lead to ignition of explosive atmospheres as well.

In the following chapter 3 the various types of protection have been described. Installation and maintenance procedures will affect the residual risk of equipment installed. These have been discussed/presented in chapter 4.

3 Description of protection principles used offshore

3.1 Flame proof enclosure (Ex-d)

For this type of protection all electrical parts of electric equipment which can ignite an explosive atmosphere are placed within an enclosure which can withstand the maximum pressures generated by an internal explosion and which has been constructed such that the flames of the internal explosion cannot transmit out of the enclosure igniting the explosive atmosphere surrounding the enclosure.
The maximum pressure inside the equipment depends, at least locally, on the possibility of pressure piling, total area of openings in the equipment and cooling due to flame contact with the inner walls of the equipment.
The size of joints (openings in the equipment allowing for ingress of flammable gas) is chosen on the basis of the Maximum Experimental Safe Gap (MESG) of the explosive gas.involved. The maximum gap width of joints is chosen with a considerable safety margin (maximum gap width < 0.5*MESG) [1].

3.2 Equipment protected by increased safety (Ex-e)

This type of protection refers to electric equipment in which measures have been applied so as to give increased security against the possibility of excessive temperatures and of the occurrence of arcs and sparks in normal service or under specified abnormal conditions. Increased safety concepts include [2]:

- No sparking contacts
- No semi-conductor devices (the failure mode is not possible to ascertain)
- No hot surfaces above temperature class
- Use of high integrity electrical connections
- Application of an increased creepage (distance over insulation surface) between live parts and to earth potential
- Application of an increased clearance distance (through air) between live parts and to earth potential (not applicable to the rotor of a rotating machine)
- Use of high quality insulation materials
- The ingress protection rating of the equipment is IP40 for equipment containing fully insulated live parts, or IP54 minimum for equipment containing non-insulated live parts

3.3 Equipment with type of protection (Ex-n)

Equipment provided with a type of protection such that in normal operation and in certain specified abnormal conditions it is not possible igniting a surrounding explosive atmosphere [3]. Several subtypes exist depending on the principle of protection:

- nA = non-sparking apparatus
- nC = sparking apparatus in which contacts are protected conveniently

- nL = energy-limited apparatus
- nR = purged/pressurized apparatus
- nZ = purged pressurized apparatus, n

3.4 Encapsulated equipment (Ex-m)

Equipment protected in a way whereby parts that are capable of igniting an explosive atmosphere by either sparking or heating are enclosed in a compound in such a way that the explosive atmosphere cannot be ignited under operating or installation conditions [4].
Two levels of protections are defined: ma and mb.
“m” apparatus of level of protection “ma” shall not be capable of causing ignition in each of the following circumstances:

a) in normal operation and installation conditions;
b) any specified abnormal conditions;
c) in defined failure conditions.

For level of protection “ma”, the working voltage at any point in the circuit shall not exceed 1 kV.

“m” apparatus of level of protection “mb” shall not be capable of causing ignition in each of the following circumstances:

a) in normal operation and installation conditions;
b) in defined failure conditions

3.5 Intrinsic safe equipment (Ex i)

Intrinsic safe equipment is protected in way to ensure that the available electrical and thermal energy in the system is always low enough that ignition of the explosive atmosphere cannot occur [5]. This is achieved by ensuring that only low voltages and currents enter the hazardous area, and that all electric supply and signal wires are protected by zener safety barriers. Sometimes an alternative type of barrier known as a galvanic isolation barrier may be used.
Two types of intrinsic safe equipment exist: types ”ia” and “ib”. Type “ia” guarantees no dangerous sparks or high temperatures occurring in components even when two independent faults occur in the electronic circuit simultaneously. Type “ib” guarantees safety when one fault occurs.

3.6 Maximum surface temperature

The various protection principles described above are for an important part addressing ignition by electric sparks and partly hot surfaces at components of electric equipment inside equipment enclosures. The surface temperature of the enclosure however may also represent an ignition source and shall not exceed the lowest ignition temperature of the explosive atmosphere.
To this end equipment is often classified in temperature classes as presented below.

Temperature class	Maximum surface temperature (ºC)
T1	450
T2	300
T3	200
T4	135
T5	100
T6	85

Alternatively one can restrict equipment for one gas only. The maximum surface temperature shall not exceed the autoignition temperature of this gas.

Temperature of small components inside enclosure which can come into contact with an explosive atmosphere may be higher. Limits have been indicated depending on the surface area of these components and the temperature class of the equipment itself (EN 60079-0 [6]).

3.7 Gas groups

For sparking equipment and equipment protected by Ex d not only the surface temperature is important but also the reactivity of the gas. For this purpose the reactivity of gases has been divided in three gas groups: groups IIA, IIB and IIC. The respective gases are subdivided in these three groups on the basis of the MESG and the minimum ignition current. The table below describes this subdivision. Natural gas and methane are in gas group IIA.

Gas group	Maximum experimental safe gap (mm)	Minimum ignition current ratio (-)*
IIA	> 0.9	> 0.8
IIB	0.5 – 0.9	0.45 – 0.8
IIC	< 0.5	< 0.45

* Relative to methane

4 Description of installation and maintenance requirements

4.1 Installation requirements

Demands need to be put to both installation and maintenance of electrical equipment approved for use in potentially explosive atmospheres. Poor installation and maintenance will affect the residual risk of electric equipment becoming an ignition source. Installation requirements have been described in EN 60079-14 [7]. Main points of attention regarding installation of electrical equipment in classified hazardous are summarised below. Maintenance aspects of electrical equipment approved for use in potentially explosive atmospheres have been presented in section 4.2.

- The equipment shall be chosen correctly regarding zone, gas group and temperature class.
- Installation of Ex-equipment shall occur in agreement with installation instructions given in the documentation accompanying the equipment.
- The equipment shall be installed in such a away that it is protected from any outer influences (impact, temperature, vibration etc.) that may influence its properties regarding protection against the equipment from becoming an effective ignition source.
- Special attention shall be given to equipment having light metal parts. An impact may lead to a mechanical spark able to ignite an explosive atmosphere.
- Attention shall be given to avoidance of contact with non-isolated “hot” parts of electric equipment
- Any grounding shall be effective avoiding stray electric currents. Potential differences shall be avoided.
- Measures shall be taken to avoid the accumulation of static electricity
- The effects of lightning and electromagnetic radiation shall be limited to an acceptable level
- Protection of electric equipment and cables against short-circuiting and grounding faults.
- Protection against overloading of electric motors and transformers
- Cables shall be installed such that impact, effects of chemical compounds, etc is not possible. If necessary cabling shall occur through special cable racks or ducts
- Ex-d equipment shall not be located close to other elements hindering flames from emerging from the equipment
- Cable connections shall be as required for the several types of protection
- Special requirements for equipment protected by increased safety (e) (regarding e.g the encapsulation, temperature measurements in the coils, cabling, monitoring of resistance based heating elements), for intrinsically safe equipment (i) (regarding e.g. cabling, termination and grounding of intrinsically safe circuits) and for equipment protected by type of protection (n) (e.g. encapsulation, cabling and termination).

4.2 Description of maintenance procedures

Maintenance procedures have been described in EN 60079-17 [8].
Main points of attention (no attempt is made to make this list to be complete) are summarised below:

- Inspection and maintenance of electric equipment for use in potentially explosive atmospheres shall only occur by qualified personnel
- Visual or detailed inspection shall be performed on a regular basis. What to be inspected and how is dependent on the type of protection of the electric equipment
- Personnel performing the inspections shall be adequately educated
- Electric equipment shall be kept clean avoiding accumulation of materials potentially causing unacceptable high temperature increases
- Weather protection shall be maintained, where necessary seals that are damaged need to be replaced
- When opening equipment this will be done in such away that hot surfaces or electric sparks able to ignite an explosive atmosphere do not arise or come into contact with these atmospheres
- It shall be assured that grounding and bonding of electric equipment is maintained
- The openings in Ex-d rated equipment shall be kept clean and provided with a layer of suitable grease to protect it from corrosion

5 Estimate of equipment reliability/residual risk for ignition

5.1 Under normal operation

In this chapter estimation of the residual risk of electrical equipment used in potentially explosive atmospheres becoming an ignition source is presented. The residual risk needs to be described for the whole life cycle of electrical equipment from concept to decommissioning or disposal.

There are several approaches possible to determine residual risk of electrical equipment used in potentially explosive atmospheres:

- Individual determination of residual risk for electrical equipment
- Use of accident statistics
- A generic approach

Each of these approaches has been presented below and discussed regarding the ability to determine the residual risk of electrical equipment becoming an ignition source and if so what this residual risk is.

5.1.1 Individual determination of residual risk for electrical equipment

The European Directive 94/9/EC (Annex II, article 1.0.2) [9] demands that companies introducing equipment for use in potentially explosive environments onto the European Union market shall determine the residual risk for this equipment becoming an ignition source. Industry should therefore be able to inform the user of the electric equipment put on the market (sold) after 1 July 2003 on the residual risk of this equipment becoming an ignition source. The influence of environmental factors and maintenance procedures (if they differ from the instructions given by the producer of the electric equipment) need to be taken into account as well. These residual risks could then be used directly.

For non-electrical equipment a standard has been developed to help industry determining this residual risk [10]. For electrical equipment such a standard does not exist.

Historically electrical equipment is constructed according to detailed descriptions given in standards. Safety devices such as

- Motor protection; especially for type ‘e’: thermal and current relays, PT100 sensors (platinum resistance thermometers), switches
- Overload monitoring devices for ‘e’ motors, which models the temperature-time characteristic
- Thermal protection devices and non-electronic control units for heating systems
- Overvoltage protection

assure a sufficiently low residual risk (without determining this residual risk). A lower residual risk is often assured by including multiple independent protection systems:

Equipment for use in potentially explosive atmospheres zone 0 (Category 1 equipment)

Equipment in this category must ensure the requisite level of protection, even in the event of rare incidents relating to equipment, and is characterized by means of protection such that: either, in the event of failure of one means of protection, at least an independent second means provides the requisite level of protection, or the requisite level of protection is assured in the event of two faults occurring independently of each other.

Equipment for use in potentially explosive atmospheres zone 1 (Category 2 equipment)

The means of protection relating to equipment in this category ensure the requisite level of protection, even in the event of frequently occurring disturbances or equipment faults which normally have to be taken into account.

Equipment for use in potentially explosive atmospheres zone 2 (Category 3 equipment)

Equipment in this category ensures the requisite level of protection during normal operation (no fault-tolerance requirement). There are no requirements for fail-safe fraction, diagnostics, diagnostic coverage or component/equipment failure rates.

In this light, manufacturers of electrical equipment in general do not determine the residual risk of the equipment they put onto the market becoming an ignition source as required by the directive 94/9/EC. It would therefore be necessary to determine the probability of each of these pieces of electrical equipment becoming an ignition individually. In general this implies the determination of the likelihood of safety functions in these various pieces of equipment failing.

To determine the probability of a certain piece of equipment becoming an ignition source a detailed analysis needs to be performed consisting of several steps similar to those described in EN 15198 [10] and EN 61508 [11];

1. functional analysis
2. failure rate prediction of components
3. failure modes, effects and criticality analysis
4. system safety assessment/quantification of probability of failure of overall system

The aim of the functional analysis is to understand and identify the safety functions of the equipment. The determination of the failure rate for the components relevant for the safety functions of the equipment allows for an analysis to identify “dangerous” failure modes, and to quantify the probability of failure occurrence.

The residual risk of ignition will vary from equipment item to equipment item and will especially depend on among other things the number of (safety) components in the electrical equipment, the reliability of each of them and their interrelationship.

The likelihood of ignition may potentially also vary from equipment item to equipment item after failure of the safety function depending on the properties of this equipment (although as described above interrelationships between safety components and other components of the electric equipment exist for at least a number of protection principles). The energy in a spark will depend on the capacitance or inductance of the electric circuit according to:

$E=1/2CU^2$ and $E=1/2LU^2$

Where the C = capacitance of the circuit (F)
U = voltage (V)
L = inductance (H)

Further resistance in the circuit may result in dissipation of energy in electric components reducing the incendivity of sparks. As a result the voltage alone is not the only parameter determining whether an ignition occurs. The resistance, capacitance and inductance of the electric circuits are also determinant. Once the minimum ignition requirements have been exceeded (voltage for given resistance, capacitance and inductance in the circuit) the ignition probability quickly becomes 100 % (both for low and high power electric circuits). Generally speaking, however, considering all equipment the likelihood of high voltage equipment becoming an ignition source after failure of the safety barrier is higher than for low voltage equipment suffering from a failure of the safety barrier.

The use of advanced tools to take into account time aspects, periodicities, etc. may be necessary. In addition to that maintenance procedures, the (potentially harsh) environment the equipment is located in (possibility of ingress of water (salt water), salt and other chemicals) and installation and repair procedures will have an impact on the probability of electrical equipment becoming an effective ignition source.

The task, determining the individual probability of each piece of electrical equipment in offshore modules becoming an ignition source may therefore be enormous. In [12] a total number of 1985 electrical pieces of equipment were identified for a single module on the Skarv FPSO.

In the light of the time/costs associated with performing such an analysis for each module on offshore facilities for which a QRA based study regarding the risks of explosions needs to be performed an approach as indicated is probably not feasible. Obviously simplifications may be possible by e.g. grouping of equipment (instrumentation, motors, etc), but the task is still considered to be very big.

Hence different approaches have been considered as well.

5.1.2 Use of accident statistics

Statistics can be consulted to determine the residual risk of electric equipment approved for use in potentially explosive atmospheres becoming an effective ignition source. According to [13] there are no records revealing statistics how often electrical equipment approved for use in potentially explosive atmospheres have been an ignition source for accidental explosions.
The Health and Safety Laboratory published a report in 2005 [14] presenting statistics gathering information on releases and ignition thereof on offshore platforms in the UK sector in the period 1992-2004. The results are given in the Table below for the different classified areas: zone 1, 2 and non-classified.

The table shows that there are tendencies that the probability of ignition in classified areas is lower than in the unclassified areas but the differences seem rather small. One would expect bigger relative differences between the different classified areas (this may be due to e.g. use of zone 1 equipment in zone 2 but there is no information available to confirm this) and perhaps lower probabilities than seen, especially for areas classified as zone 1. The report unfortunately does not give any information regarding the ignition sources themselves, and therefore any conclusions regarding the use of Ex-rated electrical equipment in each of the classified areas and their relative ignition probabilities (which would imply the need of more information such as the number of electrical equipment items on UK offshore facilities) are not possible to draw.

Nevertheless if this information would be available an estimate of probability of ignition by electrical equipment on offshore facilities would be possible.

Table 1 Events in the UK offshore industry in period 1992-2004 categorized by release type and area classification for all release sizes (from [14]).

Area classification	Fluid type	Total releases	No. ignited	%	Approximate probability
Zone 1	Oil	128	0	-	-
	Gas	355	9	2.5	1 in 39
	2-phase	60	0	-	-
	Condensate	48	2	4.2	1 in 24
	Non-process	36	9	25	1 in 4
Zone 1 total		**627**	**20**	**3.2**	**1 in 31**
Zone 2	Oil	385	11	2.9	1 in 35
	Gas	1130	35	3.1	1 in 32
	2-phase	160	0	-	-
	Condensate	157	8	5.1	1 in 20
	Non-process	223	69	30.9	1 in 3
Zone 2 total		**2055**	**123**	**6.0**	**1 in 17**
Unclassified	Oil	13	0	-	-
	Gas	41	2	4.9	1 in 21
	2-phase	6	0	-	-
	Condensate	1	1	100	1
	Non-process	71	18	25.3	1 in 4
Unclassified total		**132**	**21**	**15.9**	**1 in 6**
Total		**2814**	**164**	**5.8**	**1 in 17**

5.1.3 Generic approach

The EU sponsored project SAFEC [13] was concerned with the specification of the reliability, fault tolerances and integrity requirements related to safety devices in electrical devices in terms of a probability on demand and/or failure frequency. For equipment to be used in potentially explosive atmospheres the required probability of failure on demand (PFD) and failure frequency was presented to be as follows:

Zone	Equipment category	Target SIL	PFD	Failure frequency
0	1	SIL 3	$\geq 10^{-4}$ - $\leq 10^{-3}$	$\geq 10^{-8}$ - $\leq 10^{-7}$ (hr^{-1})
1	2	SIL 2	$\geq 10^{-3}$ - $\leq 10^{-2}$	$\geq 10^{-7}$ - $\leq 10^{-6}$ (hr^{-1})
2	3	SIL 1	$\geq 10^{-2}$ - $\leq 10^{-1}$	$\geq 10^{-6}$ - $\leq 10^{-5}$ (hr^{-1})

As a starting point for residual risks of electric equipment to be used in potentially explosive atmospheres becoming an ignition source the indicated failure frequencies could be used. One approach would be to use the upper bound of the failure frequency for the different equipment categories as a starting point for each electrical device used on offshore platforms bearing in mind a harsh environment (e.g. when there is a possibility of ingress of seawater such as on the deck of an FPSO). Lower failure frequencies may be chosen in case of encapsulation, if the location is such that the possibilities of ingress of seawater and other polluting materials are low and in case of regular maintenance operations on electric equipment (a proposed 3.3 times the lower bound of the failure frequency range).
Pure sparking electric equipment of protection type Ex-d (flameproof equipment) can be considered to have a failure frequency equal to the lower bound of the failure frequency range (i.e. 10^{-7} (hr^{-1}) since the equipment is designed with big safety margins (considering MESG). Moreover recent research showed that only in case of very severe damages to the encapsulation of Ex-d rated equipment or due to extraordinary corrosion the equipment would loose its ignition preventive capabilities [15]. Ex-d rated equipment with potentially hot surfaces has higher failure frequencies. Assuming a high maintenance standard the proposed failure frequency can be assumed (it is further pointed out that according to API RP 500 [16] Ex-d rated equipment is allowed for use in Class I, Division 1 which is equivalent to zone 0 using the EN 60079-10-1 [17] hazardous area classification scheme).

For other protection principles (not discussed here and not often used for protection of electrical equipment offshore a similar approach applies): e.g. use of protection by overpressure (Ex-p accepted for zone 1 implies a failure rate of 3.3 10^{-7} hr^{-1} for no harsh environmental conditions with good maintenance procedures in place).

As reported the suggested failure frequencies are not supported by statements regarding failure frequencies by manufacturers of Ex-rated electrical equipment. The German institute PTB performs occasionally tests for intrinsically safe equipment (type “ia”) to verify the failure frequency being such that a PFD of $\geq 10^{-4}$ - $\leq 10^{-3}$ is satisfied (in accordance with the suggestions made above). In [13] the suggested failure frequencies have been verified and confirmed for a limited number of electrical devices approved for use in potentially explosive atmospheres.

As a result the following failure frequencies are suggested for the different types of protection of electric equipment used in potentially explosive atmospheres (assuming the equipment is well-designed and installed (see Table 2)).

Table 2 Estimated failure frequency (hr^{-1}) for electric equipment resulting in a sufficiently strong ignition source (per equipment item)

Type of protection	Harsh environment/ frequency maintenance operations low	No harsh environment/ frequency maintenance operations high	Failure frequency (hr^{-1})
Encapsulated equipment (Ex ma)	X		10^{-7}
		X	$3.3.10^{-8}$
Intrinsic safe equipment (Ex ia)	X		10^{-7}
		X	$3.3.10^{-8}$
Flame proof (Ex d) (only sparking)	X		10^{-7}
		X	10^{-7}
Flame proof (Ex d) (hot surfaces and sparking)	X		10^{-6}
		X	$3.3.10^{-7}$
Increased safety (Ex e)	X		10^{-6}
		X	$3.3.10^{-7}$
Encapsulated equipment (Ex mb)	X		10^{-6}
		X	$3.3.10^{-7}$
Intrinsic safe equipment (Ex ib)	X		10^{-6}
		X	$3.3.10^{-7}$
Type of protection "n" (Ex n)	X		10^{-5}
		X	$3.3.10^{-6}$

The likelihood of having an effective ignition source in a volume (f_i) depends on the respective number of pieces of equipment of each protection type (n) within that volume and their respective individual failure frequencies f:

$f_i=n_{ma}*f_{ma} + n_{ia}*f_{ia} + n_d*f_d + n_e*f_e + n_{mb}*f_{mb} + n_{ib}*f_{ib} + n_n*f_n$

If it would be possible to obtain more information from the that happened in the UK sector as described in section 5.1.2 a "calibration" or confirmation of the suggested failure frequencies would be possible.

5.1.4 Ignition source characterization

An aspect important regarding ignition probability modeling is the character of the ignition source.

Ignition sources can be characterized to be a spark of a hot surface. A spark can be continuous (arc), intermittent or a single event upon opening or breaking a contact (switch). After isolation a spark is normally vanished shortly after (unless an RL- or RC-circuit with a long discharge time (time constant) exists). A hot surface may prevail considerably longer after isolation.

In Table 4 an attempt has been made for these characterizations for each of the protection principles used offshore.

With regard to the table the following has been considered:

For a spark to be continuous, i.e. to be an arc is dependent on several factors: a minimum combination of voltage and current, which again depends on the gap between the electrodes and the material of the electrodes. Also the characteristics of the electric circuit from which the arc arises play a role. Babrauskas [18] gives the following example table for the minimum voltage and current needed in resistive circuits to sustain an electric arc in air:

Table 3 Minimum voltage and current needed in resistive circuits to sustain an electric arc in air [18]

Electrode material	Min voltage (V)	Minimum current (A)
aluminium	12	0.4
brass	11	NA
cadmium	8.5	0.03
carbon	20	0.01
copper	13	0.45
gold	9.5 - 15	0.38
iron	12 - 14	0.72
iron oxide	14	0.70
lead	9 - 11	0.21
nickel	8 - 14	0.5
palladium	15	0.5
platinum	13.5 – 17.5	0.9
silver	8 - 15	0.4
steel, carbon	14	NA
steel, stainless	15	0.5
tin	11.2	0.4
tungsten	10 – 16.1	1.0
zinc	9	0.03

If conditions for an arc are met, the arc still does not necessarily last forever. In AC-circuits, current goes to zero twice each cycle and the arc may fail to get re-established once current flow restarts (this is especially the case for voltage lower than 150 V). For AC-voltages between 150 V and 600 V arcs tend to not be extinguished. On the other hand the electrodes may get eroded causing the arc to be extinguished. The duration of the arc then depends on electrode material, voltage and current combination and original gap width. Alternatively an arc may cause the insulation material to catch fire resulting in a continuous ignition source still.

This indicates that intermittent sparks are very unlikely. Either the spark is a single event (or short duration event upon contact or breakage) or it is continuous.

The ignition temperature of a hydrocarbon gas is not a material constant but depends on several factors:

- Fuel concentration
- Contact time between ignition source and explosive atmosphere
- Quiescent or turbulent gas
- Geometry and material properties of surface

Figure 1 shows that for small hot surfaces (< 3 cm^2) temperatures have to exceed 1100 ºC to be able to ignite mixtures of methane and air.

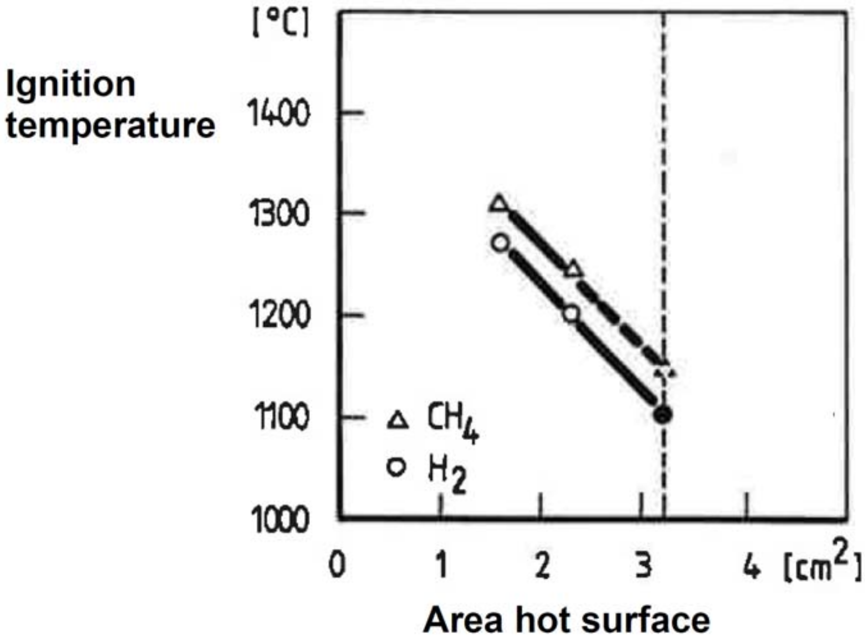


Figure 1 Ignition temperature of methane- and hydrogen-air mixtures depending on the surface area of the hot surface [19].

In case of flowing gases or just due to buoyancy because of the higher temperature the heated gas mixture attains the temperature needed to ignite a gas-air mixture in reality is considerably higher than published auto-ignition temperatures determined in laboratory equipment. According to the API 2216 [20] ignition of hydrocarbons by a hot surface should not be assumed unless the surface temperature is approximately 360ºF (182 ºC) above the accepted minimum ignition temperature of the hydrocarbon involved.

This implies that ignition of natural gas-air mixtures at hot surfaces is only possible if temperatures exceed the auto-ignition temperature of natural gas considerably.

Table 4 Ignition source characterisation

Type	Typical protection measure	Ignition mechanism	Failure type	Ignition type
Motor	Ex d	Spark, hot surface	Fire or flame, sparking, overheating	Continuous
	Ex n			
Junction box/sockets	Ex de	Hot surface	Creep currents	Continuous
Push button	Ex md	Spark	Spark on make/break	Single event
Lighting	Ex de	Hot surface, spark depending on type of lighting	High temperature or discharge	Continuous
Heat tracing/ heaters	Ex de	Hot surface, sparks	Sparking, fire, hot surface, emission of hot particles	Continuous
Solenoids	Ex ia	Spark, hot surface	Short circuit	Continuous
Instrumentation	Ex ia	Spark, hot surface	Mainly spark, but in case of high currents hot surfaces are also possible	Continuous

5.2 Isolation of electric equipment

The residual risk of electric equipment after isolation will either become negligible (for purely sparking equipment) or gradually decrease in time (for equipment containing hot surfaces). The decrease in time is dependent on the initial temperature of the hot surface, the size of the hot components and the heat transfer to the environment.

6 Conclusion

In spite of the fact that the ATEX directive 94/9/EC demands manufacturers of electrical equipment for use in potentially explosive atmospheres to determine the residual risk of this equipment becoming an effective ignition source, such information is not available. The complexity of the equipment itself and sometimes the safety functions in the equipment make it an enormous task to determine the residual risk of electrical devices becoming an ignition source on offshore facilities.

Data available on accidents involving releases and subsequent ignition in the UK offshore sector are not sufficiently detailed to allow for determining the residual risk of ignition at electrical equipment on offshore platforms either.

Based on work performed as part of an EU sponsored project required failure frequencies of electrical equipment for use on potentially explosive atmospheres depending on the hazardous area classification of the explosive atmosphere (or equipment category) were defined (see Table below).

Zone	Equipment category	PFD	Failure frequency
0	1	$\geq 10^{-4}$ - $\leq 10^{-3}$	$\geq 10^{-8}$ - $\leq 10^{-7}$ (hr^{-1})
1	2	$\geq 10^{-3}$ - $\leq 10^{-2}$	$\geq 10^{-7}$ - $\leq 10^{-6}$ (hr^{-1})
2	3	$\geq 10^{-2}$ - $\leq 10^{-1}$	$\geq 10^{-6}$ - $\leq 10^{-5}$ (hr^{-1})

These requirements have been used as a generic approach to estimate residual risks of ignition by electrical equipment depending on the type of protection used the potential failure mode (sparks only or hot surfaces possible) and the environment in which the electrical devices are installed.

Ignition sources are either continuous or a single event. Intermittent ignition sources are not likely to occur.

7 References

[1] EN 60079-1, *Explosive atmospheres. Equipment protection by flameproof enclosures "d"*, European standard, 2007

[2] EN 60079-7, *Explosive atmospheres. Equipment protection by increased safety "e"*, European standard, 2007

[3] EN 60079-15, *Electrical apparatus for explosive gas atmospheres. Type of protection "n"*, European standard, 2003

[4] EN 60079-18, *Explosive atmospheres. Equipment protection by encapsulation "m"*, European standard, 2009

[5] EN 60079-11, *Explosive atmospheres. Equipment protection by intrinsic safety "i"*, European standard, 2007

[6] EN 60079-0, *Electrical apparatus for explosive gas atmospheres. General requirements*, 2006

[7] EN 60079-14, *Explosive atmospheres. Electrical installations design, selection and erection*, European standard, 2008

[8] EN 60079-17, *Explosive atmospheres. Electrical installations inspection and maintenance*, European standard, 2007

[9] Directive 94/9/EC of the European Parliament and the Council of 23 March 1994 *on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres* (OJ L 100, 19.4.1994)

[10] EN 15198, *Methodology for the ignition hazard assessment of non-electrical equipment and components for intended use in potentially explosive atmospheres*, European standard, 2007

[11] EN 61508 (parts 1-7), *Functional safety of electrical/electronic/programmable electronic safety-related systems*

[12] Kvalø, T., *Reliability of ignition source isolation*, project report Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), December 2009

[13] Wilday A. J., Wray A. M., Eickhoff F., Unruh M., Fae E., Halama S., Conde Lazaro E. and Reina Perbal P., *Determination of Safety Categories of Electrical Devices used in Potentially Explosive Atmospheres (SAFEC)* Contract SMT4-CT98-2255 Final Report HSL/2000/01, 2001'

[14] Thyer, A.M., *Offshore ignition probability arguments*, Health and Safety Laboratory Report Number HSL/2005/50, 2005

[15] Grov, A., Opsvik, H.E.Z. and Eckhoff, R.K. *Effects of significant damage of flame gap surfaces in flameproof electrical apparatus on flame gap efficiency*, 8th ISHPMIE, September 5-10, 2010, Yokohama, Japan

[16] American Petroleum Institute RP 500, *Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Division 1 and Division 2*, 2002

[17] EN 60079-10-1, *Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres,* European standard, 2008

[18] Babrauskas, V., *Ignition handbook*, Fire Science Publishers, 2003

[19] Bartknecht, W., *Explosionsschutz*, Springer-Verlag, Heidelberg, 1993

[20] API Recommended practice 2216; *Ignition Risk of Hydrocarbon Liquids and Vapors by Hot Surfaces in the Open Air,* American Petroleum Institute, 2003

Appendix C

Ignition model for gas turbines and diesel engines

Table of contents

Page

1 Introduction

Air intakes to combustion engines, i.e. gas turbines and diesel engines, are regarded as potential ignition sources if exposed to flammable gas. In the previous revision of the offshore ignition model, Ref. /1/, a very coarse assessment was provided for turbine air inlets and no special ignition probabilities were given for diesel air intakes. The current offshore ignition model provides a more detailed ignition probability model for these potential ignition sources.

Note that the presented model gas turbine air intakes should be updated when Phase 1 of the JIP project investigating ignition control of gas turbine air intakes has been executed (Ref. /4/).

2 Ignition probability model for gas turbine air intakes

2.1 Basis for the current model

The current model is based on the following work:

- “Gas turbine ignition control – Phase 0”, Joint Industry Project, Partners: ConocoPhillips Skandinavia AS, Maersk Olie & Gas A/S, Statoil ASA and Lloyd’s Register. Report No. 104998/R1, Rev. Final, Date: 22 June 2016. Report only distributed on client’s acceptance (Ref. /4/).
- "Ignition probability of a flammable mixture exposed to a gas turbine", NTNU project report and Master Thesis by A. Pedersen 2005, Ref. /2/
- "Ignition probability of a gas turbine", GexCon Technical Note 40489-7, 5.10.2012 by Kees van Wingerden, Ref. /3/.

Ref. /2/ was also used as part of the basis for the previous offshore ignition model for turbine air inlets together with an internal simplified Statoil model, Ref. /1/. The two models predicted rather opposite ignition probability models for the phase after turbine shutdown, and the resulting turbine ignition model was basically chosen as the average of the two models.

2.2 Ignition mechanism for turbine air inlets

2.2.1 Description of a gas turbine

A gas turbine consists of 3 main components:

- Inlet compressor
- Combustion chambers
- High and low pressure power turbine.

A typical gas turbine, like LM 2500, is shown in Figure 2.1. This is used as basis for the analysis and is considered as being conservative with respect to larger turbines as further discussed in Section 2.2.3.

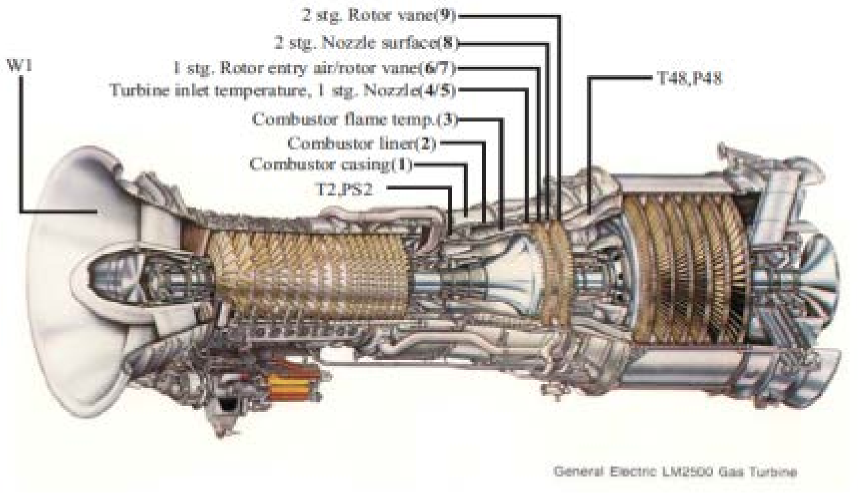
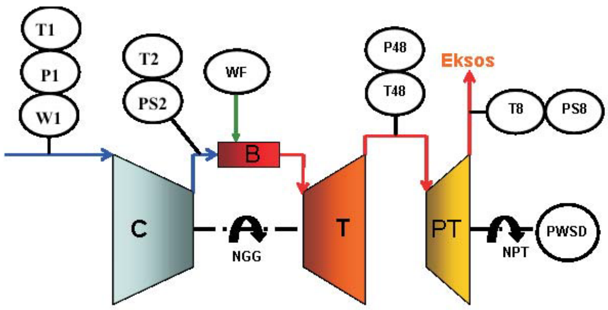


Figure 2.1 - LM 2500 gas turbine

When running, air moves from the external inlet through the inlet duct to the compressor air inlet. The flow speed through the compressor is constant and about 160 m/s while being compressed from 1 bara to about 16 to 18 bara at the combustion chamber inlet as shown in Figure 2.2.



PWSD (kW)	PS2 (bara)	P48 (bara)	T2 (°C)	T48 (°C)	T8 (°C)	W2 (kg/s)	WF (kg/s)	NGG (rpm)
23292	18.19	4.149	450.3	813.0	524.1	68.20	1.403	9424
22000	17.64	4.036	436.8	785.9	506.6	67.13	1.327	9221
20000	16.73	3.848	420.3	751.5	486.6	64.93	1.218	9030
18000	15.78	3.655	407.2	724.6	474.1	62.26	1.119	8912
16000	14.80	3.453	394.9	699.7	646.3	59.26	1.023	8791
14000	13.77	3.243	381.5	674.7	455.3	56.00	0.927	8662
12000	12.71	3.024	367.0	648.6	446.6	52.52	0.831	8515
10000	11.61	2.799	351.3	619.9	437.5	48.84	0.734	8361
6000	9.220	2.312	313.9	556.4	421.7	40.46	0.537	8024
2000	6.461	1.739	266.0	487.0	426.6	29.86	0.341	7561
500	5.275	1.467	240.7	439.5	418.4	25.27	0.259	7307

Figure 2.2 - Performance of LM 2500 at different loads from Ref. /2/

The combustion chamber is shown in Figure 2.3. The fuel is injected into the inner chamber where the flame is confined by the liner. A set of holes in the liner allows part of the inlet air to flow along the inner surface of the liner to avoid interference between the flame and liner walls. The flame has a temperature of 1500 - 2000°C depending on the combustor being a low-NO_x (DLE) or standard (SAC). The liner temperature is about 1000°C while the casing has a temperature of about 600 - 650°C.

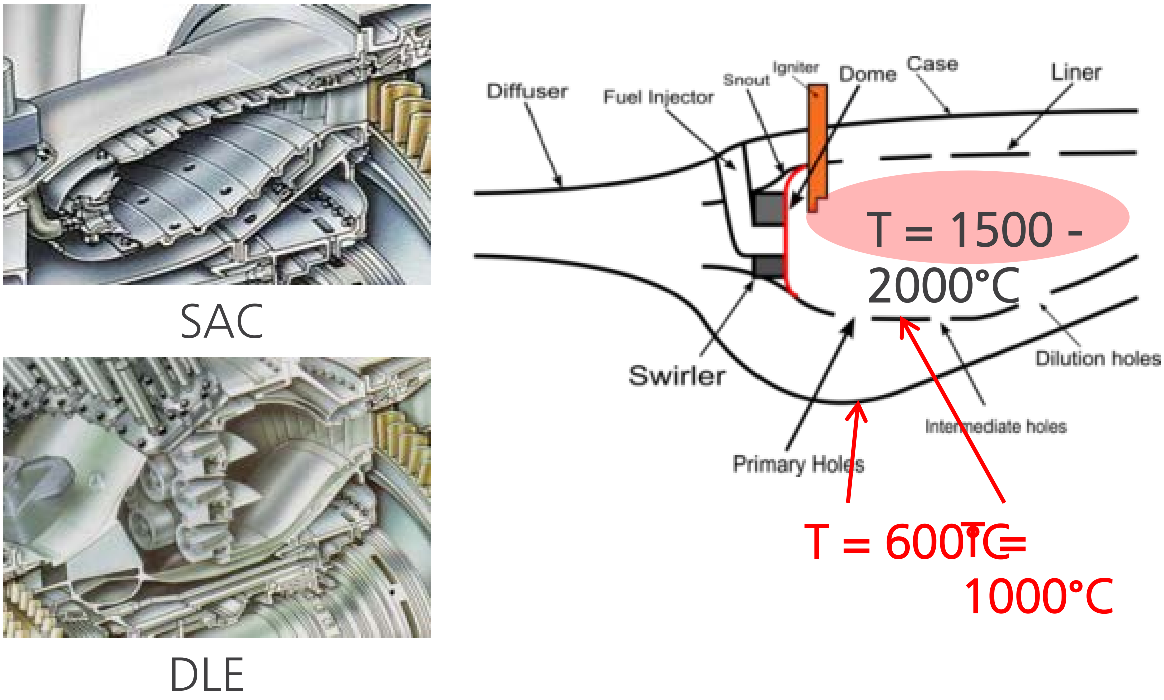


Figure 2.3 - Combustion chamber for LM2500 with inner liner and outer casing, general principles

In case gas exposes the external air inlet, the gas-air mixture will be drawn into the inlet duct, transported to the compressor air inlet, through the compressor and into to combustor where it may be ignited by the high temperatures. The potential mechanism igniting the external gas outside of the compressor is depending on the operational condition of the compressor at the time gas reaches the combustion chamber, the gas concentration at the air inlet as well as the rate of increase of the gas concentration.

The air to the gas turbine is supplied through an air inlet system comprising filters, dampers etc. as illustrated in Figure 3.4. The gas detection is in the inlet to this system, so there is a transport time for the air from the system inlet to the compressor air intake.

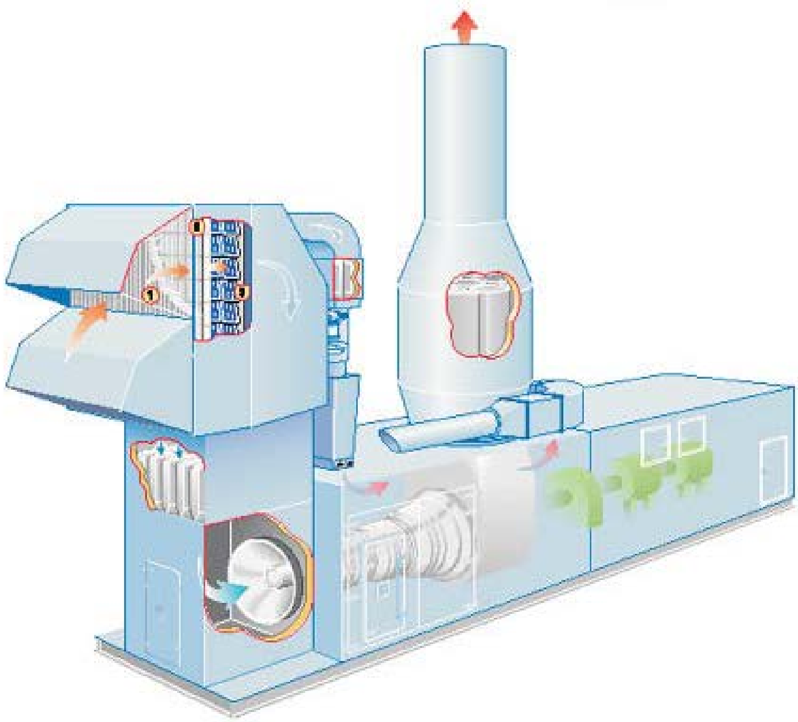


Figure 2.4 - Typical gas turbine air inlet system

2.2.2 Turbine exposed to explosive gas while running (prior to shutdown)

Gas in the combustion air will contribute to the combustion in the combustor thereby increasing the combustion rate and heat output. This will occur even if the gas concentration in the combustion air is well below LEL. As an example, assuming the fuel gas concentration in the combustor to be 10%, an air flow with 1% of gas (roughly corresponding to 20% LEL for methane) would result in 10.9% in the combustor, alternatively with 5% in the air, the combustor concentration would be 14.5%, close to UEL.

To analyse the potential for ignition of gas outside of the compressor air inlet the following problems needs to be addressed:

- In case of flammable gas concentration in the turbine inlet will flame in the combustor be able to backfire through the compressor and emerge from the air inlet
- Can the gas in the combustion air influence the combustion in the combustor and the turbine response such that ignition of external gas is possible.

2.2.2.1 Flame propagating upstream the compressor flow and backfiring through the compressor igniting gas at compressor inlet

If the gas concentration in the air inlet is flammable, the question is whether the flame in the combustor will be able to backfire against the inlet flow.

In order for the flame to propagate out of the combustor and upstream the compressor, the flame needs to have a speed exceeding the compressor flow of about 160 m/s. Ref. /3/ has analysed this situation, but based on the assumption that the air flow speed is reduced from 160 m/s at the inlet to about 40 m/s at the combustor inlet, which is not the case, and a combustor pressure of about 4 bar which, however, is more relevant for the pressure at the exit of the high pressure turbine than the pressure at the combustor inlet which according to Figure 2.2 is of about 16 – 18 bara. Modifying the analysis in Ref. /3/ assuming a flow velocity of 160 m/s at the combustor inlet and a combustor pressure of 18 bara, the following conclusions can be drawn:

- The maximum acceleration of a flame due to turbulence is by a factor of about 20 which occurs when the turbulence intensity/laminar burning velocity = 20. Increasing the turbulence intensity decreases the turbulent flame speed until the flame is quenched at a turbulence intensity ration of about 50

- The turbulence intensity in a fully developed pipe flow is of the order 5 -20 % of the main flow velocity. Considering that the flow has passed over airfoil blades in typically 15 compressor steps, assumed turbulence intensity would likely be in the upper range, say 10-15 % of the main flow, corresponding to 16 - 24 m/s. With a burning velocity of 0.4 m/s the turbulence intensity/burning velocity would be of the order 16-24/0.4 = 40 - 60 which would result in very low turbulent burning velocities or even flame extinction due to quenching. This factor alone suggests that flashback is not likely to occur
- However, if it should be possible to obtain a flame acceleration factor of 20 the laminar burning velocity multiplied by the expansion factor has to exceed 160/20 = 8 m/s for flashback to occur. The flame acceleration factor of 20 occurs for a turbulent intensity of 20 x burning velocity of 0.4 m/s = 8 m/s. This would correspond to a main flow velocity of about 8/0.15 = 55 m/s, much lower than the real flow velocity of 160 m/s. This means that the flame acceleration by a factor of 20 will not occur
- Assuming nevertheless that the maximum flame acceleration by a factor 20 occurs, the expansion factor of the flame will have to exceed 8/0.4 = 20. The expansion factor is the volume of combustion products at ambient pressure/volume of combustible gas. The expansion factor is about 8 times the pressure in the combustor, i.e. 8 x 4 = 32 for 4 barg and 8 x 18 = 144 for 18 barg. However, only a fraction of the expansion will contribute to an upstream velocity, most will expand downstream and out of the combustor in direction of the turbine where the resistance to flow is lower. It is difficult to estimate the part contributing to counterstream velocity, but Ref. /3/ assumes this to be 25 %. On this basis the expansion factor for 18 barg pressure is 0.25 x 144 = 36. This exceeds the factor of 20 needed. Hence, if an acceleration factor of 20 had been possible, flashback would be possible for those concentrations where the burning velocity is above 0.4 m/s x 20/36 = 0.22 m/s. This would be the case for gas in the range of 7.5 % to 12
- The conclusion based on performing this reanalysis of Ref. /3/ with more realistic assumptions is that flashback is not likely to occur because the high air flow velocity prevents sufficiently high flame acceleration for flashback to be possible. In fact, any counterflow propagating flame will most likely be extinguished due to the very high turbulence intensity in the flow exceeding the quenching conditions for turbulent combustion.

2.2.2.2 Behaviour of a running turbine on gas in combustion air

The response of a running turbine to gas in the combustion air is primarily determined by the rate of increase of the gas concentration – whether this increases slower or faster than the turbine control system is able to compensate for.

a. Slow rate of increase of gas concentration

As more fuel is added to the combustion the power output increases and thereby the acceleration (torque) of the rotor. This will be sensed by the control system and compensated by a reduction in the fuel supply rate. The regulation will be fast, as it is regulated by the acceleration (torque) and not the rotational speed and is thus not delayed by the inertia of the rotor. The response time of the regulation system is typically < 1 sec.

So for this scenario the turbine will most likely operate as normal only with less fuel consumption. It may be questioned if there is an upper limit for the concentration in the inlet air for which the turbine control system is able regulate by reducing the fuel supply. It is assumed that the lower fuel rate limit for control system is close to zero fuel and that the turbine will shut down when this limit is reached. Hence we assume for simplicity that control system can handle gas concentrations close to stoichiometric in the air inlet.

As long as the control system regulates the fuel supply there will be no excess fuel in the combustion chamber, and the total combustion rate will not exceed the design rate irrespectively of the combustion being confined to the combustion chamber or partially occurs in the upstream region close to the combustion chamber inlet. Hence the compressor will not likely surge, and as flames upstream of the combustor will not be able to flashback through the compressor, external ignition is not likely.

A small ignition probability of 5% is nevertheless set to account for unexpected events, e.g. acoustic instabilities that may lead to backfire.

b. Fast rate of increase of gas concentration

In this scenario the control mechanism will not able to compensate for the extra amount of ingested fuel. The higher than design fuel rate will lead to a pressure increase in the combustor that likely will lead to a surge of the compressor with potential for flames emerging from the air inlet.

There is also a probability of heterogeneous ignition (e.g. blade rubbing) in the compressor. Combustion in the last stages of the compressor (or at the compressor discharge) due to a sudden ingestion of a significant concentration of fuel will generate an increase in pressure that will likely lead to stall and surge of the compressor. The reverse flow associated with the surge will cause a temporary extinction of the flame. After surge re-ignition of the gas from contact with hot surfaces can occur. The stall or surge will not lead to catastrophic failures of the compressor (at worst blades may be liberated in the last stages of the compressor), but flames may emerge from the compressor inlet.

It is difficult to estimate the maximum rate of change of concentration the control system is able to compensate for. A conservative approach would be to select a low value of dC/dt. A rough estimate can be based on the following:

- Experience from tests where 5 % LEL ingested into turbine air intake did not lead to any maloperation or ignition
- The response time of the control system is < 1 sec, assumed to typically be 0.1 sec.

A conservative estimate for the critical dC/dt would then be 5 %LEL/0.1sec = 50 % LEL/sec. This is likely on the conservative side as the control system may be able to handle larger increases than 5 % LEL and the response time is likely below 0.1 sec.

There is very limited historical experience from accidents to support the probability values. The only case where it is documented that that the gas ignited before the turbine shut down is the Centrica B explosion as discussed in the main report. However, we do not know, dC/dt in the incident and furthermore not how many leak scenarios that have exposed turbine air intakes without being ignited except that they are likely to be few,, but an assumed ignition probability of 0.25, i.e. 1 out of 4 exposures, is at least not contradicted by the historical evidence. There was an incident at NCS in 2015 where gas concentration less than LFL probably was ingested by a gas turbine, but did not cause any damage to the machinery. However, the incident has not been investigated in detail and is not used to support the model development.

2.2.3 Turbine exposed to gas after shutdown

On gas detection in the external air inlet to the duct the turbine is shut down by shutting off the fuel supply. Thereby the flame in the combustor extinguishes and the only potential ignition source for flammable gas in the air flow is the remaining hot surfaces of which the liner has the highest temperature.

The temperature of a hot surface sufficient to ignite a gas flowing over the surface is dependent on both the flow velocity and surface area:

- the larger the surface area the lower is the necessary ignition temperature
- the lower the flow velocity, the lower is the necessary ignition temperature.

The potential for hot surfaces to ignite flammable gas is a balance between two opposing effects:

- As the turbine runs down, the airflow velocity is reduced due to the reduced rotation speed as shown in Figure 3.5. This reduces the necessary surface temperature to ignite the gas.
- As the turbine runs down, the liner is cooled by the airflow, the cooling effect being strongest in the initial phase of the rundown where the flow velocities are still high, as shown in Figure 3.6. The cooling time in the figure is indicative. Probably, the cooling time is shorter for most components, but this has to be verified by vendor data.

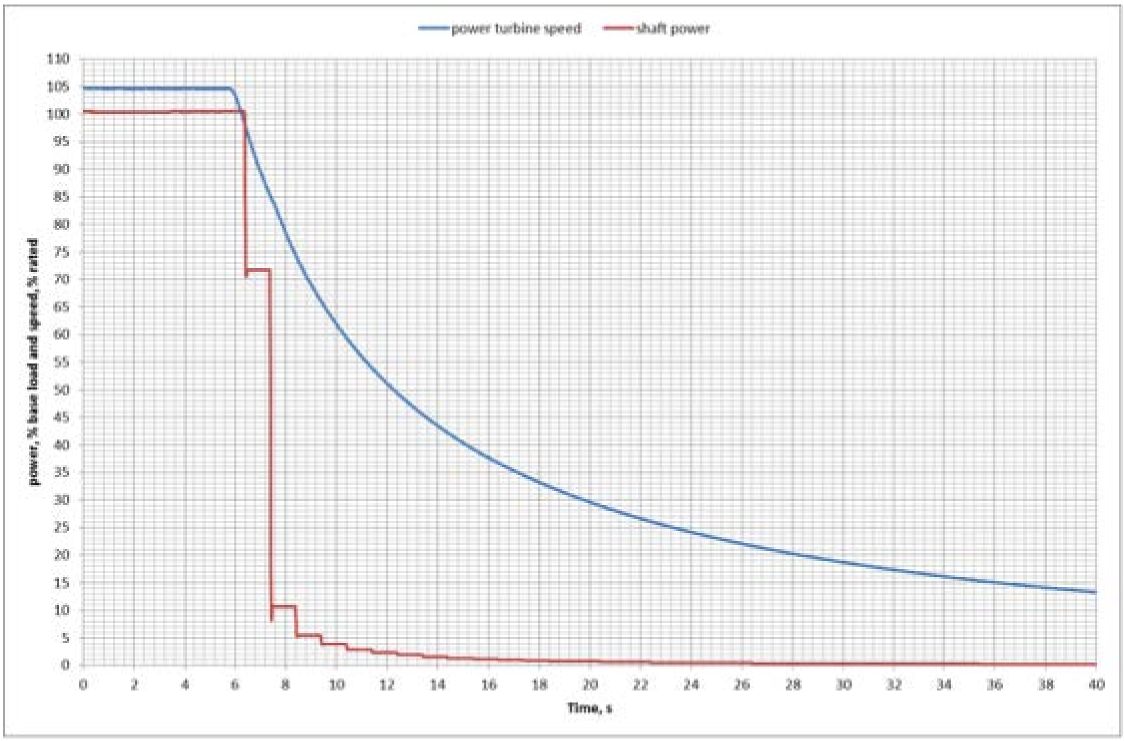


Figure 2.5 - Shaft power and turbine speed during rundown of LM2500

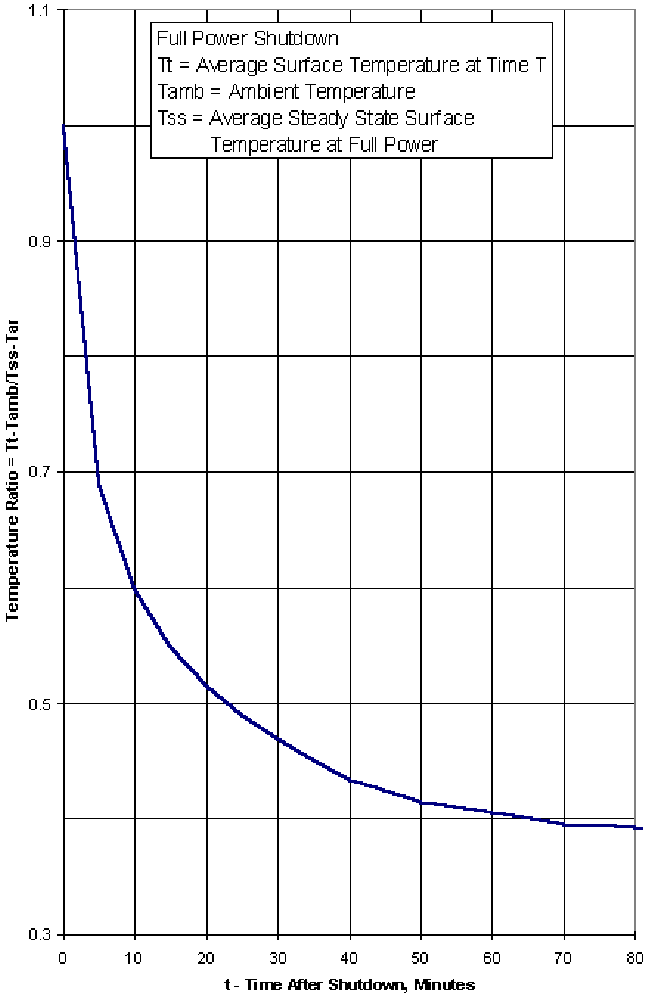


Figure 2.6 - Reduction of surface temperatures in LM2500 after shutdown. The cooling time in the figure is indicative. Probably, the cooling time is shorter for most components, but this has to be verified by vendor data

Hence, at a given moment in time the liner will be an ignition source provided the actual liner temperature as determined by the cooling rate exceeds the ignition temperature as determined by the flow velocity.

Both Ref. /2/ and Ref. /3/ agrees on two different regimes or phases of probabilities of ignition:

1. Phase: Regime from immediately after shutdown (t = 0) until a time t_1. In this phase the flow velocity is so high that ignition temperature is higher than the liner temperature and ignition is not likely. The ignition probability in this phase is set as p_1

2. Phase: As the air flow speed is reduced much faster than the cooling rate of the liner, at some time t_1 the ignition temperature is reduced to a value lower than the liner temperature and the gas can ignite with an ignition probability p_2. This condition lasts until a time t_2 where the liner temperature becomes lower than the minimum AIT where the gas cannot ignite even if at rest over the surface.

In practice, it is extremely difficult to perform quantitative predictions of t_1 and t_2 due to lack of data:

- The relevant surface area of the liner is difficult to find
- Data for ignition temperature as function of both area and flow velocities are limited, especially for the high initial flow velocities.

Fortunately, the ignition probability for a specific scenario is more sensitive to the ignition probabilities p_1 and p_2 than the duration of phase 1 and 2 as discussed below. The different ignition mechanisms are considered as continuous sources in the suggested turbine ignition model, therefore the duration is not so critical.

The evaluation is based on the run-down time and the cooling time for LM 2500 as taken from Ref. /2/. There is no information on the load case for the actual turbine which the run-down curve is based on, i.e. if the curve is representative for a fast or slow run down. The faster the run down the worse as the flow velocity will drop fast compared to the cooling of the liner and increasing the probability that the liner temperature is above AIT. The ignition window will on the other be shorter, but as the ignition source is continuous this has a limited effect.

For a larger turbine like LM 6000, one would expect a longer run down time simply from the larger mass and rotational energy in the system. The cool-down time may, however, not increase correspondingly as a larger turbine likely will apply more combustors of LM2500 size rather than increase the size of each combustor. This means that when increasing the turbine size the run down will increase faster than the cooling time making the conditions for ignition more difficult and the ignition window $t_2 - t_1$ smaller. Basing the ignition model on data from a smaller turbine like LM 2500 would thus be conservative.

2.3 Ignition probability model for turbines

2.3.1 The model

Based on the current understanding of the potential ignition mechanisms, the Ignition probability of an external gas cloud entering the air intake of a gas turbine can be modelled by use of the following phases depending on when the gas initially exposes the air intake (shutdown is considered to take place at $t = 0$ as illustrated in Figure 2.7):

- Initial gas exposure while the gas turbine is running, *i.e.* prior to $t = 0$
- Initial gas exposure during phase 1 of the gas turbine run down
- Initial gas exposure during phase 2 of the gas turbine run down
- Initial gas exposure after phase 2 of the gas turbine run down

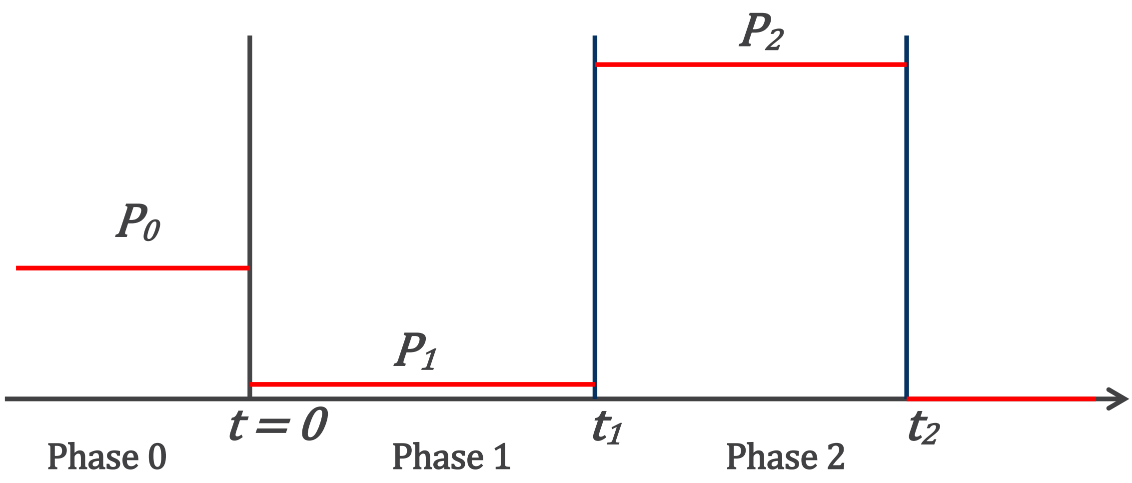


Figure 2.7 - The phases and parameters of the gas turbine ignition model

The ignition mechanisms in the three phases are considered as continuous; either the gas ignites or does not when it is exposed to the gas turbine in any of the phases, and there is no random discrete behaviour increasing the ignition probability with time of exposure. Due to this nature, the durations of the phases are less important than the probability levels; the duration only affects the probability of exposing the air intake in the first place, not the ignition probability given exposure of the air intake.

This also means that if gas initially exposes the air intake while the gas turbine is running, *i.e.* phase 0 in Figure 2.7, it will also expose the air intake during the subsequent phases (assuming the exposure duration is sufficiently long). The ignition probability p_2 then applies to the fraction of scenarios which did not ignite in phase 0. The same argument applies to those scenarios that ignited neither in phase 0 nor in phase 1. For exposure after phase 2 the ignition probability is 0.

It has been attempted to set the values for the various phases in the model. In lack of information regarding the design and operation of gas turbines, it has been concluded to rather use a simple model represented by a single probability, denoted P_{GTAI}. This probability covers ignition inside a gas turbine due to ingestion of combustible fluid leading to ignition of the external cloud. The probability applies to exposure at any point in time before 5 minutes after shut down of the turbine. The figure also applies to exposure before shutdown. The conditional ignition probability is set to

$$P_{GTAI} = 50\%$$

for a gas turbine air intake exposed to combustible gas at any point before 5 minutes after shut down of the gas turbine. Hence, 5 minutes equals t_2 in the model in Figure 2.7.

The assessment above is based on the results of Phase 0 of a JIP on gas turbine air intake ignition control headed by Lloyd's Register (Ref. /4/). The overall objective of the project was to investigate the behaviour of gas turbines when intake air includes combustible fluid in order to evaluate whether risk mitigating measures are required to enhance the safety levels of the systems for ignition control of gas turbines.

The project established the following hypothesis for the likelihood of ignition of a combustible fluid mixed with air being ingested by a gas turbine through the air intake has been established:

- Combustible fluid included in gas turbine intake air is likely to be ignited inside the gas turbine if ingested prior to shutdown of the gas turbine and/or within a certain time frame after gas turbine shuts down. The exact time frame must be investigated further, but is believed to be limited to the first few minutes after shutdown

And:

- if the gas exposure of the air intake is continuous over a prolonged period of time (the exact period of time must be investigated further) ignition of the external gas cloud is believed to occur, either through propagation of the initial flame from inside the gas turbine to the external environment or through damage of the gas turbine.

The hypothesis was based on observed incidents taking place at oil and gas facilities in the North Sea (see Table 7.1 in main report, *i.e.* incident at Gorm C at DCS in 2001 and Centrica B at UKCS in 2006), assessment of the potential ignition mechanisms and discussions with one gas turbine vendor.

The uncertainty associated with the hypothesis cannot be neglected as the ignition scenarios are not fully understood. However, an overarching principle in safety design is to account for such uncertainty if the potential consequences are significant, which the case for the scenario is considered.

In order to falsify or verify the hypothesis for the likelihood of ignition, it is judged that comprehensive research work including experimental work and development of numerical models will be necessary. In addition, access to detailed gas turbine data for the relevant gas turbine designs is required. A scope of work that cover these aspects have been included in the project proposal for the consecutive phase (Phase 1) of the mentioned JIP. The MISOF model for gas turbine air intakes should be updated when Phase 1 of the JIP project has been executed.

2.3.2 Dependency on gas concentration, correction factor f

The gas concentration, C, will probably influence the ignition probability p_1 and p_2 but not p_0 as p_0 is dependent on dC/dt rather than C. In case the gas concentration at the air inlet is known, its effect on the ignition probabilities can be modelled by multiplying p_1 and p_2 by a concentration dependent correction factor f. The following outline such a model, but should not be used unless supported by a relevant gas turbine vendor.

In a simplified approach, the probabilities p_1 and p_2 can be applied to any natural gas-air mixture of flammable concentration. However, in a more refined model these probabilities will be dependent on the concentration of the natural gas-air mixture exposing the air intake. If the gas concentration is closer to LEL or UEL the ignition probabilities will be reduced.

As discussed in Section 2.2.3 two conditions need to be fulfilled for flashback to occur:

- The gas must ignite at the hot internal surfaces, primarily at the combustor liner
- The flame must have sufficient flame speed to be able to propagate against the inlet air flow.

The mechanisms for ignition and flame propagation have different dependencies on gas concentration.

For ignition to occur when gas flows over a hot surface the ignition delay time, or induction time, has to be shorter than the contact time between gas and surface. The shorter the induction time for a given flow speed the higher is the flow velocity where ignition is possible. The ignition delay time is strongly dependent on the gas concentration. As illustrated in Figure 2.8 the ignition time is reduced as the concentration is reduced and is shortest at $\Phi = 0.5$ corresponding to LEL.

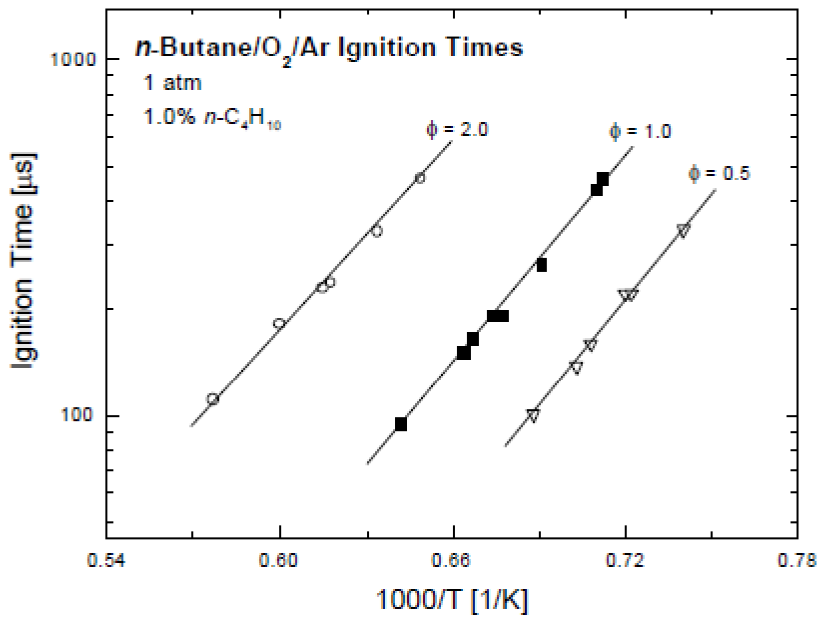


Figure 2.8 - Effect of stoichiometry on ignition delay time for butane, from Ref. /5/

For butane the ignition delay at LEL is about 1/3 of the delay at Φ = 1 and consequently gas at Φ = 0.5 can ignite at 3 times higher flow velocities than for Φ = 1. Hence low concentration favours ignition as it extends the range of flow velocities where ignition is possible.

On the other hand, the flame speed has the opposite dependency on gas concentration between Φ = 0.5 and 1. The flame speed is reduced as the concentration is reduced as illustrated in Figure 2.9.

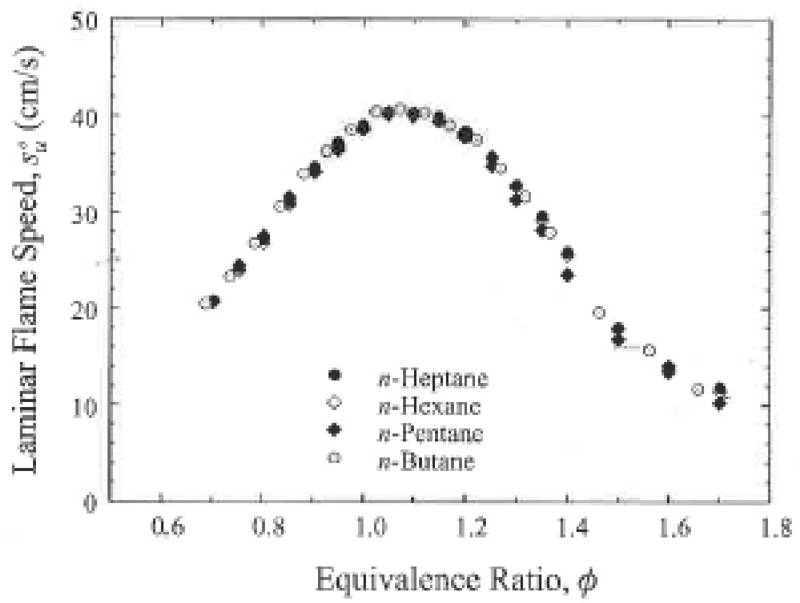


Figure 2.9 - Effect of stoichiometry on laminar burning velocities, from Ref. /6/

The total dependency on gas concentration depends on how the two opposing effects balance. How the specific conditions for ignitions at the hot combustor surfaces is dependent on surface area, ignition delay and surface temperature is not known. However, the reduction in flow velocity after shutdown is very fast (reduced by a factor of 2 within 6 sec and to 10 % or 15 m/s within 1 min, Ref. Figure 2.5) whereas the cooling of internal surfaces is very slow (ΔT reduced by a factor of 2 within 24 min, Ref. Figure 2.6). Consequently the auto-ignition conditions for the surfaces will likely dominate over the flow dependent conditions (ignition delay and flame speed).

For natural gas the auto-ignition temperature increases with decreasing concentration as shown in Figure 4.4.

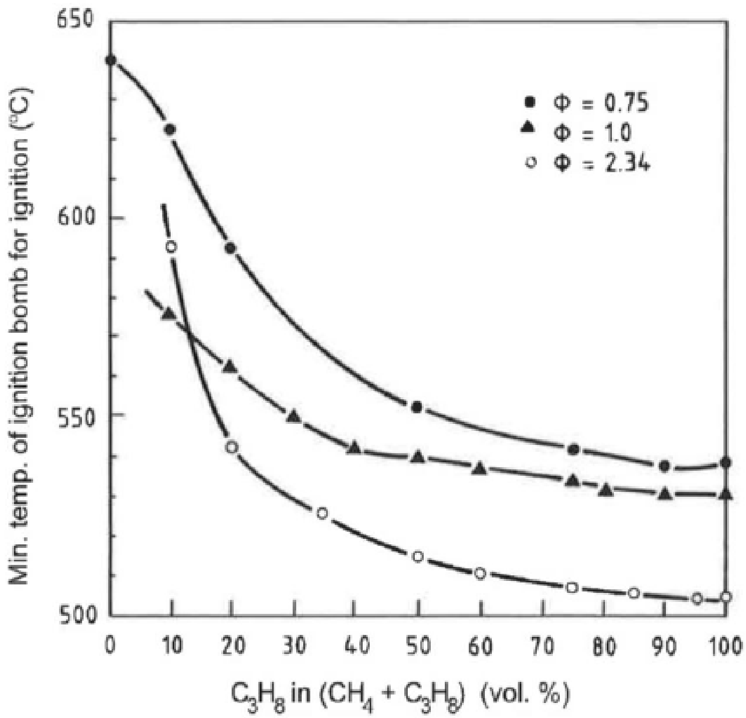


Figure 2.10 - Auto-ignition temperatures for mixtures of methane and propane, from Ref. /3/

Based on this, Ref. /3/ recommends a correction factor of 1 for mixtures of Φ = 1 to Φ = 1.5, dropping linearly off to 0 at Φ =2 and Φ = 0.75 respectively as shown in Figure 2.11. The reason the correction factor is not reduced between Φ = 1 and 1.5 is that AIT actually is reduced from Φ = 1 to Φ =1.5 as seen from Figure 4.4, i.e. AIT is at its lowest close to UEL.

How one could account for the resulting concentration dependencies are presented in Figure 2.12. However, it is not recommended to include these concentration dependencies in the model. These effects should only be considered based on data made available by turbine vendors. Most likely, more information will be provided in the next phase of the JIP addressing ignition control of gas turbine air intakes (Ref. /4/).

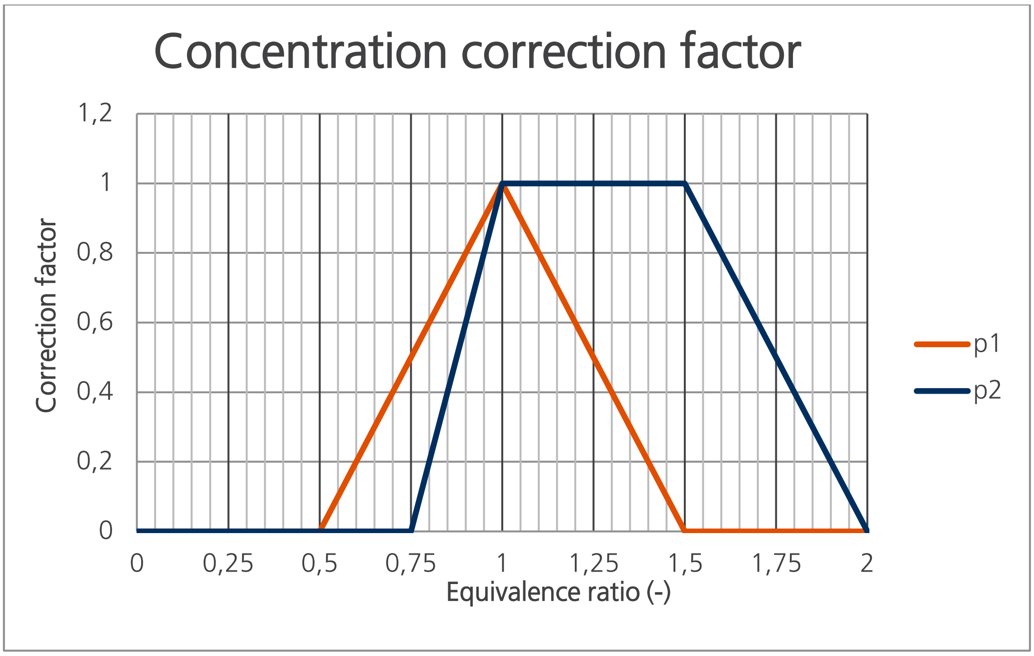


Figure 2.11 – How the correction factor f can be used to adjust the ignition probabilities p_1 and p_2 in the model

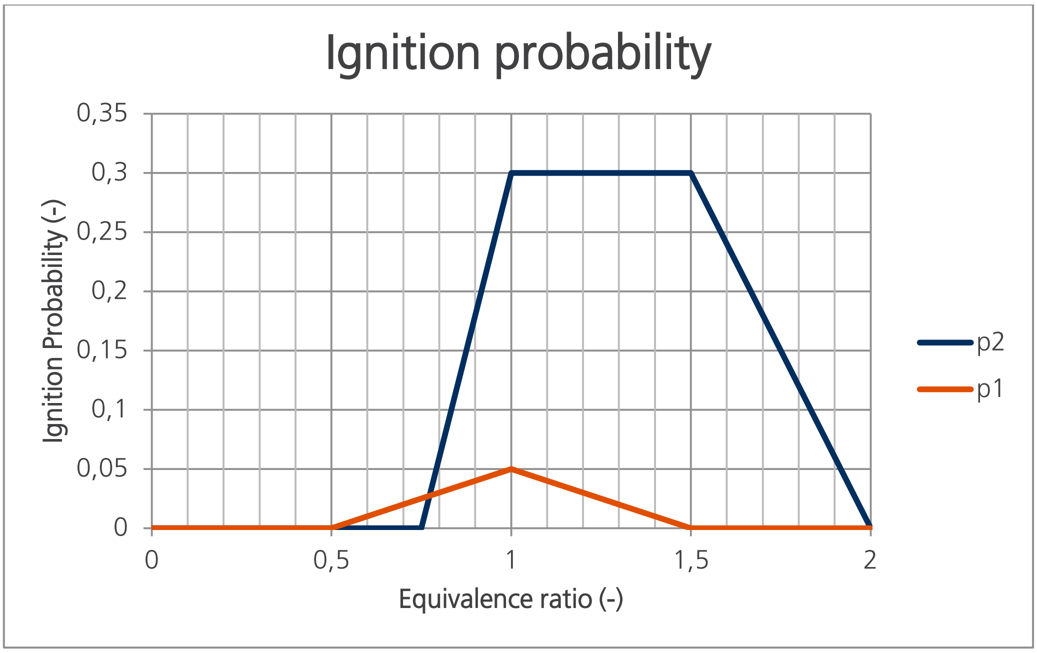


Figure 2.12 – How concentration dependency for the ignition probabilities p_1 and p_2 could be taken into account

2.4 Use of the model

Some aspects should be observed when estimating the frequency of exposing the air inlet to be combined with the turbine ignition probabilities:

1. As the compressor part of the turbine will be a perfect mixer of any concentration variations in the inlet air flow, the average concentration over the entire air inlet cross section should be used when calculating the ignition probabilities p_i
2. The turbine will draw a considerable amount of air, hence it is recommended to include the suction from the inlet flow in the CFD simulations if the exposure probability is based on such simulations. As a minimum, the effect of the suction should be discussed
3. When gas reaches the air inlet, the turbine is shut down, normally at confirmed detection of 20 % LEL in the air inlet (2oo3 gas detectors is a typical layout and voting philosophy). From the air inlet to the compressor air intake there is a transport time given by the distance divided by the average flow velocity in the channel. The shutdown will occur several seconds later than the time of first exposure of the air intake due to the response time of the detector and signal processing time in F&G and ESD system. The response time of gas detectors is strongly dependent on the exposed gas concentration relative to the alarm set point as well as on the detector type. If the transport time of gas from the air inlet to the turbine is shorter than the shutdown time the turbine will be running upon initial exposed to gas, otherwise it has been shut down prior to exposure
4. Exposure to gas detectors in the area prior to exposure of the gas detectors located at the air intake may have resulted in initiation of turbine shut down prior to gas exposure of the turbine air intake. With regard to the point 3., this effect should be assessed
5. The transient behaviour of the release itself may affect the duration of the exposure, and should be reflected. For large releases, which tend to dominate the exposure frequency, the release rate may start to drop immediately after start of the release
6. The consequences being generated from ignition at the specified location of the air intake should be assessed specifically. In particular it may be the case that the explosion loads being generated are different from the loads arising on average by ignition at an arbitrary point in the area.

3 Ignition probabilities for diesel engines

A diesel engine may be capable of igniting gas when exposed to gas but by different ignition mechanisms than gas turbines. As opposed to gas turbines there is experimental experience that can be used as basis for determining ignition probabilities based on real tests rather than purely theoretical models.

There are also cases where accidental releases have been ignited by diesel engines. The problem with deriving ignition probabilities from historical data is, however, that diesel engines on an offshore installation are usually run on an intermittent basis making it very difficult to estimate the number of cases where running diesel engines have been exposed to gas releases, whether ignition did occur or not.

There are several possible exposure scenarios of a diesel engine that potentially could lead to ignition:

- Exposure to air intake: Experience from tests, Ref. /6/, shows that:
  - o When exposed to stoichiometric gas-air concentration the gas will ignite in practically all cases
  - o The ignition occurs immediately on exposure
  - o For lover concentrations the flame speed is lower and hence the likelihood of the flame being capable of propagating against the air flow is reduced

- Ref. /6/ suggests that the reliability of flame arrestors is very high, a probability of failure on demand of 0.01 is considered conservative. Note that the effect of the flame arrestor presumes that the air intake system as such is able to contain the generated overpressure

- Exposure to exhaust pipe or engine casing: Experience, Ref. /6/, shows that ignition probability in this case is likely to be very low.

Based on this, the recommended ignition probabilities for diesel engine air intakes are given in Table 3.1.

Table 3.1 - Recommended ignition probabilities for diesel engine air intakes

Scenario	P_{ign}
Stoichiometric gas in air intake, no flame arrestor	0.9
Non- stoichiometric gas in air intake, no flame arrestor	$P_{ign} = 0.9 \cdot \frac{s(EQ)}{s(1)}$ Where s = laminar flame speed EQ = Equivalence ratio
Flame arrestor in air intake The air intake system must be able to contain the explosion.	0.01

4 References

/1/ Scandpower AS: "Ignition modelling in risk analysis", report no. 89.390.008/R1, March 2007.

/2/ A. Pedersen:"Ignition probability of a flammable mixture exposed to a gas turbine", NTNU report EPT-H-2006-47 and Master Thesis December 2005.

/3/ GexCon: "Ignition probability of a gas turbine", GexCon Technical Note 40489-7, 5.10.2012 by Kees van Wingerden.

/4/ Lloyd's Register Consulting: "Gas turbine ignition control – Phase 0", Joint Industry Project, Partners: ConocoPhillips Skandinavia AS, Maersk Olie & Gas A/S and Statoil ASA. Report No. 104998/R1, Rev. Final, Date: 22 June 2016. Report only distributed on client's acceptance.

/5/ D. C. Horning: "A study of the high-temperature autoignition and thermal decomposition of hydrocarbons", Report No. TSD – 135, Stanford University 2001.

/6/ C. K. Law: "Combustion Physics", Cambridge University Press 2006.

/6/ Kees van Wingerden, mail to Jan A. Pappas 12.12.2013.

Appendix D

Test of the MISOF ignition model for generic offshore modules

REPORT

TITLE:	**Test of the MISOF ignition model for generic offshore modules**	REPORT NO.:	R1812
		PROJECT NO.:	100498
		CLASSIFICATION:	Open
CONTRIBUTOR(S):	Bjørn Erling Vembe, Nils Inge Lilleheie, Ingar Fossan	ELEC. FILE CODE:	Z:\Dist\Prosjekt\100498\Rapport\R1812\R1812_Final.docx
RESPONSIBLE:	Trond Evanger	CHECKED BY:	Bjørn Erling Vembe
CLIENT:	Lloyd's Register	NO OF PAGES:	84
CLIENT'S REF.:	Are Sæbø	DATE:	14.11.2018

SAMMENDRAG:

This report describes the results from testing of the MISOF ignition model for a set of generic offshore modules in order to investigate the performance with respect to:

- previous probabilistic leak frequency and ignition models used in industry in Norway, i.e. the model described in the report "Offshore QRA – Standardised Hydrocarbon Leak Frequencies" (SHLFM) and the ignition model described in "Ignition modelling in risk analysis" (denoted OLF model). It must be noted that both of these models are not recommended to be used for estimation of the fire and explosion risk at offshore installations. Both models deviate much from the observed historical data and our understanding of the performance of the barriers affecting the risk. Hence, the SHLFM and OLF models are to be considered obsolete. Testing of this models is included in this study for comparison with the superseding models (PLOFAM and MISOF).

- the observed historical fire and explosion frequency in the North Sea applying the model in combination with the PLOFAM leak frequency model described in Ref. /1/.

In order to calculate the ignition probability, a dispersion model that estimates the probability for exposure to live ignition sources is required. In this study, the fully coupled ignition model in the advanced CFD simulator Kameleon FireEx KFX® has been used. The model is a part of the risk modelling feature denoted Kameleon FireEx KFX® Risk & Barrier Management (KFX™-RBM) developed by ComputIT.

ADDRESS	PHONE	FAX	E-MAIL	ENT. NO.
P.O. Box 1260 Torgård N-7462 Trondheim, Norway	+47 73 89 59 00	+47 73 89 59 01	computit@computit.no	NO 981 248 252 VAT

Computational Industry Technologies AS

Content

1 Introduction

This report describes the results from testing of the MISOF ignition model for a set of generic offshore modules in order to investigate the performance with respect to:

- previous probabilistic leak frequency and ignition models used in industry in Norway, i.e. the model described in the report "Offshore QRA – Standardised Hydrocarbon Leak Frequencies" (Ref. /2/) and the ignition model described in "Ignition modelling in risk analysis" (Ref. /3/). These models are hereafter denoted the "SHLFM leak frequency model" and the "OLF ignition model" respectively. It must be noted that both the SHLFM and the OLF model is not recommended to be used for estimation of the fire and explosion risk at offshore installations. Both models deviate much from the observed historical data and our understanding of the performance of the barriers affecting the risk. Hence, the SHLFM and OLF models are to be considered obsolete. Testing of these models is included in this study for comparison with the superseding models (PLOFAM and MISOF).

- the observed historical fire and explosion frequency in the North Sea applying the model in combination with the PLOFAM leak frequency model described in Ref. /1/.

In order to calculate the ignition probability, a dispersion model that estimates the probability for exposure to live ignition sources is required. In this study, the fully coupled ignition model in the advanced CFD simulator Kameleon FireEx KFX® has been used. The model is a part of the risk modelling feature denoted Kameleon FireEx KFX® Risk & Barrier Management (KFX™-RBM) developed by ComputIT.

It is important to note that the generated probability distributions from the probabilistic model are based on a limited number of samples (*i.e.* leak scenarios). A few hundred scenarios are too few to give a very accurate estimate of the underlying distribution for the various modules. A representative selection of scenarios in terms of leak location, leak direction and wind conditions has been selected. This means that if more simulations where run, it is considered equally likely that the updated risk estimates results in higher or lower risk figures (ignition probabilities, fire frequencies and explosion frequencies). The uncertainty with regards to the number of simulated scenarios must hence be considered when evaluating the results. It is judged that the relative differences between the modules are less uncertain.

2 Objective

The objective is to test the MISOF ignition model using a state-of-the-art exposure model for a set of typical process modules at offshore oil and gas installations located on the Norwegian Continental Shelf.

3 Methodology

3.1 General

In order to calculate the ignition probability, a dispersion model that estimates the probability for exposure to live ignition sources is required. In this study, the fully coupled ignition model incorporated in the KFX™-RBM feature has been used. KFX™-RBM is embedded in Kameleon FireEx KFX®.

The physical behaviour of the dispersing atmosphere is modelled based on time-dependent modelling of the leak rate coupled with models of the process system, safety systems in place to control loss of containment as well as the ignition control barrier elements.

The initial conditions of the leak scenario including wind conditions are selected manually in the study, but how the dispersion scenario unfolds after that, is modelled by the simulator itself, including time-dependent modelling of the ignition probability according to the algorithm described in MISOF.

Some of the benefits of using this model are:

- No assumption regarded time to detection and time to the automatic initiating actions taking effect required. The model monitors gas concentration at the specified location of the detectors and initiates emergency shut down, blowdown and isolation of potential sources of ignition according to platform specific layout of detectors, voting philosophy, response time of ESD system, ESD valves, BD valves and Cause & Effect design.

- Modelling of the significance of the location of ignition sources relative to the location of the leak sources. This is believed to be of most importance for big areas (e.g. FPSO's and land based facilities). In large areas, certain types of ignition sources can be concentrated in one part of the facility relative to the location of the leak source. Additionally, there could be a link through scenarios generating dense gas dispersing along the ground/lower deck level over long distances. Another example very relevant for offshore installations is gas turbine air intakes. This feature is demonstrated in the study.

The main steps of the methodology are summarized in Figure 3-1 and described in the consecutive sections.

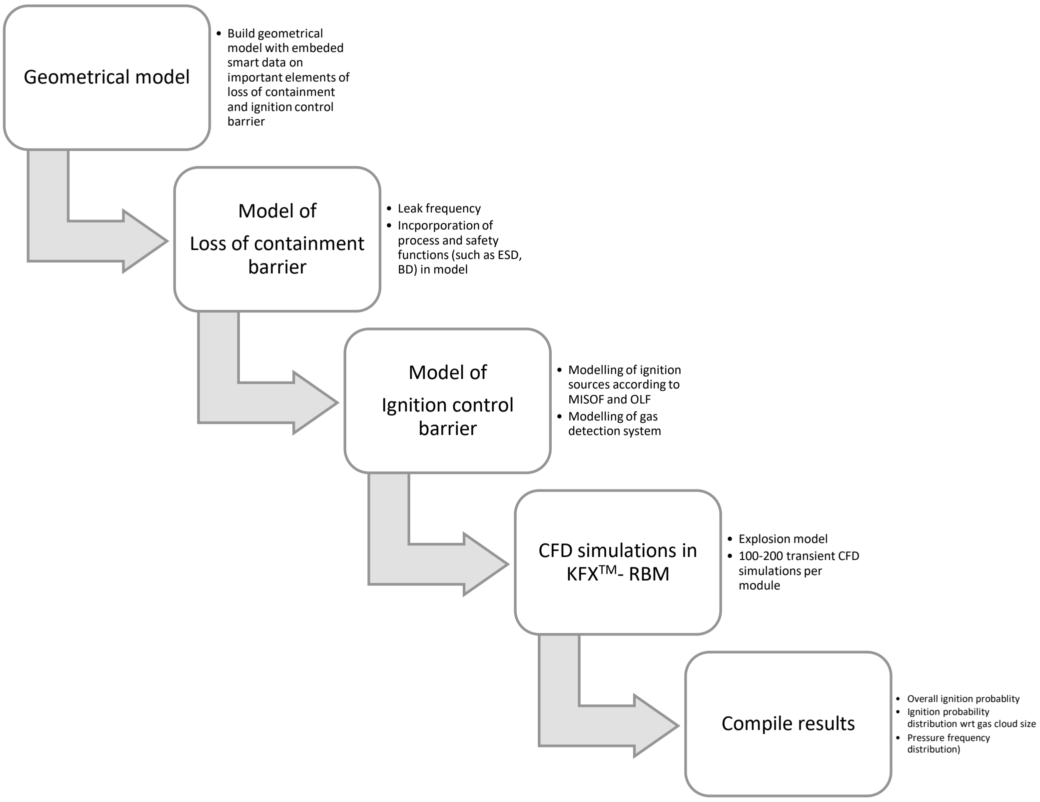


Figure 3-1: Main steps in methodology for testing of MISOF using the risk analysis software Kameleon FireEx Risk & Barrier Management (KFX-RBM)

3.2 Geometrical model

3 generic offshore modules have been established to study the importance of the geometrical layout for the estimated fire and explosion risk.

The generic modules envelopes the typical size of offshore modules located at the NCS, ranging from 4,000 to 40,000 gross m^3. The ventilation conditions in terms of openness of peripheral walls represent typical layout found at offshore installations.

It should be noted that the modules studied are considered to represent rather unfavorable designs in terms of explosion risk, *i.e.* due to quite poor global ventilation conditions. The estimated explosion risk using PLOFAM and MISOF is therefore expected to be less for many equally sized modules in the North Sea.

The modules have been built manually in KFX^{TM}, but the text format can easily be transferred to other formats. The geometrical models can be shared upon request.

The models are displayed in the following figures. White coloured objects are anticipated equipment included to represent the general equipment density in a typical offshore module. The main equipment (including piping) and structures are built according to typical design. The global properties of the modules are summarized in Table 3-1.

The name of the module is given based on its size and ventilation conditions according to the following using CM42EW as an example:

- CM = Module
- 4 = 4,000 m^3 gross volume
- 2 = number of open outer walls
- E = East wall is open (North is parallel with Y-axis in model)
- W = West wall is open

The y-axis is directed towards North.

Table 3-1: Description modules

Module	Size	Open walls	Equipment
CM42EW	30 m x 15.9 m x 8.25 m	Two shortest walls open. Solid deck and roof.	One separation train Anticipated equipment 4 pumps
CM132EW	52 m x 24.9 m x 10.25 m	Two shortest walls open. Solid deck and roof.	Two separation trains including 1st stage scrubber Anticipated equipment 12 pumps
CM402EW *)	74.7 m x 52 m x 10.25 m	Two longest walls open. Solid deck and roof.	Six separation trains including 1st stage scrubber Anticipated equipment 36 pumps

*) Made up of three exact copies of M132EW placed next to each other (side walls of the central unit were taken out)

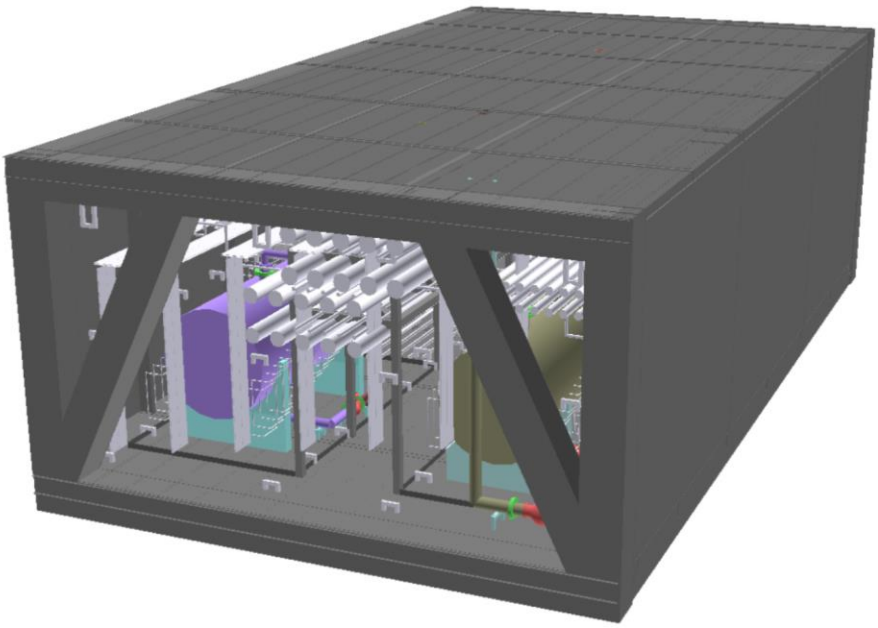


Figure 3-2: CM42EW; about 4 000 gross m^3, two open walls.

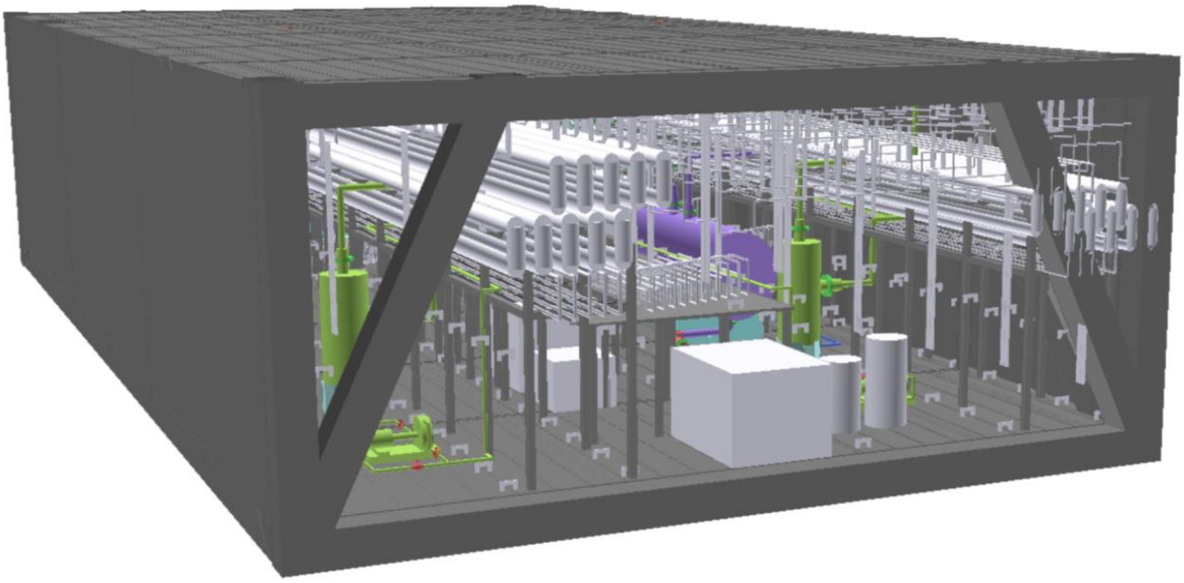


Figure 3-3: M132EW; about 13 000 gross m^3, two open walls

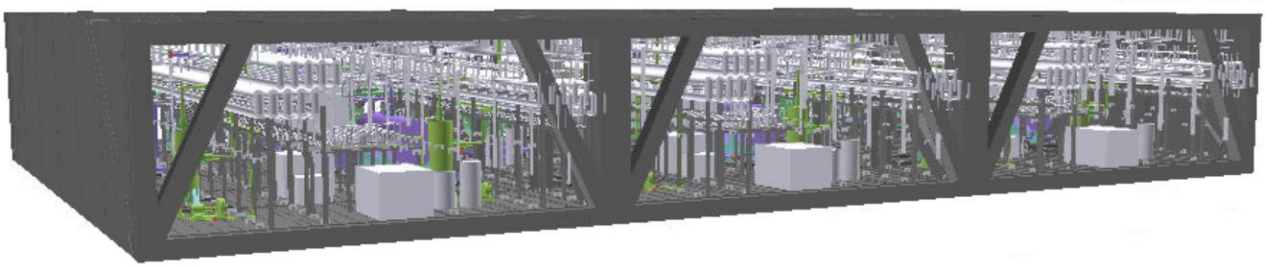


Figure 3-4: CM402EW; about 40 000 gross m^3, two open walls

3.3 Model of loss of containment barrier

The PLOFAM leak frequency model (Ref. /1/) forms the basis for the loss of containment model. A sensitivity study has been run using the SHLFM model (Ref. /2/). The caption ‘PLOFAM2’ is used in the figures to denote that rev. 2 of the PLOFAM model issued in December 2018 has been applied.

Based on the PLOFAM validation model, an approximate model describing the typical distribution with respect to the initial leak rate has been established for both PLOFAM and SHLFM. The approximate models are shown in Figure 3-5. The parameters are set targeting that the approximate model is somewhat conservative. The most significant conservative bias is for leaks > 100 kg/s.

The approximations allow for effective estimation of the distribution of a given total leak frequency for the various modules.

The complementary cumulative leak frequency fraction distribution, denoted $A(Q)$, is approximated by the following function:

$$A(Q) = C \cdot Q^{-k} \tag{4.1}$$

The parameter values for k and C can be found in Table 3-2. C are given by k requiring that the distribution is continuous and starts at 1.0 for $Q = 0.1$ kg/s. For example, C for the interval below 1 kg/s is given by the following expression for the approximation of PLOFAM:

$$C_{0.1-1} = \frac{1}{0.1^{-0.5}} \approx 0.3162 \tag{4.2}$$

which also for applies for $Q > 1$ kg/s as the distribution must be continuous:

$$C_{>1} = \frac{C_{0.1-1} \cdot 1^{-0.5}}{1^{-0.7}} = C_{0.1-1} \approx 0.3162$$

Table 3-2: Parameters for approximate leak frequency model

	PLOFAM	SHLFM
k	For Q ≤ 1 kg/s: -0.50 For Q > 1 kg/s: -0.70	For Q ≤ 300 kg/s: -0.43 For Q > 300 kg/s: - 0.80
C	For Q ≤ 1 kg/s: 0.3162 For Q > 1 kg/s: 0.3162	For Q ≤ 300 kg/s: 3.0657 For Q > 300 kg/s: 0.3715

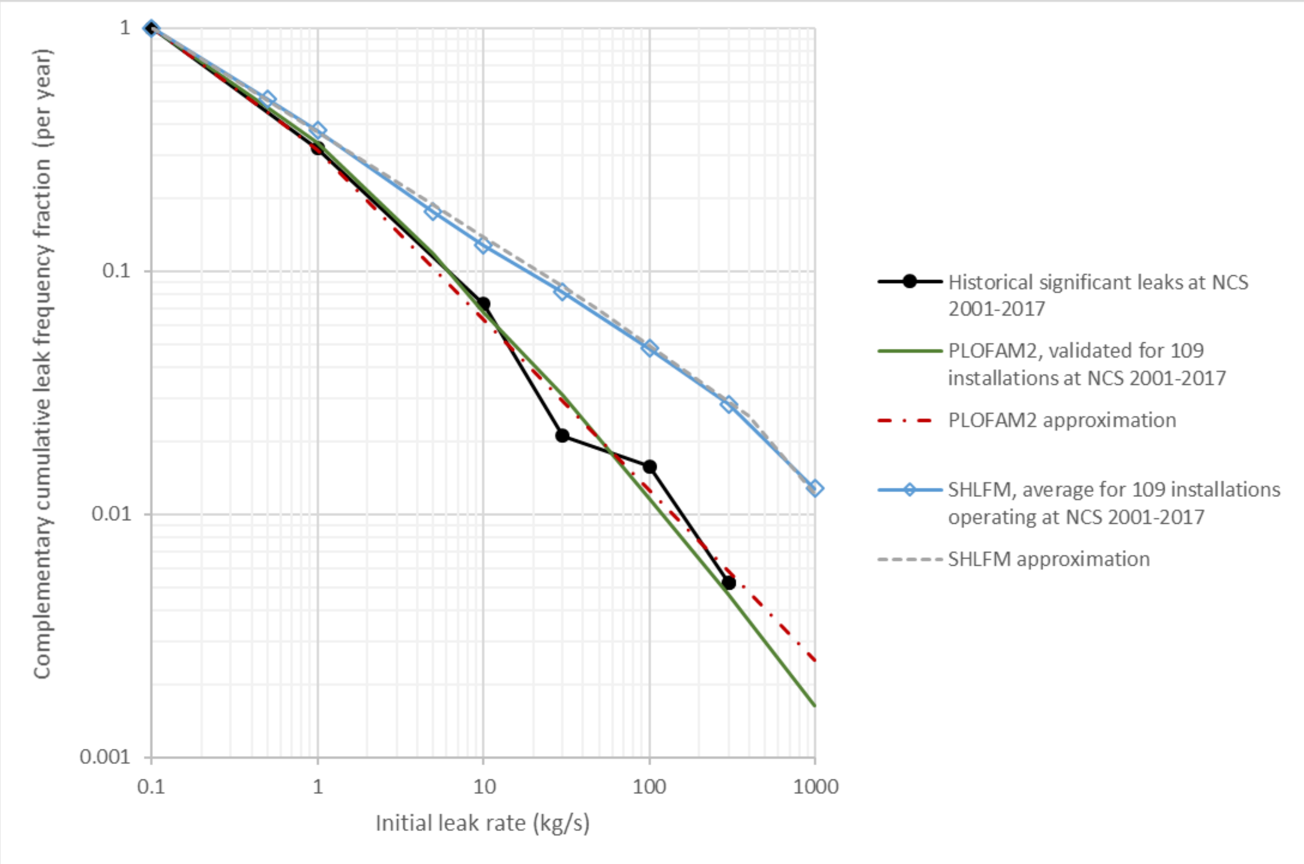


Figure 3-5: Leak frequency fraction distribution approximations. The PLOFAM approximation applies to significant leaks. The SHLFM approximation applies to both full and limited leaks.

Furthermore, also based on the benchmark model in PLOFAM and the SHLFM report, the following leak frequency model properties for the modules have been established:

- Marginal leaks are disregarded (10 kg or less released) for the studied modules. Such leaks could be relevant for small poorly ventilated modules (*e.g.* compressor enclosures).

- The total leak frequency for significant PLOFAM leaks having an initial leak rate larger than 0.1 kg/s per volume unit for a process module is:

    - $4.7 \cdot 10^{-6}$ significant PLOFAM leaks per m^3 gross process module. The frequency parameter is calculated from the LRP data set presented in Table 8.9 in the main report. The PLOFAM leak frequency model generate a frequency of about $5.0 \cdot 10^{-6}$ per m^3 per year for all of the installations in the LRP data

- The ratio between the total frequency for full pressure leaks according to the SHLFM model and significant PLOFAM leaks:

    - 3.28

- The fraction limited leaks according to the SHLFM model:

    - Gas leaks: 0.35

  - Liquid leaks: 0.75

- Fluid fractions (applies to both PLOFAM and SHLFM model).

  - 60% gas leaks
  - 40% liquid or multi-phase leaks

- Gaseous fraction liquid leaks contributing to exposure to ignition sources

  - 10% of the released fluid is assumed to flash off instantaneously in the dispersion model. The remaining liquid is assumed to rain out and form a pool on the deck drained to open drain or directly to sea without contributing to the probability for ignition or participating in the reaction process generating overpressure in case of ignition

- Six potential leak directions covering the 6 perpendicular directions in an orthogonal system

- The following initial leak rates are included

  - 0.2 kg/s, 0.5 kg/s, 1 kg/s, 2 kg/s, 4 kg/s, 8 kg/s, 16 kg/s, 32 kg/s, 64 kg/s, 128 kg/s, 256 kg/s, 512 kg/s and 999 kg/s

- A constant mass flow of 30 kg/s into the process segment is assumed to prior to ESD and BD being effective. This is a simple model reflecting that the neighbouring segments will feed the segment the leak is originating from in the time window before closure of isolation valves. This means that the leak rate is constant if the leak rate is less than 30 kg/s. For leak rates above 30 kg/s, the pressure will decrease proportionally with the released amount (see example in Figure 3-12). For massive leaks, the model allows for that the segment is drained before the isolation has taken effect. The delay time from detection until ESD and BD are effective is set to 30 seconds. The delay time is dominated by the closure time of the ESD valves.

The resulting leak frequency for the various modules and the two leak frequency models are shown in Table 3-3.

The resulting complementary cumulative leak frequency for the smallest generic module is shown in Figure 3-6.

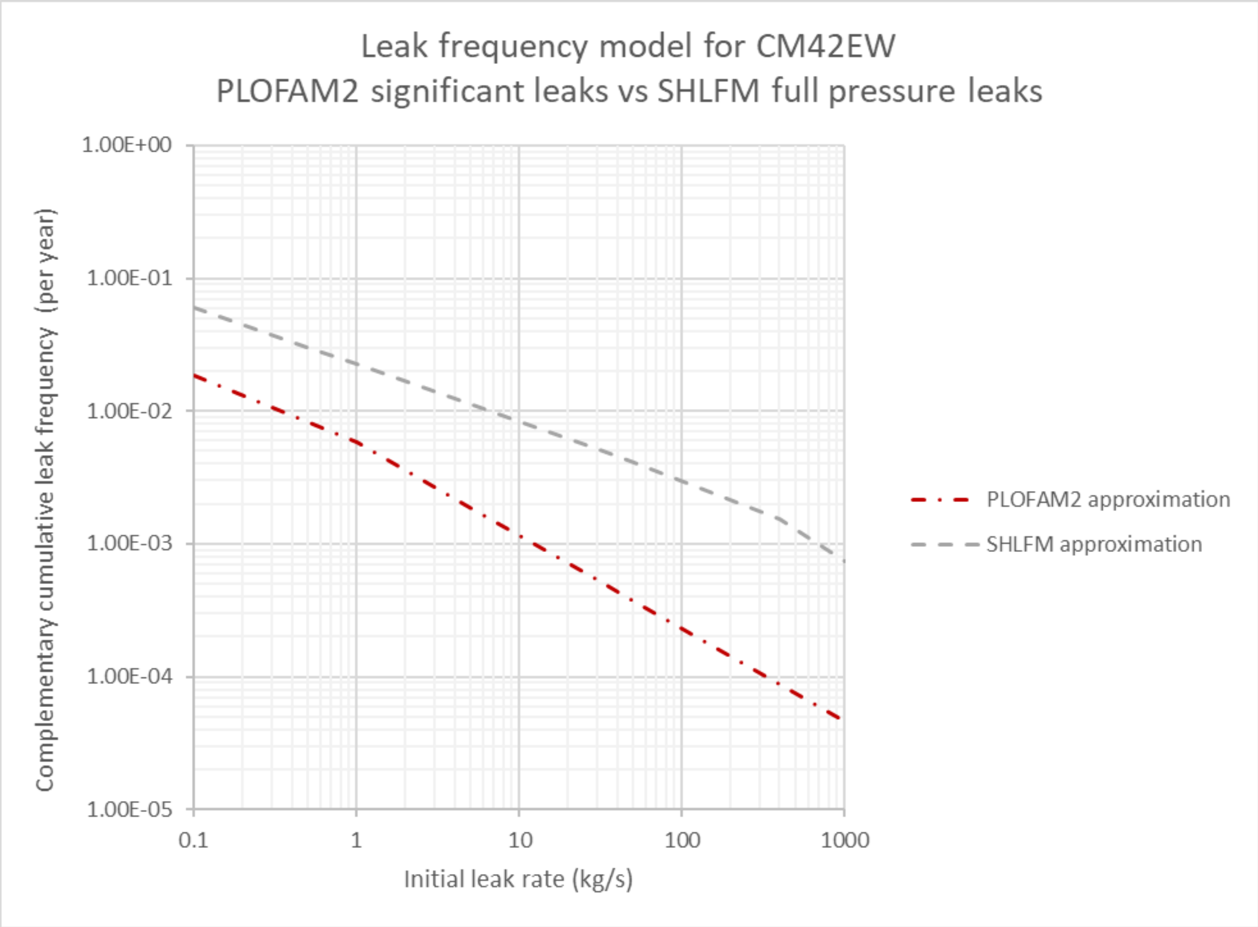


Figure 3-6: Leak frequency distributions for CM42EW.

The base case segment for all modules reflects a single ESD process segment with the following properties:

- Inventory: 70 m^3
- Temperature: $30^{O}C$
- Pressure: 50 barg
- Gas composition: 90% Methane, 10% Ethane
- Depressurisation time: 10 minutes to 6.9 barg

This results in a segment inventory of around 2.5 ton. Inventory in terms of gas (mol weight < C4) for a segment at offshore installations typically range from a few hundred kgs to 5 tons.

The gas flashing from liquid leaks are modelled as pure C3 (propane) leaks to represent dense gas dispersion, which is expected for most liquid leaks.

Limited leaks according to the SHLFM model are modelled with a pure gaseous segment having

- 1/3 of the original inventory
- An initial reservoir pressure of 2.5 barg and setting the effect of blowdown as follows: 5 minutes to 1.25 barg.

The model of limited leaks is considered approximate according to how the scenario is defined in SHLFM. However, for the sake of the comparison with the PLOFAM model, the approach is expected to generate a reasonable estimate of the relative difference in fire and explosion frequencies for the different modules.

Table 3-3: Leak frequency (per year) for the different modules. Leak rate in kg/s.

Discretisation			Fraction per category		Leak frequency					
					CM42EW		CM132EW		CM402EW	
Lower class boundary	Rate used in simulations	Upper class boundary	SHLFM	PLOFAM2	SHLFM	PLOFAM2	SHLFM	PLOFAM2	SHLFM	PLOFAM2
Gas leaks										
0.1	0.5	0.75	0.580	0.635	2.11E-02	7.05E-03	7.11E-02	2.38E-02	2.14E-01	7.16E-02
0.75	1	1.5	0.108	0.127	3.94E-03	1.41E-03	1.33E-02	4.76E-03	4.01E-02	1.43E-02
1.5	2	3	0.080	0.092	2.93E-03	1.02E-03	9.87E-03	3.43E-03	2.97E-02	1.03E-02
3	4	6	0.060	0.056	2.17E-03	6.25E-04	7.33E-03	2.11E-03	2.21E-02	6.35E-03
6	8	12	0.044	0.035	1.61E-03	3.85E-04	5.44E-03	1.30E-03	1.64E-02	3.91E-03
12	16	24	0.033	0.021	1.20E-03	2.37E-04	4.04E-03	7.99E-04	1.22E-02	2.41E-03
24	32	48	0.024	0.013	8.89E-04	1.46E-04	3.00E-03	4.92E-04	9.03E-03	1.48E-03
48	64	96	0.018	0.008	6.60E-04	8.98E-05	2.22E-03	3.03E-04	6.70E-03	9.12E-04
96	128	192	0.013	0.005	4.90E-04	5.53E-05	1.65E-03	1.86E-04	4.97E-03	5.61E-04
192	256	384	0.010	0.003	3.63E-04	3.40E-05	1.23E-03	1.15E-04	3.69E-03	3.46E-04
384	512	768	0.012	0.002	4.36E-04	2.09E-05	1.47E-03	7.06E-05	4.43E-03	2.13E-04
768	999	1E+13	0.017	0.003	6.10E-04	3.35E-05	2.06E-03	1.13E-04	6.20E-03	3.41E-04
Total gas			**1**	**1**	**3.64E-02**	**1.11E-02**	**1.23E-01**	**3.74E-02**	**3.70E-01**	**1.13E-01**
Liquid leaks										
0.1	0.5	0.75	0.580	0.635	1.41E-02	4.70E-03	4.74E-02	1.58E-02	1.43E-01	4.77E-02
0.75	1	1.5	0.108	0.127	2.63E-03	9.40E-04	8.87E-03	3.17E-03	2.67E-02	9.55E-03
1.5	2	3	0.080	0.092	1.95E-03	6.77E-04	6.58E-03	2.28E-03	1.98E-02	6.88E-03
3	4	6	0.060	0.056	1.45E-03	4.17E-04	4.89E-03	1.41E-03	1.47E-02	4.23E-03
6	8	12	0.044	0.035	1.08E-03	2.57E-04	3.63E-03	8.65E-04	1.09E-02	2.61E-03
12	16	24	0.033	0.021	7.98E-04	1.58E-04	2.69E-03	5.33E-04	8.11E-03	1.60E-03
24	32	48	0.024	0.013	5.93E-04	9.72E-05	2.00E-03	3.28E-04	6.02E-03	9.88E-04
48	64	96	0.018	0.008	4.40E-04	5.99E-05	1.48E-03	2.02E-04	4.47E-03	6.08E-04
96	128	192	0.013	0.005	3.26E-04	3.68E-05	1.10E-03	1.24E-04	3.32E-03	3.74E-04
192	256	384	0.010	0.003	2.42E-04	2.27E-05	8.17E-04	7.65E-05	2.46E-03	2.30E-04
384	512	768	0.012	0.002	2.91E-04	1.40E-05	9.81E-04	4.71E-05	2.96E-03	1.42E-04
768	999	1E+13	0.017	0.003	4.07E-04	2.24E-05	1.37E-03	7.54E-05	4.13E-03	2.27E-04
Total liquid			**1**	**1**	**2.43E-02**	**7.40E-03**	**8.18E-02**	**2.50E-02**	**2.47E-01**	**7.52E-02**
Total			**1**	**1**	**6.07E-02**	**1.85E-02**	**2.05E-01**	**6.24E-02**	**6.16E-01**	**1.88E-01**

3.4 Model of loss of ignition control barrier

Ignition sources have been implemented according to the MISOF model and OLF ignition models. The default parameters have been used in both models. In particular, this is important with regards to the fraction of ignition sources being isolated upon detection, represented by the parameter denoted P_{iso}.

The MISOF model enable specific modelling of the rotating machinery, such as pumps and compressors, and electrical equipment (specific failure rates per type has been derived in MISOF), but this functionality is not utilized in the base case. The generic models for the three equipment categories have been used to make model as equivalent with the OLF model as possible. In the OLF model, ignition sources only can be modelled being uniformly distributed.

A sensitivity analysis has been run demonstrating the effect of specific modelling of pumps as described in the MISOF model for the two smallest modules (see section 4.6).

No external ignition sources, such as gas turbine air intakes or supply vessels, have been incorporated in the base case. Hence, only ignitions due to faulty Ex-classified equipment inside the area where the leak take place are included in the probabilistic model.

Ignition due to external sources can however be the dominant contributor in many cases, in particular where gas turbines are used for mechanical drive of compressors in the process area. A sensitivity study has been run for all of the modules demonstrating the potential importance of gas turbine air intakes (see 4.7).

The MISOF ignition model parameters are summarized in Table 3-4. The OLF parameters are summarized in Table 3-5.

Table 3-4: MISOF ignition parameters used in the study (see MISOF main report for explanation)

Parameter	Rotating equipment	Electrical equipment	Other equipment
$\lambda_{i,C}$ **[per m^3]**	$3.7 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$	$6.1 \cdot 10^{-7}$
$\lambda_{i,D}$ **[per m^3 per sec]**	$1.5 \cdot 10^{-9}$	$1.5 \cdot 10^{-9}$	$1.2 \cdot 10^{-8}$
P_{iso}	100%	25%	30%
Cooling time continuous sources (half time)	20 sec	5 sec	20 sec
Immediate ignition (all leaks and all rates)	0.0023	0.0023	0.0023

Table 3-5: OLF ignition model parameters used in the study (see Ref. /3/ for further explanation)

Parameter	Value
P_{if} **[per m3]**	$5.0 \cdot 10^{-6}$
i_b	0.5
i_a	0.75
Reference duration	180 sec
P_{iso}	75%
Cooling time continuous sources (half time)	20 sec
Immediate ignition	< 1 kg/s: 0.0005 1 – 10 kg/s: 0.001 > 10 kg/s: 0.01
Correction factor	No correction factors used in the base case. The correction factors (age and technology) in the OLF model result in a total factor of about 0.9 and 1.5 for a 33 and a 34 year old installation respectively. The correction factor for technology shifts from 1.2 to 0.75 in 1985. This means that no installations will generate a correction of 1.0 (which is the same as not using any correction factor), but roughly the base case model can be said to apply to an installation put on stream in the mid 80's. The OLF correction factors have been disregarded in the MISOF model in lack of evidence supporting them (both statistically and technically). See Figure 3-7 for the total effect of the OLF correction factors for increasing age. See Figure 3-8 for the absolute value for various ages of the installation compared with the MISOF model. The results for a new installation according to the OLF model has also been presented.

A comparison of the ignition model parameters is presented in Table 3-6. The results show that the generic ignition parameters in MISOF are considerable higher than in the OLF model. The main reasons for this are:

- Two out of the relevant ignited leaks registered at North Sea installations used to derive the model parameters occurred after the OLF report was issued in 2007, which has increased the observed historical ignition probability considerable
- A thorough review of the leaks taking place at installations in the North Sea after 1991 executed in the PLOFAM project lead to a considerable reduction of the number of leaks considered relevant for modelling of fires and explosions in a QRA. The reduction in the denominator when deriving the ignition model parameters has had a profound effect.
- The fraction of potential ignition sources isolated upon initiation of ignition control is considerably lower than what was assumed in the OLF model (the parameter was set based on engineering judgement). A detailed review of the Cause & Effect for three installations, executed as part of the MISOF project (no such study has been performed previously to support

the parameterisation of P_{iso}), demonstrated that the number of potential ignition sources isolated upon gas detection is rather low. This is because most of the potential sources of ignition are electrical equipment units required to be in operation after ESD to ensure safe shut down.

- Correction factors based on that the basic ignition probability per volume unit (denoted P_{if} in the OLF model) is less for newer installations with new technology were embedded in the OLF model (see Figure 3-7 for description of relative factors as a function of age). The OLF correction factors have been disregarded in the MISOF model in lack of evidence supporting them (both statistically and technically). The base case model in this study has been based on no correction factor in the OLF model, which would equal an installation put on stream in the 80's. Using the correction factor model for a new installation would lead to a considerably less probability for delayed ignition (see Table 3-6 and Figure 3-8). The correction factor for new technology is 0.75 for installations set in operation 1986 onwards, and 1.2 for older installations. The correction factor has been set to 0.9 for a new installation (and increasing with 0.01 per year since it was first time set in operation), hence resulting in a correction of 0.675 for a new installation.
- The estimate of the exposed volume used to derive $\lambda_{i,C}$ and $\lambda_{i,D}$ in the MISOF model is targeting the actual underlying exposed volume. The equivalent exposed volume generated in a QRA is believed to be bigger than the exposed volume generated for observed leaks due to many of the observed leaks not being fully pressurised or limited in duration due to intervention and/or process components hindering internal flow to the leak point. This means that the actual ignition probability per volume unit is targeted in MISOF. The bias related to the leak scenarios is

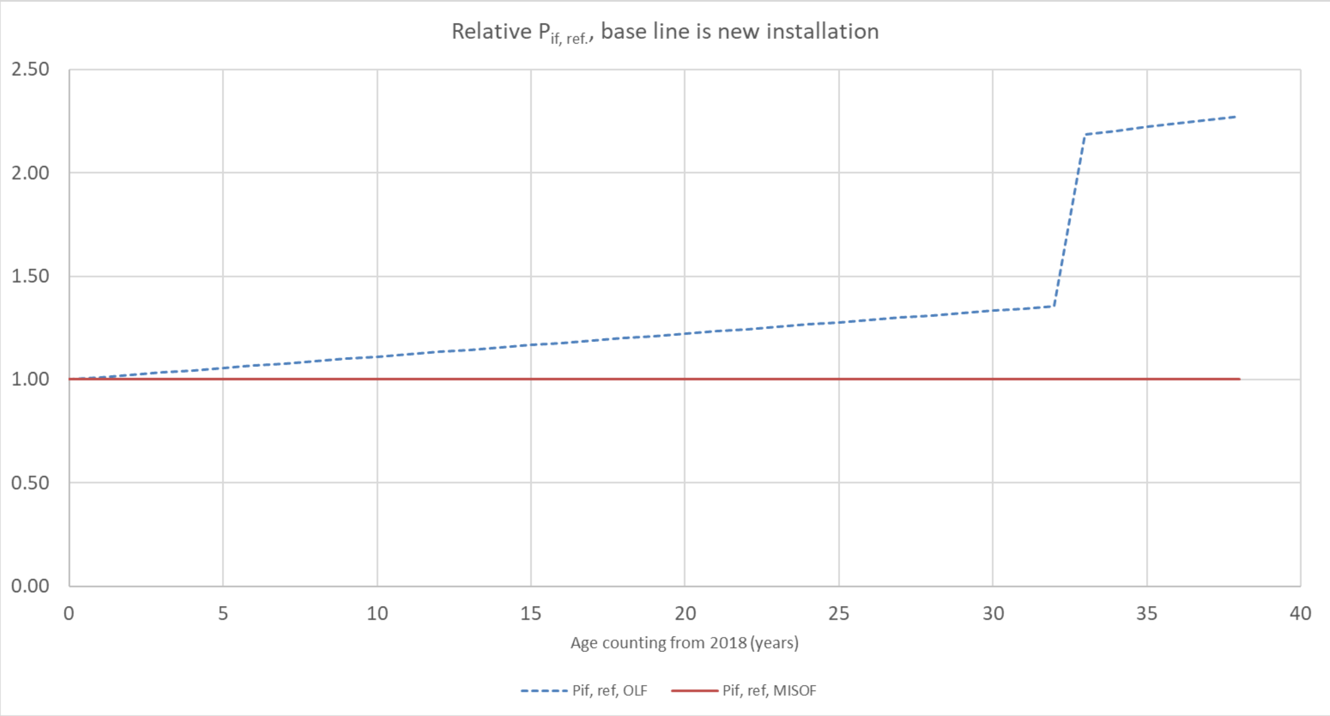


Figure 3-7: Comparison MISOF and OLF in terms of the effect of correction factors in the OLF model. $P_{if,ref}$ for MISOF is estimated based on $\lambda_{i,C}$ and $\lambda_{i,D}$. In the OLF model, P_{if} increase with increasing age.

Table 3-6: Comparison MISOF and OLF ignition model parameters (see also Figure 3-8)

Parameter	OLF		MISOF	Relative MISOF/OLF	
	New installation with correction	Base case in this study		New installation	Base case
Correction factor	Technology: 0.75 Age: 0.9 Total: 0.675=0.75·0.9	1.0	NA	NA	NA
Continuous before detection [per m³]	$1.7 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$	$6.1 \cdot 10^{-6}$	3.7	2.5
Continuous after detection [per m³]	$2.1 \cdot 10^{-7}$	$3.1 \cdot 10^{-7}$	$1.8 \cdot 10^{-6}$	8.8	5.9
Discrete before detection [per m³ per sec]	$9.4 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	1.6	1.1
Discrete after detection [per m³ per sec]	$3.5 \cdot 10^{-9}$	$5.2 \cdot 10^{-9}$	$9.6 \cdot 10^{-9}$	2.8	1.9
Immediate ignition (all leaks and all rates)	0.00186*)	0.00186*)	0.0023	1.2	1.2

*) Calculated based on a weighted average using the SHLFM leak frequency distribution presented in Table 3-3. Correction factors in OLF model does not apply to immediate ignition.

In particular, the difference in the parameter value for continuous sources is important for the resulting delayed ignition probability. For the same leak scenario, the MISOF model will for typical leak scenarios result in considerable higher ignition probability. The exception is cases with long duration where prolonged exposure may cause discrete sources to dominate.

The difference in terms of the basic parameter value for delayed ignition, denoted $P_{if,ref}$ in the OLF model, is shown in Figure 3-8. $P_{if,ref}$ represent the number of ignitions resulting from a cloud with a flammable volume of 15,000 m^3 exposing live ignition sources in a classified area for 3 minutes (180 sec). $P_{if,ref}$ is calculated directly from $\lambda_{i,C}$ and $\lambda_{i,D}$ in the MISOF model. The ignition probability (the probability for 1 or more ignitions) can be derived using the Poisson distribution. In practice, $P_{if,ref}$ approximated from $\lambda_{i,C}$ and $\lambda_{i,D}$ will be approximately equal to the ignition probability (deviation a few percent).

The result demonstrates that the basic target is much higher for the MISOF model compared to the OLF model, which has a profound effect on the resulting ignition probabilities.

The undocumented application of correction factors in the OLF model not benchmarked towards the historical fire and explosion frequency in addition to the excessive value for P_{iso} leads to the conclusion that the OLF model should not be used to estimate the ignition probability at oil and gas installations.

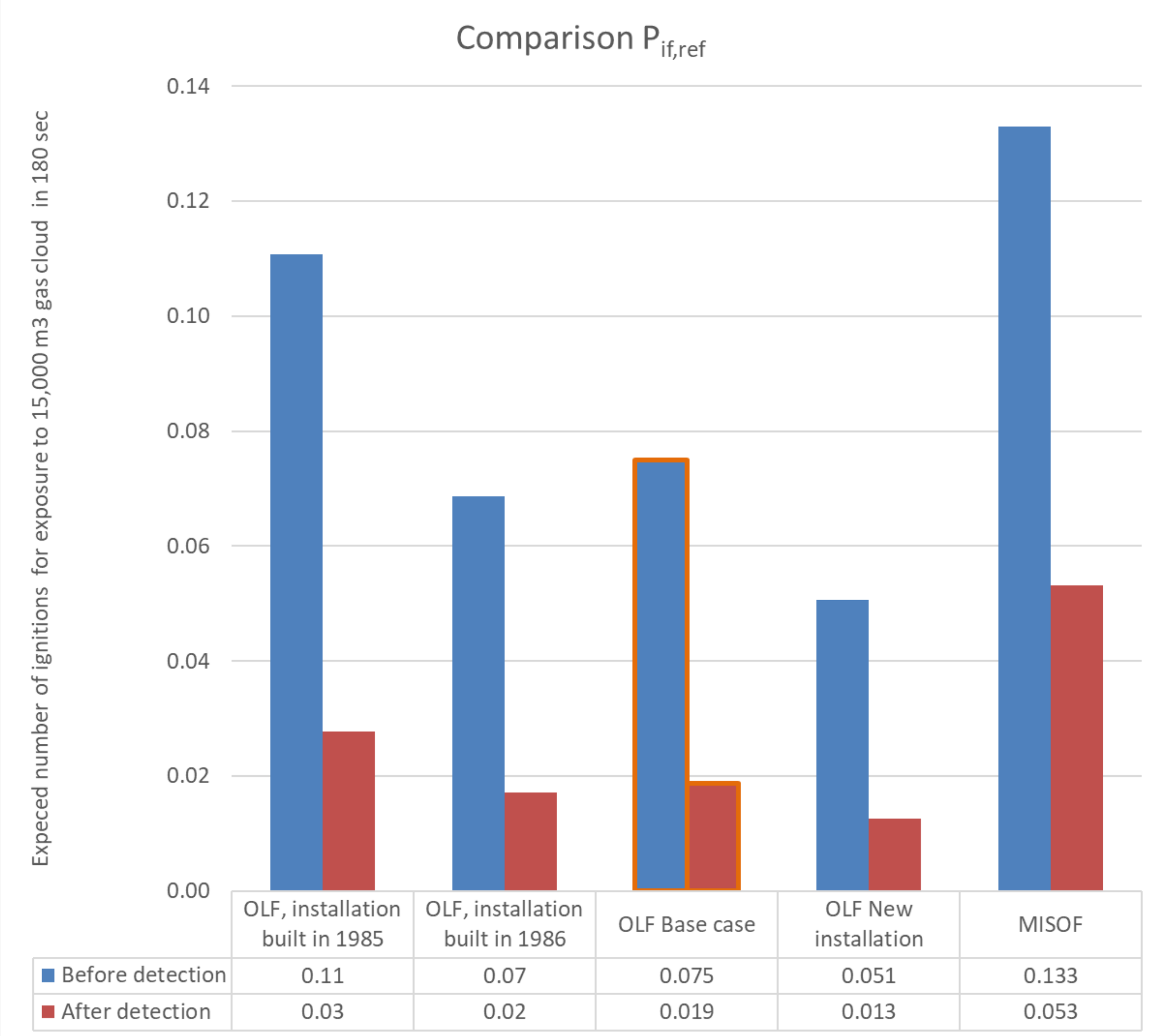


Figure 3-8: Comparison MISOF and OLF in terms of the basic parameter value $P_{if,\ ref}$. established in the OLF model.

A typical gas detection system has been implemented (see table below). The set points are as follows:

- IR point high: 30%LEL
- IR point low: 20% LEL
- LOS high: 2 LELm (LOS = Line of Sight)
- LOS low: 1 LELm

The detectors are distributed in the module based on engineering judgement with regards to the typical layout of detectors in offshore modules. LOS detectors are placed at the edges and parallel to the main pipe rack at the centre of the module.

Isolation of ignition sources are initiated 2 seconds after confirmed detection (*i.e.* upon exposure to 2 out of N detectors). ESD and BD become effective exactly 30 seconds after detection. The delay time is dominated by the closure time of the ESDV's.

Table 3-7: Description modules

Module	Number of IR point detectors	Number of LOS detectors
CM42EW	14	4
	14	4
CM132EW	42	12
	42	12
CM402EW	128	36
	128	36

3.5 Model for dimensioning explosion pressure

A coarse model for the relationship between the stoichiometric gas cloud volume and the expected dimensioning explosion pressure has been used.

The dimensioning pressure in this context is considered to be the global pressure acting on walls and decks in the module.

A coarse model has been used because detailed estimation of explosion loads is not focused in the study. The main aims of the explosion model are to capture that the explosion pressure for a given gas cloud size decrease with increasing module size and the general layout of the modules in terms of global ventilation conditions. The general positive effect of the module size is explained by that the combustion products are allowed to expand more freely in a bigger module. This effect decreases with the gas cloud size.

The model is partly based on engineering judgement and partly based on sensitivity calculations run with KFX^{TM}-EXSIM for the different modules.

The general mathematical expression for the relationship between the stoichiometric gas cloud size, V, and the dimensioning explosion pressure, $P_{ExDim}(V)$, is as follows:

$$P_{ExDim}(V) = P_{Max} \cdot \left(\frac{V}{V_{Max}}\right)^m \cdot B(V, \alpha, \beta) \qquad (5.1)$$

where $B(V, \alpha, \beta)$ is the regularized incomplete beta function, which is a cumulative probability distribution ensuring that $P'_{ExDim}(V) > 0$ for $V > 0$.

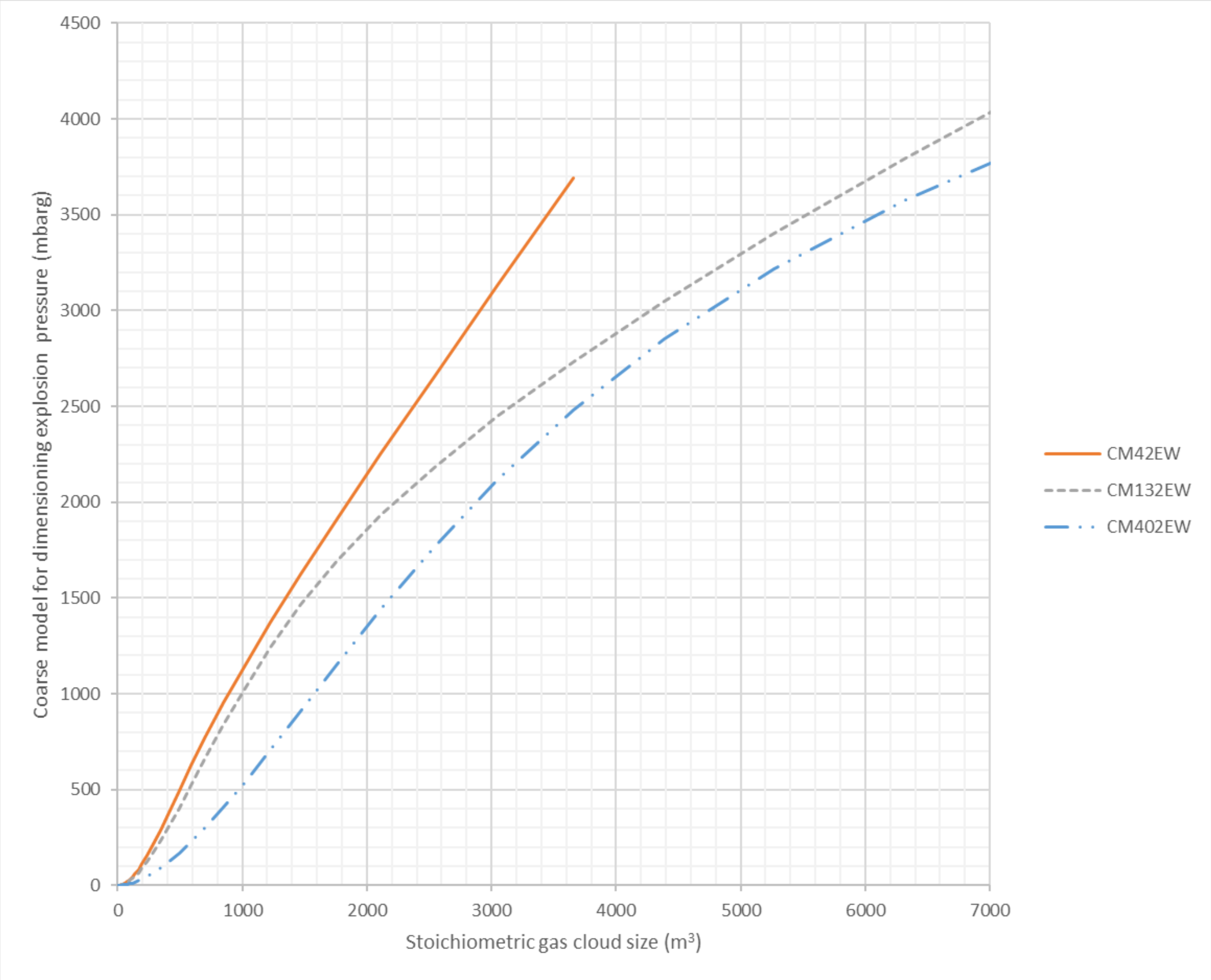


Figure 3-9: Coarse model for dimensioning explosion pressure.

Table 3-8: Parameters in the explosion model (Equation (5.1))

Parameter	CM42EW	CM132EW	CM402EW
P_{Max} $(mbar)$	4,000	5,000	7,000
V_{Max} (m^3)	4,000	10,000	25,000
m	0.9	0.6	0.48
α	1.3	1.35	1.4
β	16	20	18

3.6 Time-dependant model in KFX^{TM}-RBM

About 200 leak scenarios have been selected manually covering various initial leak rates and wind conditions. The leak scenarios are similar, but not exactly the same for all modules. The number of scenarios per module is presented in Table 3-9.

A list describing the simulated leak scenarios is enclosed in Appendix A.

Table 3-9: Number of scenarios per module

Number of scenarios	CM42EW	CM132EW	CM402EW
Number of scenarios	190	257	182

The KFX^{TM}-RBM feature calculates the ignition probability per control volume in the domain per ignition mechanism and per equipment type. For the generic ignition sources, results can be divided according to any volumetric representation put into the module. The results for one leak scenario in CM42EW varying the initial leak rates are shown in the following figures.

The boundary condition describing the leak rate is calculated automatically versus time based on the detection time (plus response time of the detector and delay time due to signal processing and ESD valve closure time) resulting from exposure to any two of the detectors in the module. The time dependent leak rate reflects the capacity of the BD system (10 minutes to 6.9 barg is assumed). The delay time until closure of the ESD valves and opening of the BDV is 30 seconds.

Note the transient behaviour of the leak rate in Figure 3-12. The segment of which the leak is stemming from is fed by 30 kg/s prior to closure of the ESD valves. Thus, for leaks above 30 kg/s the pressure in the segment will decrease before the ESD valves has closed. This pressure decrease is calculated transiently in KFX-RBM. The actual response of a process system in such will be more complex than the model applied.

For the example below, detection occurred after a few seconds, which is the general result for almost all cases. The only cases with detection time significantly longer than 10 seconds are the small leaks (< 1 kg/s) in CM132EW and CM402EW.

It is important to note that the generated probability distributions from the probabilistic model are based on a limited number of samples (*i.e.* leak scenarios). A few hundred scenarios are too few to give a very accurate estimate of the underlying distribution for the various modules. A representative selection of scenarios in terms of leak location, leak direction and wind conditions has been selected. This means that if more simulations where run, is considered equally likely that the updated risk estimates results in higher or lower frequencies/ignition probabilities.

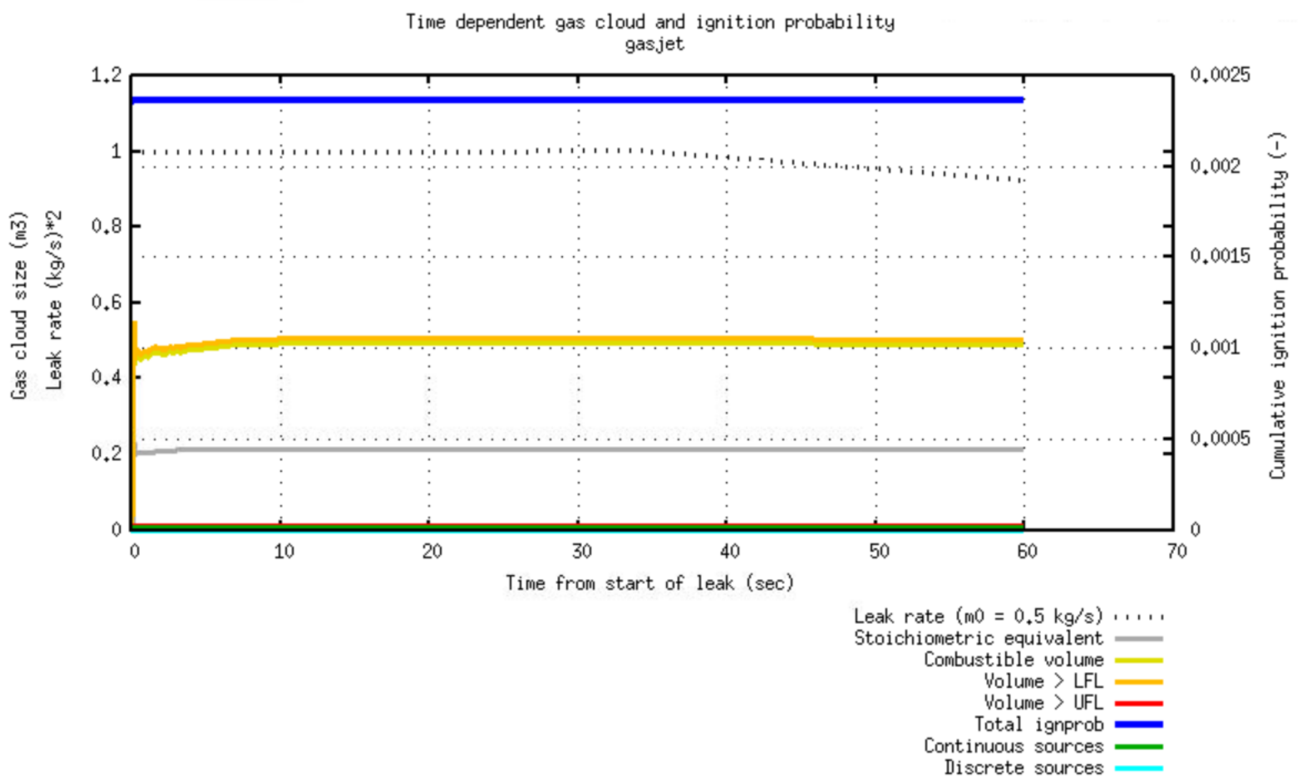


Figure 3-10: Transient result for 0.5 kg/s gas leak in CM42EW.

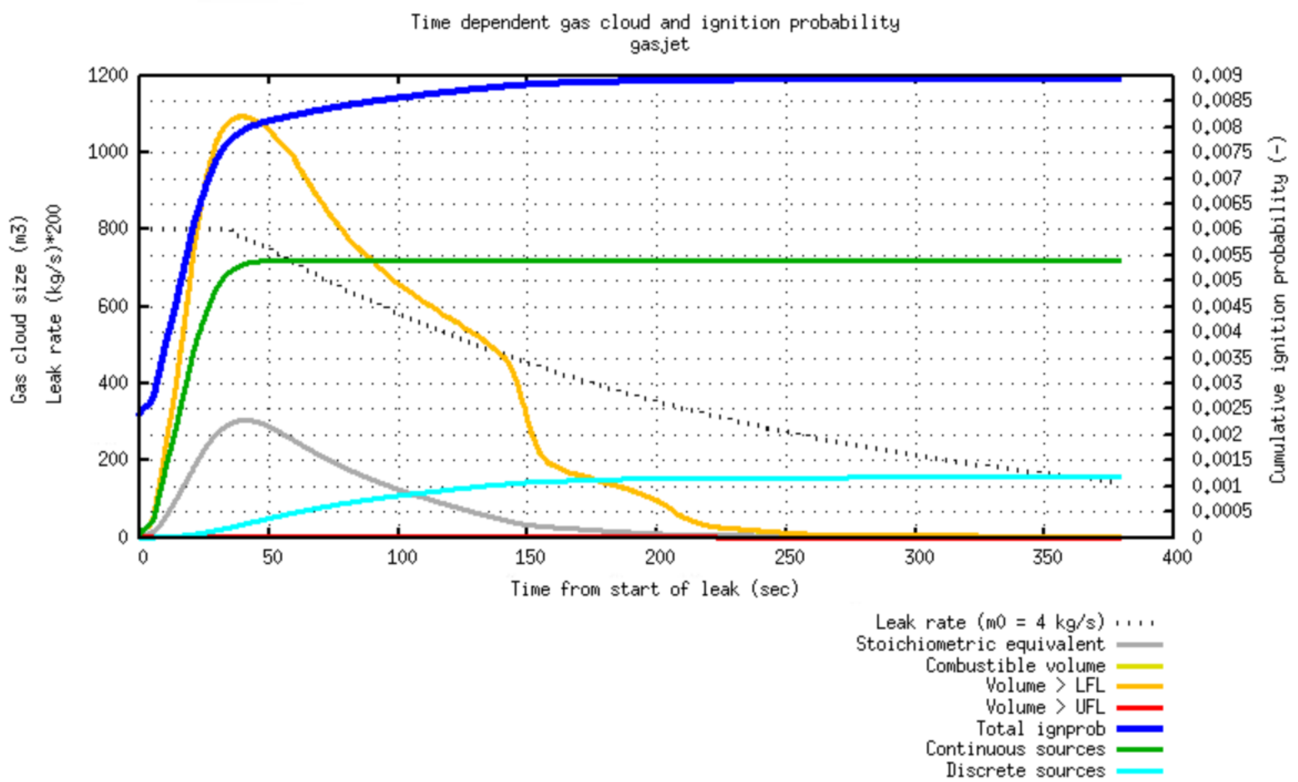


Figure 3-11: Transient result for 4 kg/s gas leak in M43OSV

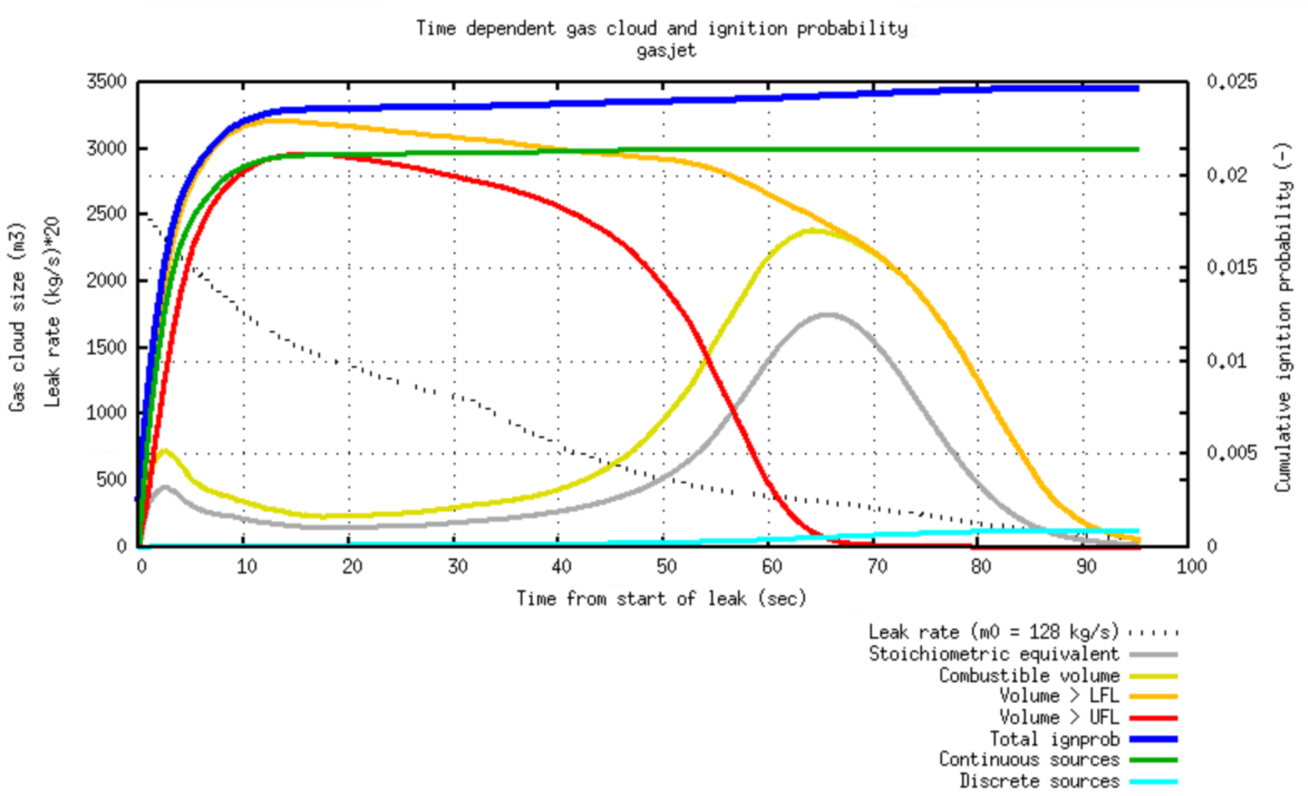


Figure 3-12: Transient result for 128 kg/s gas leak in M43OSV

4 Ignited gas cloud distributions

4.1 General

The resulting ignited gas cloud frequency distributions are presented in the following sections focusing on various aspects.

The first section looks at the differences between the obsolete models (SHLFM and OLF) and the superseding probabilistic models (PLOFAM and MISOF).

The caption ‘PLOFAM2’ is used in the figures to denote that rev. 2 of the PLOFAM model issued in December 2018 has been applied.

4.2 Comparison previous leak frequency and ignition models

The resulting ignited gas cloud frequency distributions are presented in Figure 4-1, Figure 4-2 and Figure 4-3 for the three modules based on the two probabilistic models for loss of containment and ignition control:

- PLOFAM and MISOF.
- SHLFM and OLF

It must be noted that the used correction factors in the OLF model corresponds to a platform that has been set in operation in the 80’s. These correction factors are not applicable in the MISOF model. If a new installation was used as basis, the ignition probabilities generated by use of the OLF module would be significantly less.

The resulting total fire frequency and total ignition probability for the two probabilistic models is presented in Figure 4-5 and Figure 4-6 (the corresponding leak frequency can be found in Figure 4-4).

The following are extracted from the results:

- the relative distribution generated by application of the previous models (SHLFM and OLF) is somewhat skewed towards ignition of smaller gas clouds compared to the upgraded models. This does not appear looking at the frequency distribution due to the effect of the leak frequency model (SHLFM predicts much higher leak frequency than PLOFAM). This is judged to be explained by two aspects:
  - the limited leak scenario in SHFLM reducing the frequency for delayed ignition of big clouds
  - the much higher P_{iso} value in OLF reducing the delayed ignition probability of big clouds
- the frequency distribution for ignited gas clouds is shifted towards much smaller gas using the the PLOFAM-MISOF models compared to the SHLFM-OLF model. Here it must be emphasized that the applied OLF model parameters corresponds to a module set in operation in the 80’s. The correction factors in the OLF model favour new installations, and the distributions are expected to become more similar if it were assumed that the modules were green fields. This is demonstrated in Figure 4-7 through Figure 4-9 where the result assuming

that the installation is new (see Table 3-6) is shown. These correction factors have been disregarded in the MISOF model in lack of evidence supporting them (both statistically and technically).

- the generated total fire frequency will be considerably less using the upgraded models. The leak frequency generated by the PLOFAM model is considerably less than the leak frequency estimate provided by the SHLFM model, especially for large leaks. The large reduction in leak frequency outweighs the significant increase in ignition probability generated by MISOF. Based on these results, it is expected that the new models will generate lower fire frequencies in most cases. Hence, PLOFAM-MISOF will produce lower risk figures in terms of risk metrics measuring consequences due to fires, for example impairment of escape ways due to smoke and escalation to pressurized equipment or structures. The generated fire frequency using PLOFAM and MISOF is in line with the observed historical frequency. The SHLFM-OLF models generated excessive estimates of the fire frequency.

It must be noted that the SHLFM and the OLF model is not recommended to be used for estimation of the fire and explosion risk. Both models deviate much from the observed historical data and our understanding of the performance of the barriers affecting the risk.

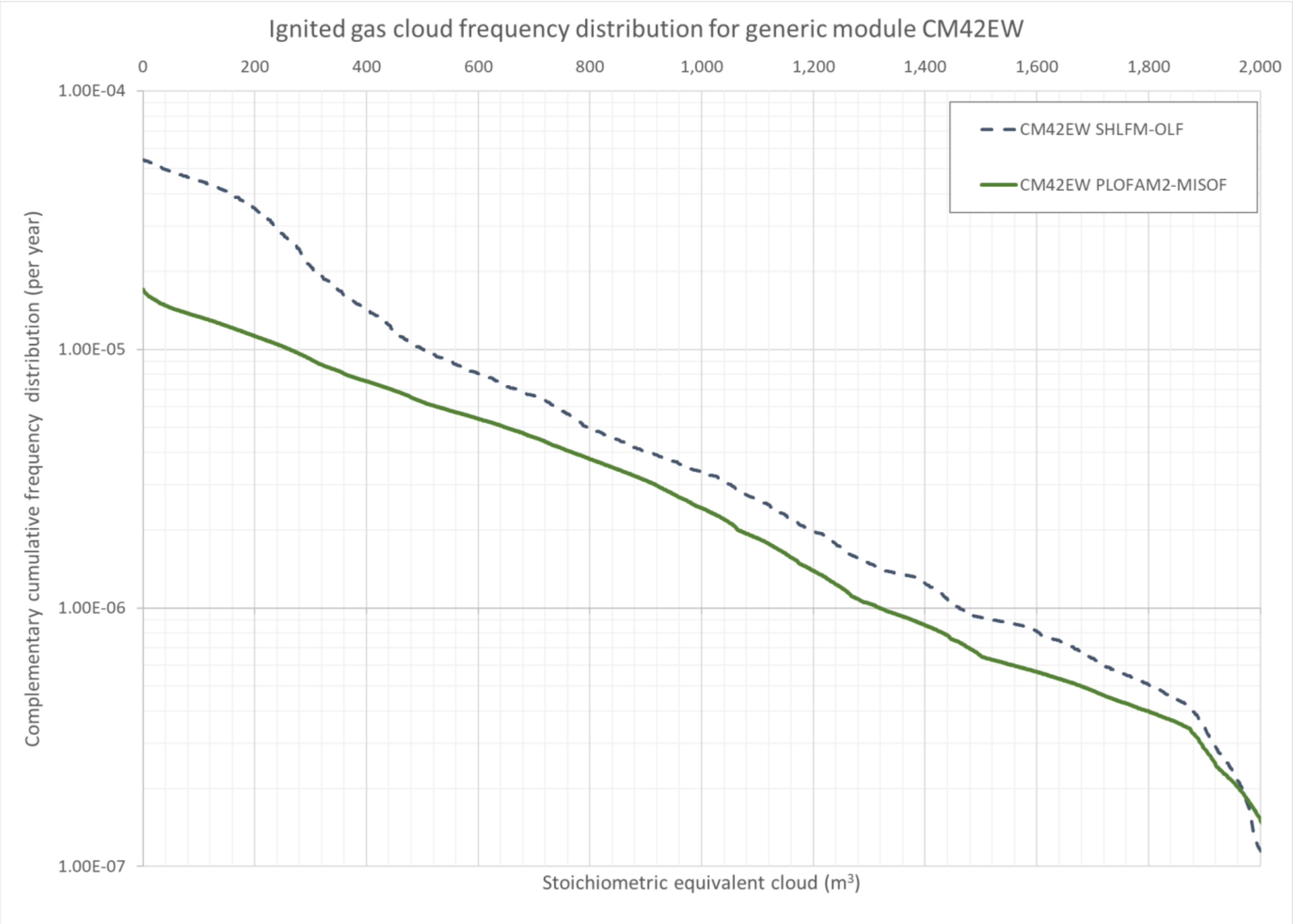


Figure 4-1: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM42EW.

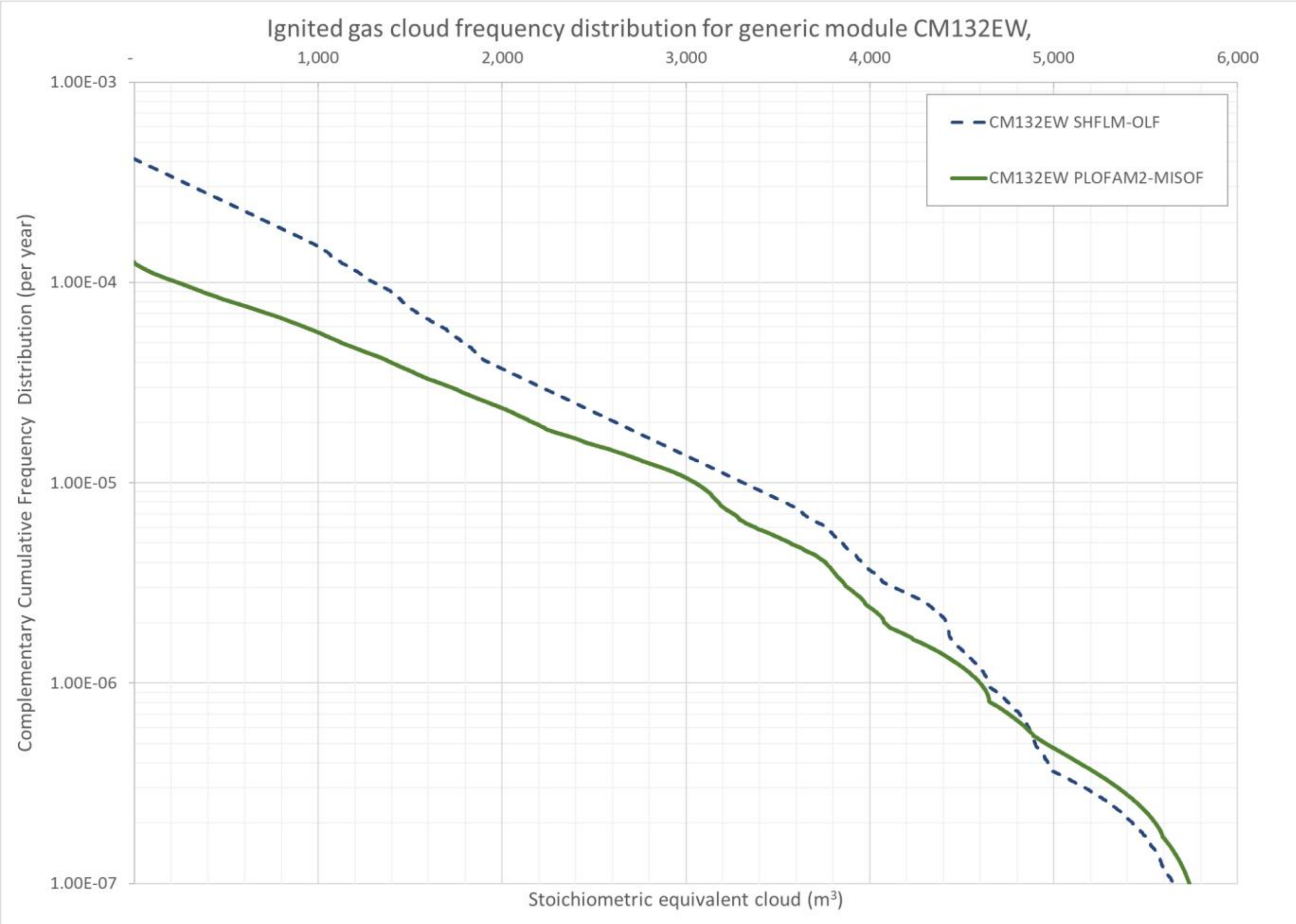


Figure 4-2: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM132EW.

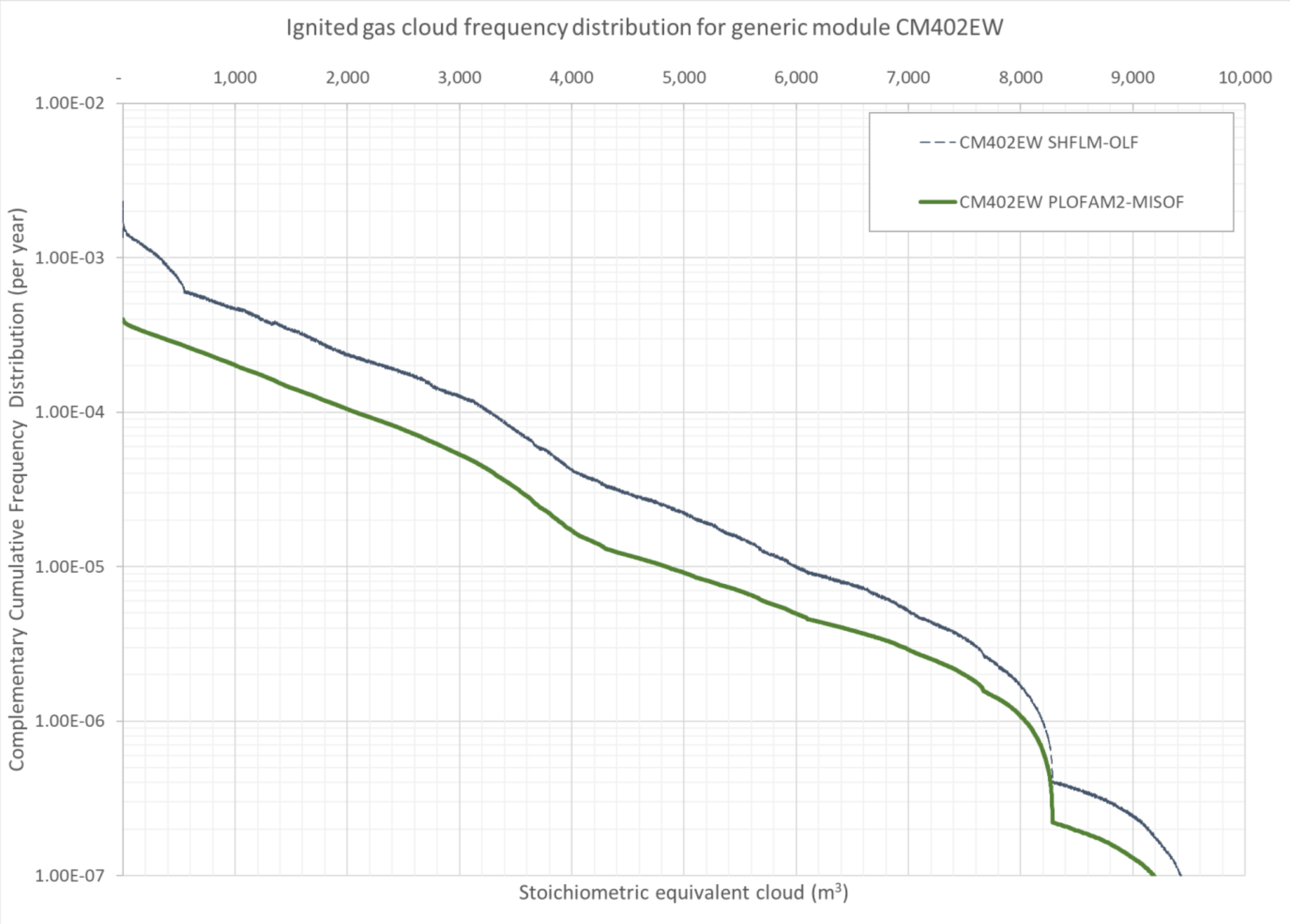


Figure 4-3: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM402EW.

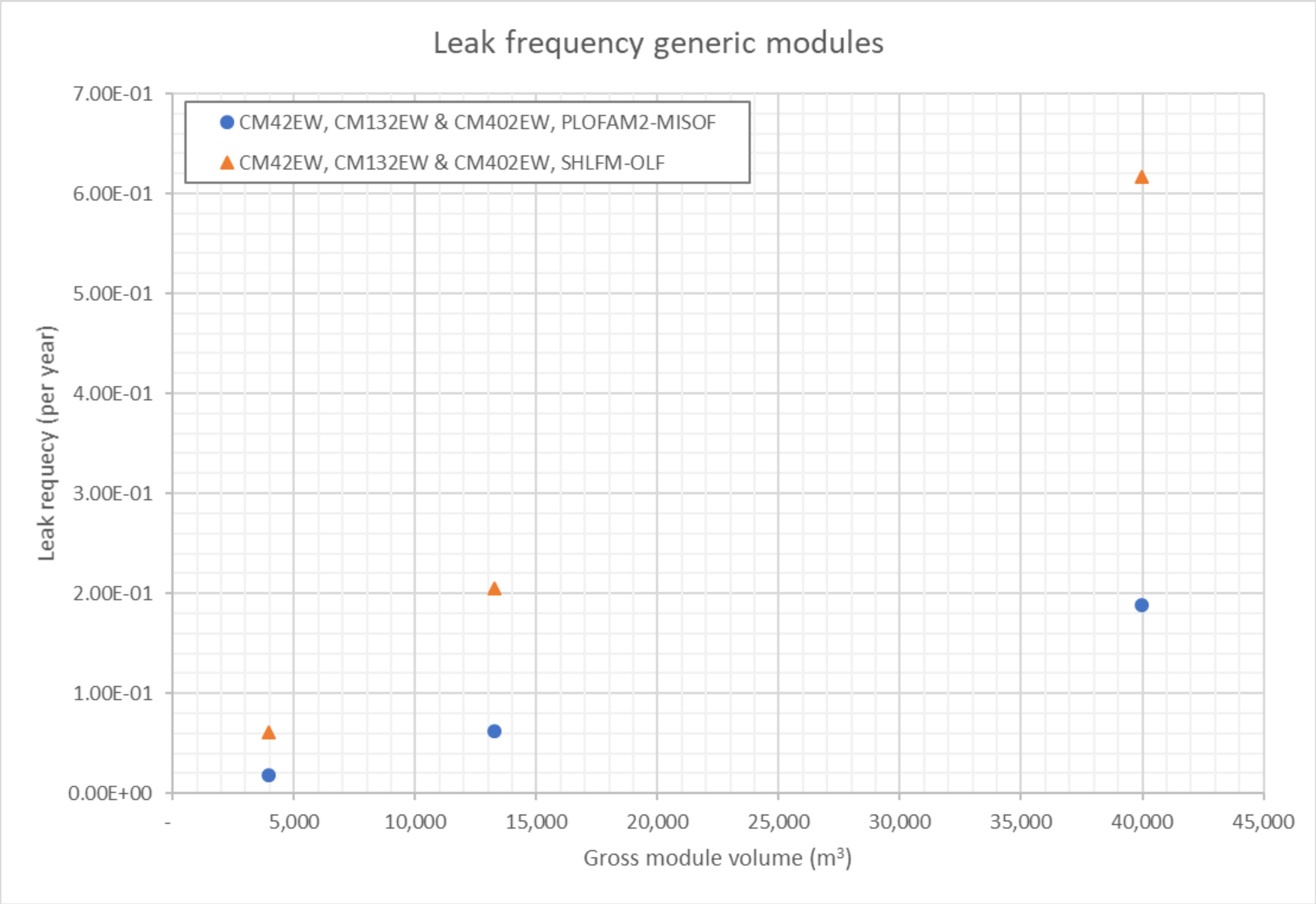


Figure 4-4: Leak frequency vs. module volume for the various modules and probabilistic models

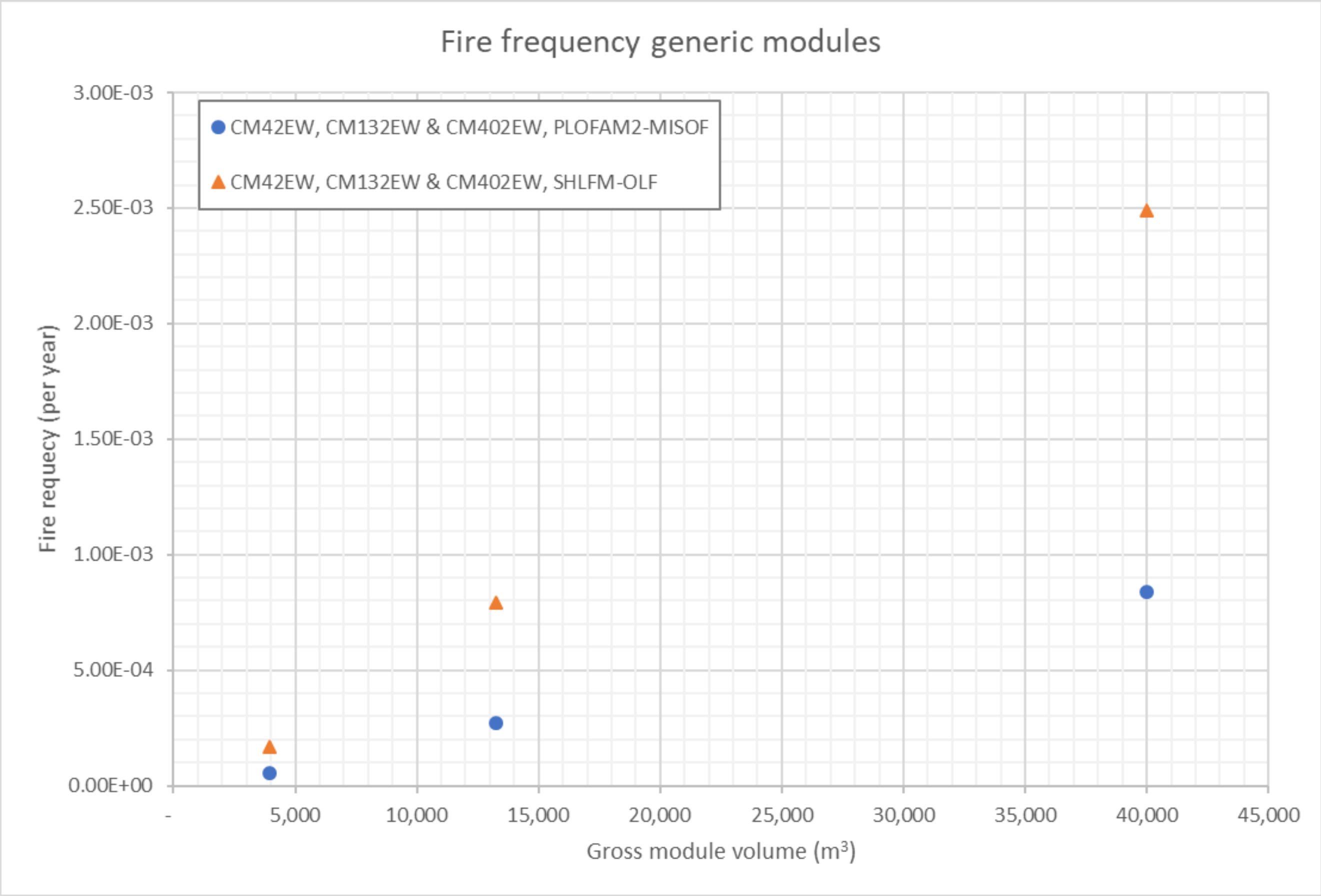


Figure 4-5: Fire frequency vs. module volume for the various modules and probabilistic models

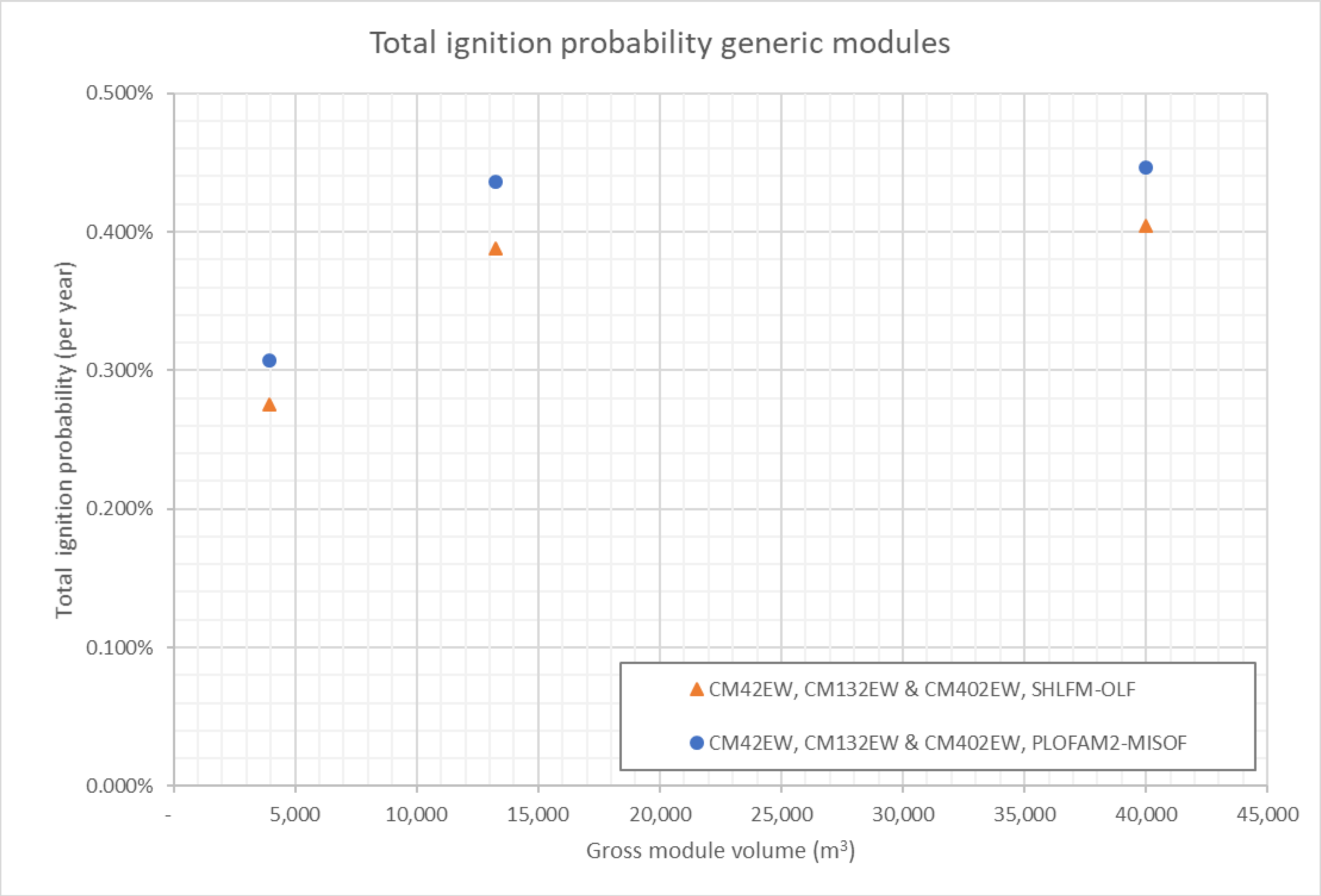


Figure 4-6: Total ignition probability vs. module volume for the various modules and probabilistic models

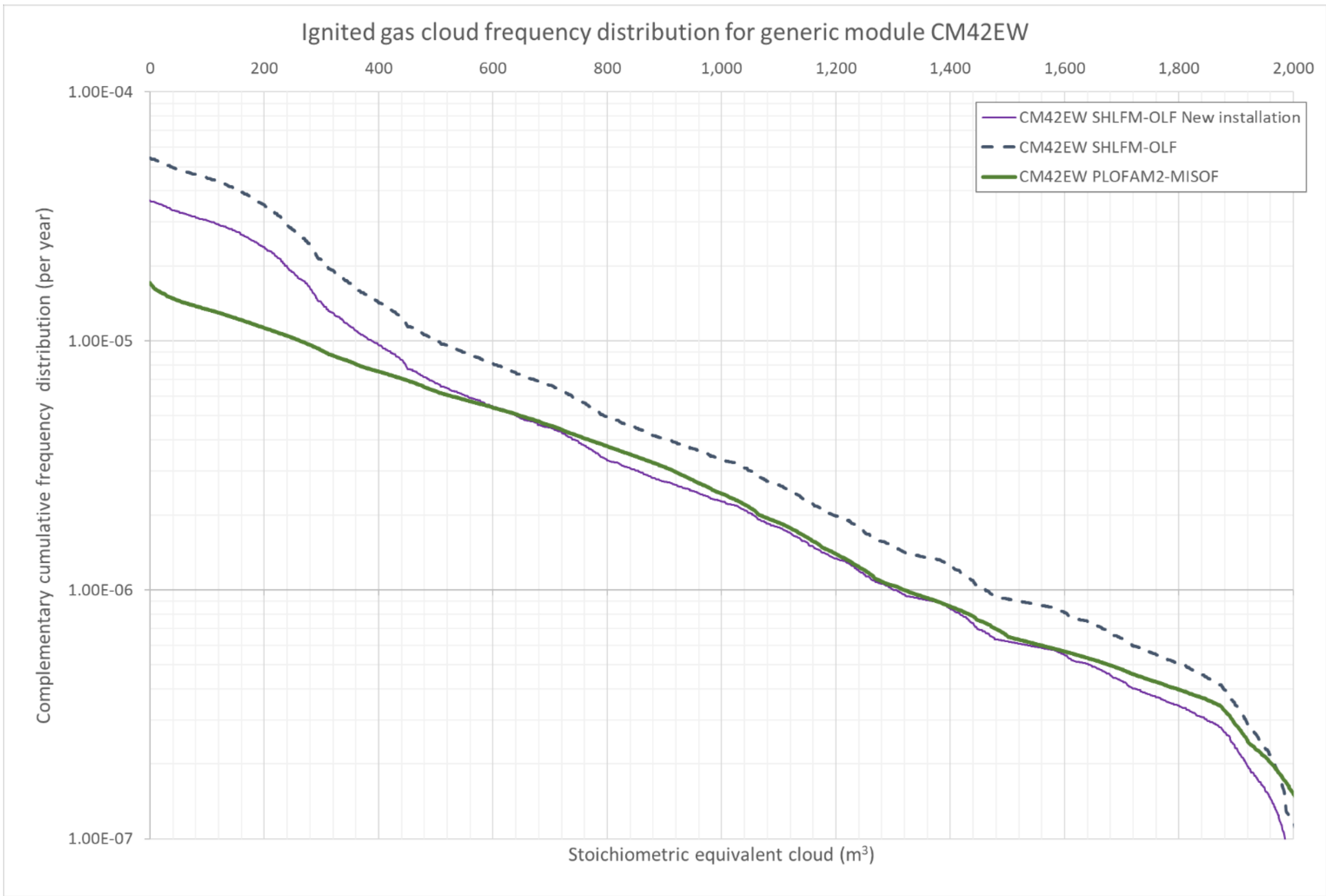


Figure 4-7: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM42EW including sensitivity with OLF model assuming new installation. A correction factor of 0.675 has been used to reflect a new installation (see Table 3-6).

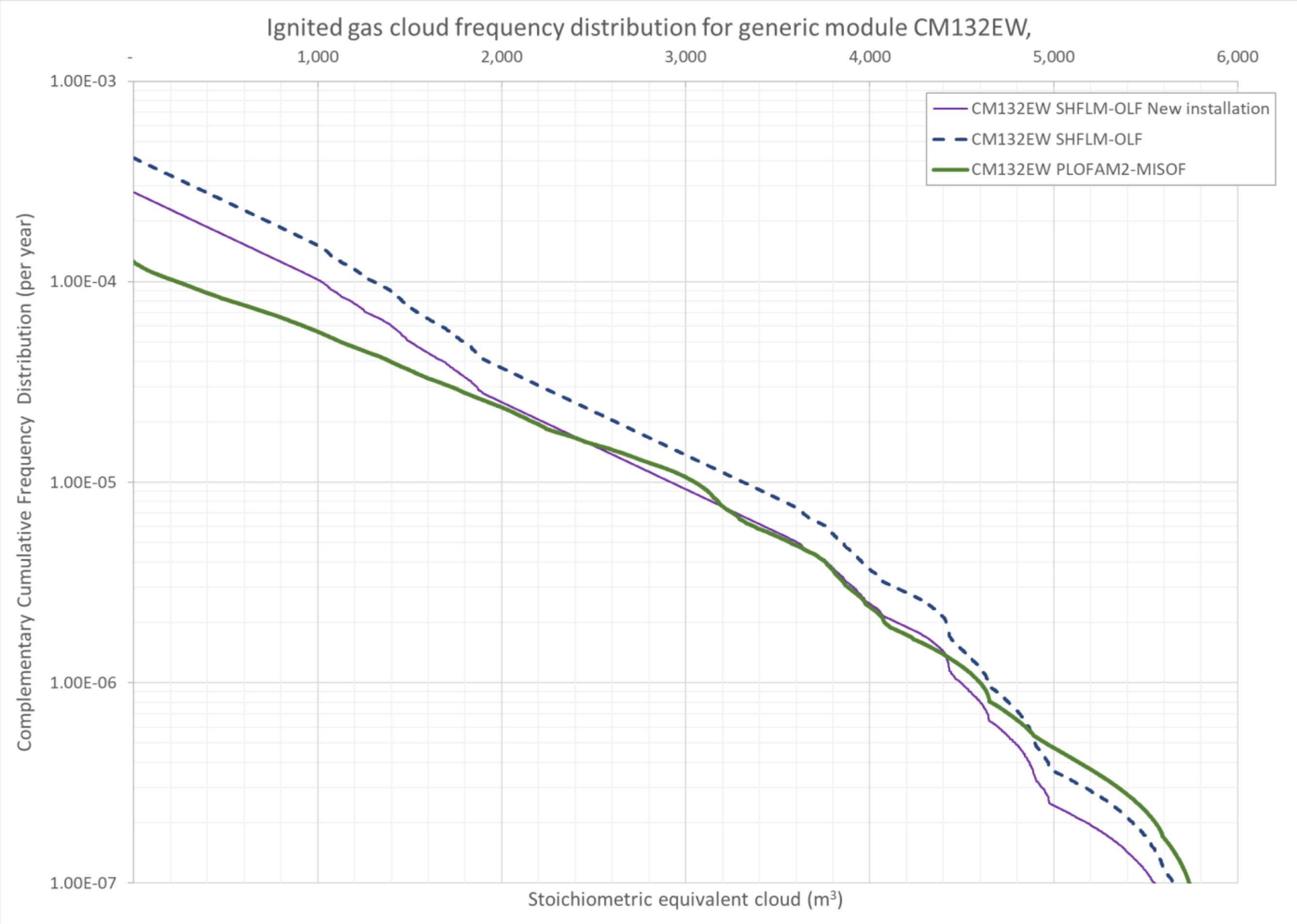


Figure 4-8: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM132EW including sensitivity with OLF model assuming new installation. A correction factor of 0.675 has been used to reflect a new installation (see Table 3-6).

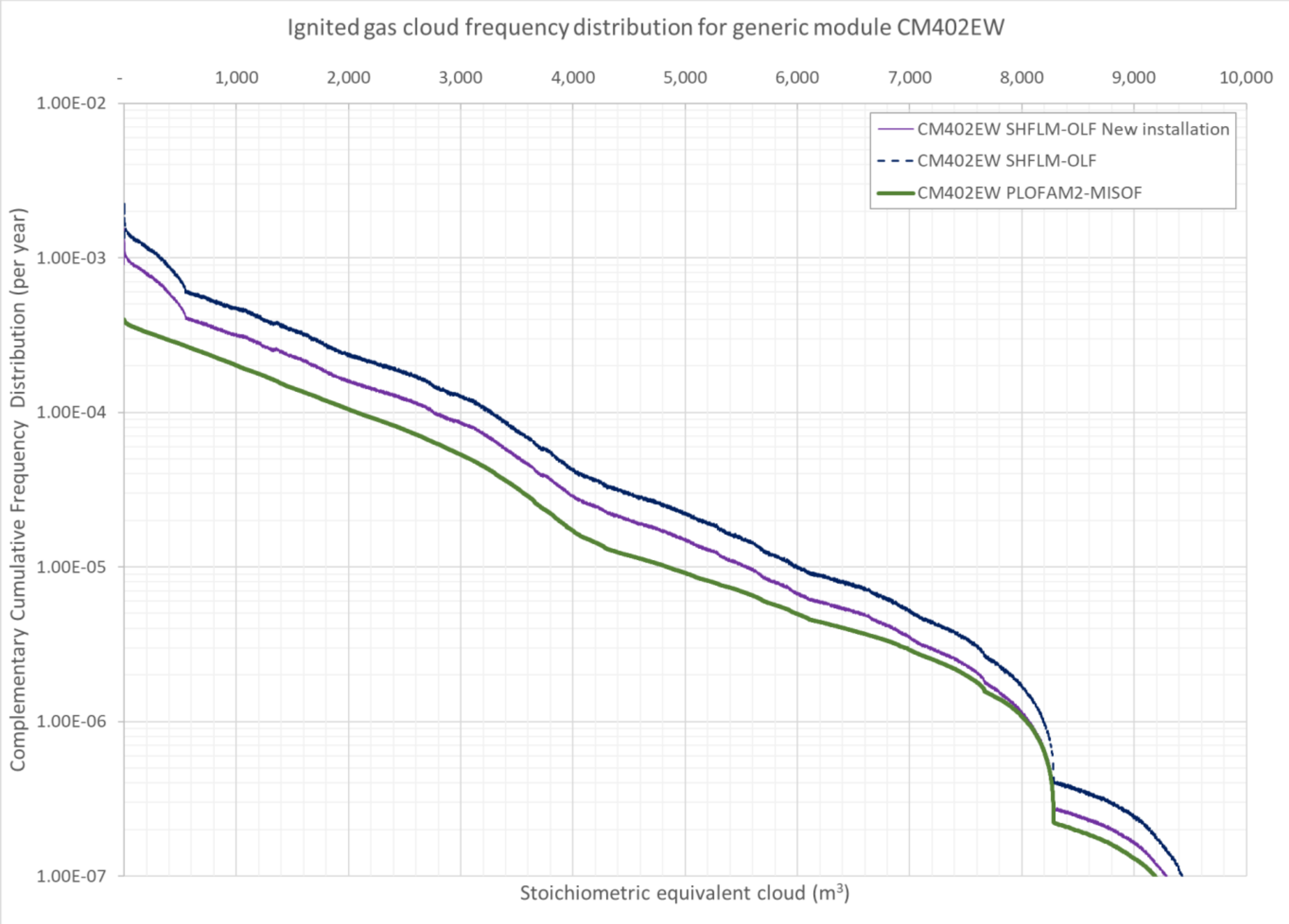


Figure 4-9: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM402EW including sensitivity with OLF model assuming new installation. A correction factor of 0.675 has been used to reflect a new installation (see Table 3-6).

4.3 Contribution from continuous vs. discrete sources

The figures below display the frequency distributions per module per ignition mechanism in the MISOF model.

The results show that the dominant contributor is continuous sources for all modules. The contribution from discrete sources is most prominent for CM132EW, which is due that this module has the poorest ventilation rate. Slow ventilation of the combustible atmospheric cause prolonged exposure to potential sources of ignition in the late part of the leak scenario.

The dominant contribution from continuous sources in the biggest module (CM402EW) is caused by large leaks generating a rapidly expanding gas cloud materialising ignition within short time after start of the leak (see Figure 4-15). Hence, massive leaks (larger than about 50 kg/s) are a key driver for the resulting frequency distribution, which implies that the modelling of large leaks are in many situations critical for the accuracy of a QRA.

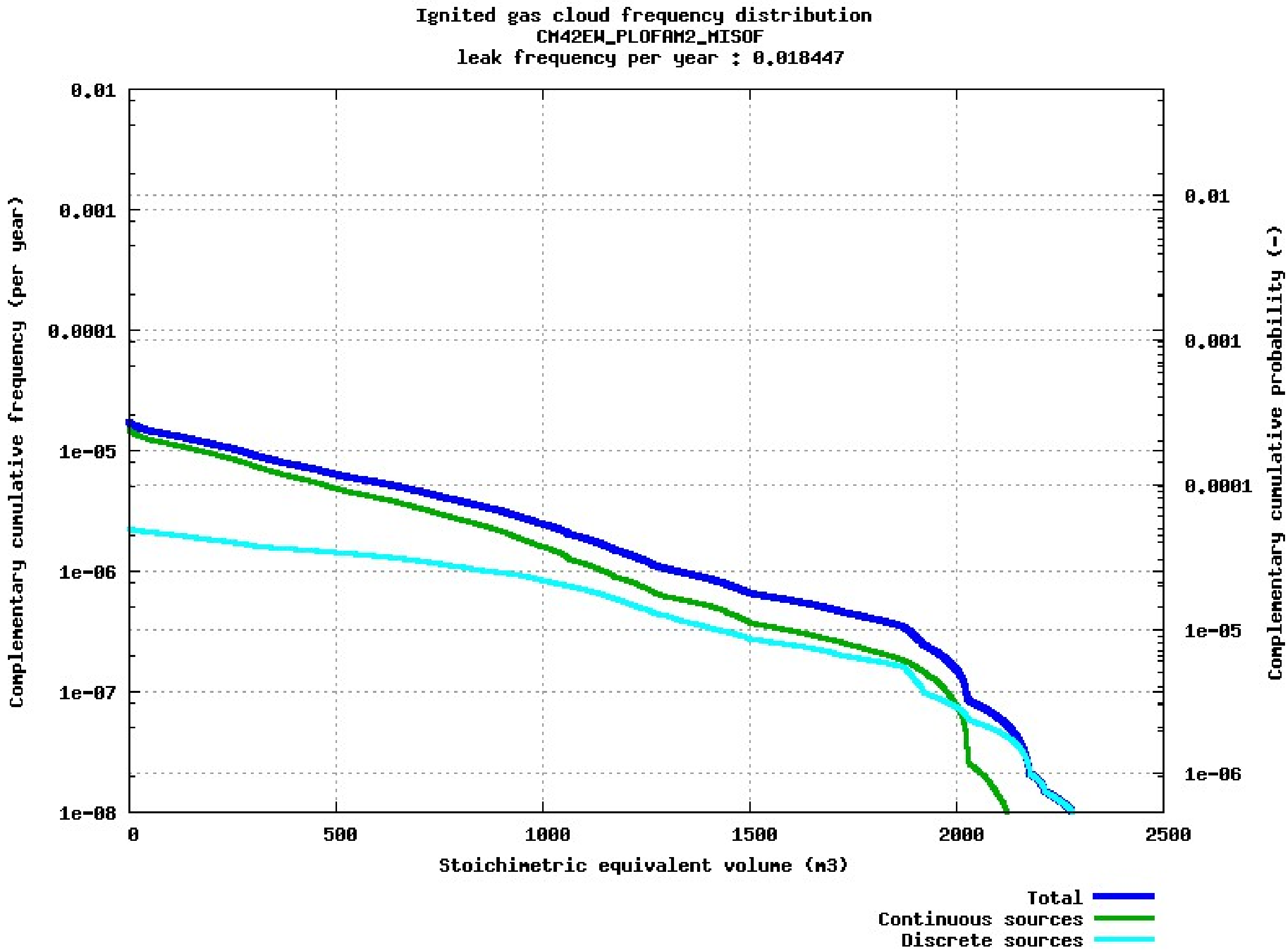


Figure 4-10: CM42EW PLOFAM-MISOF: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud

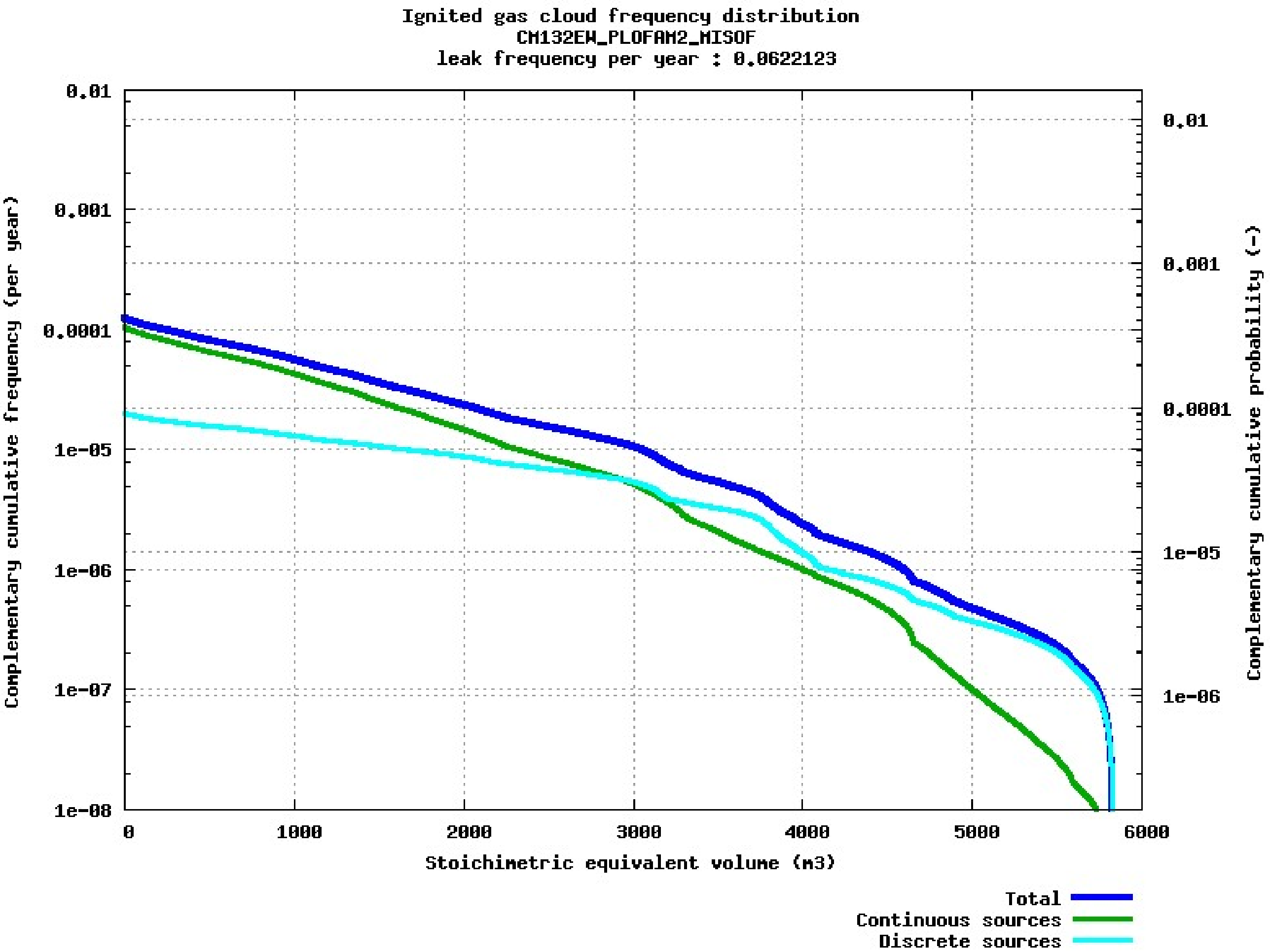


Figure 4-11: CM132EW PLOFAM-MISOF: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud

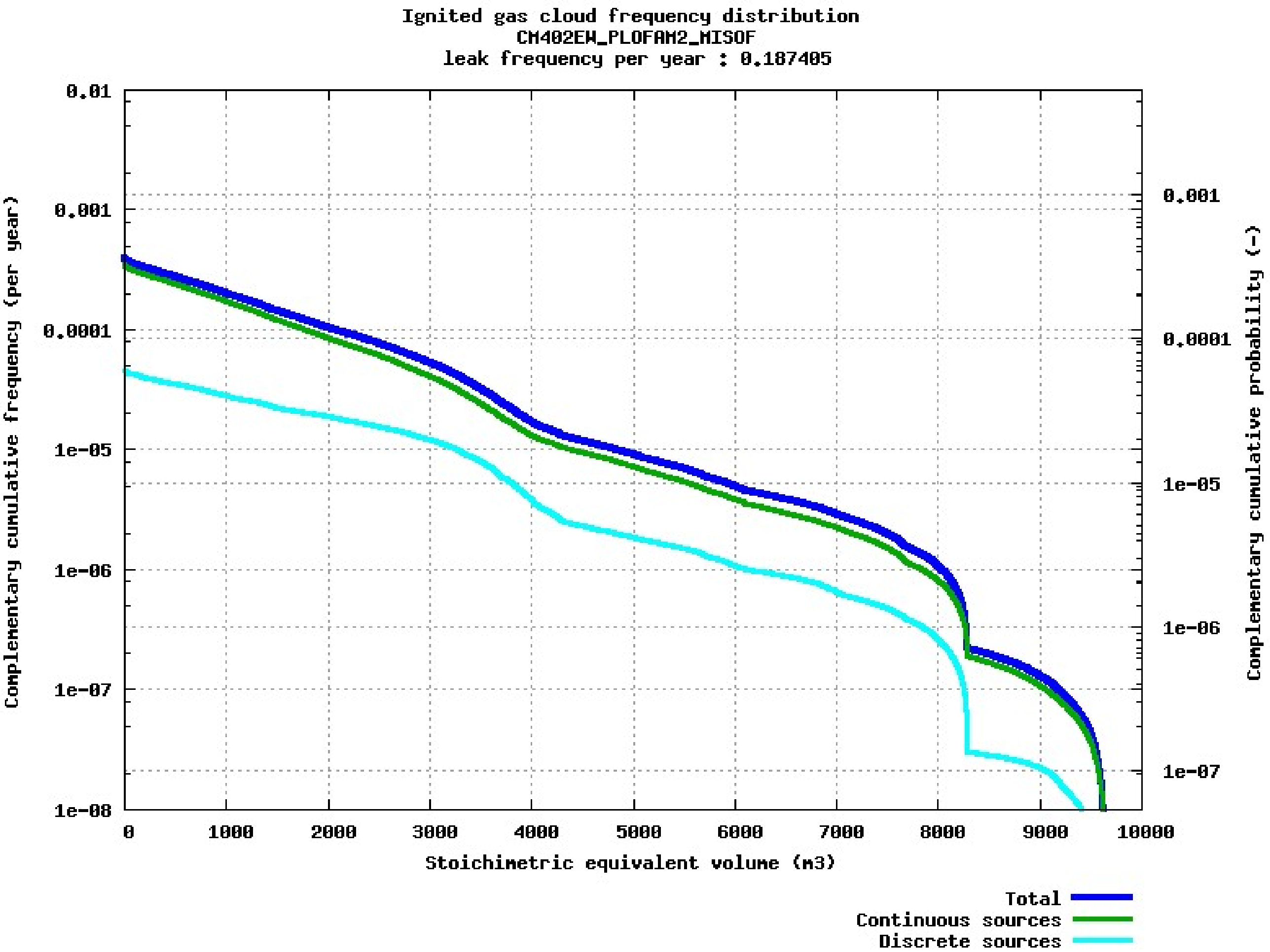


Figure 4-12: CM402EW PLOFAM-MISOF: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud

4.4 Ignition time

The figures below present the frequency distributions with respect to the ignition time.

The results show that most ignitions tend to occur before 1 minute after start of the leak. This is related to that the continuous ignition mechanisms are the dominant idealisation of ignition mechanisms in the MISOF model. Large leaks that generates big gas clouds within a few seconds drives the explosion risk according to the model. The continuous ignition mechanism is materialized upon first time exposure, and the effect of the safety functions is relatively small within the initial half a minute or so. It is hard to find basis for the ignition time. The statistical basis for the MISOF model indicates that ignitions take place rather early.

It is important to be aware of that MISOF will tend to lead to ignitions at an early stage of the unfolding scenario. This result may lead to the conclusion that the safety functions controlling the duration of the leak has little importance for the explosion safety. The idealization of ignition mechanisms in MISOF is uncertain, and the result from MISOF in this regard should not be used to compromise the performance of systems in place to control ignition and loss of containment. The main objective of the MISOF model is to generate a reasonable distribution of ignited gas clouds on line with the historical data. Further work should address the uncertainty related to the idealization of ignition mechanisms in MISOF.

Discrete sources dominate after 1 minute, but the contribution is small relative to the contribution materialized from continuous sources at the early stage of the scenario.

The late ignitions are typically stemming from long duration liquid leaks in low wind conditions.

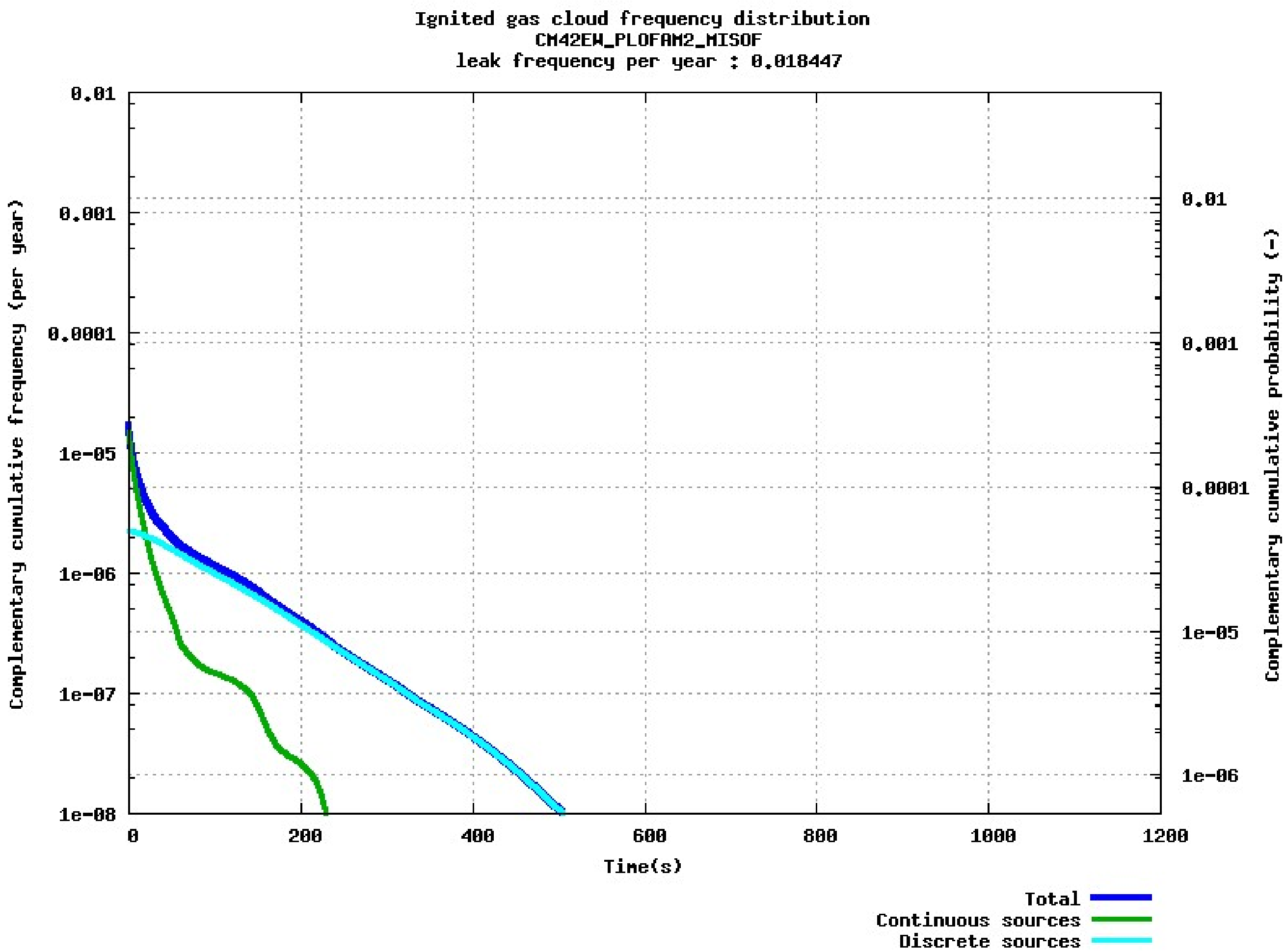


Figure 4-13: CM42EW PLOFAM-MISOF: Complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

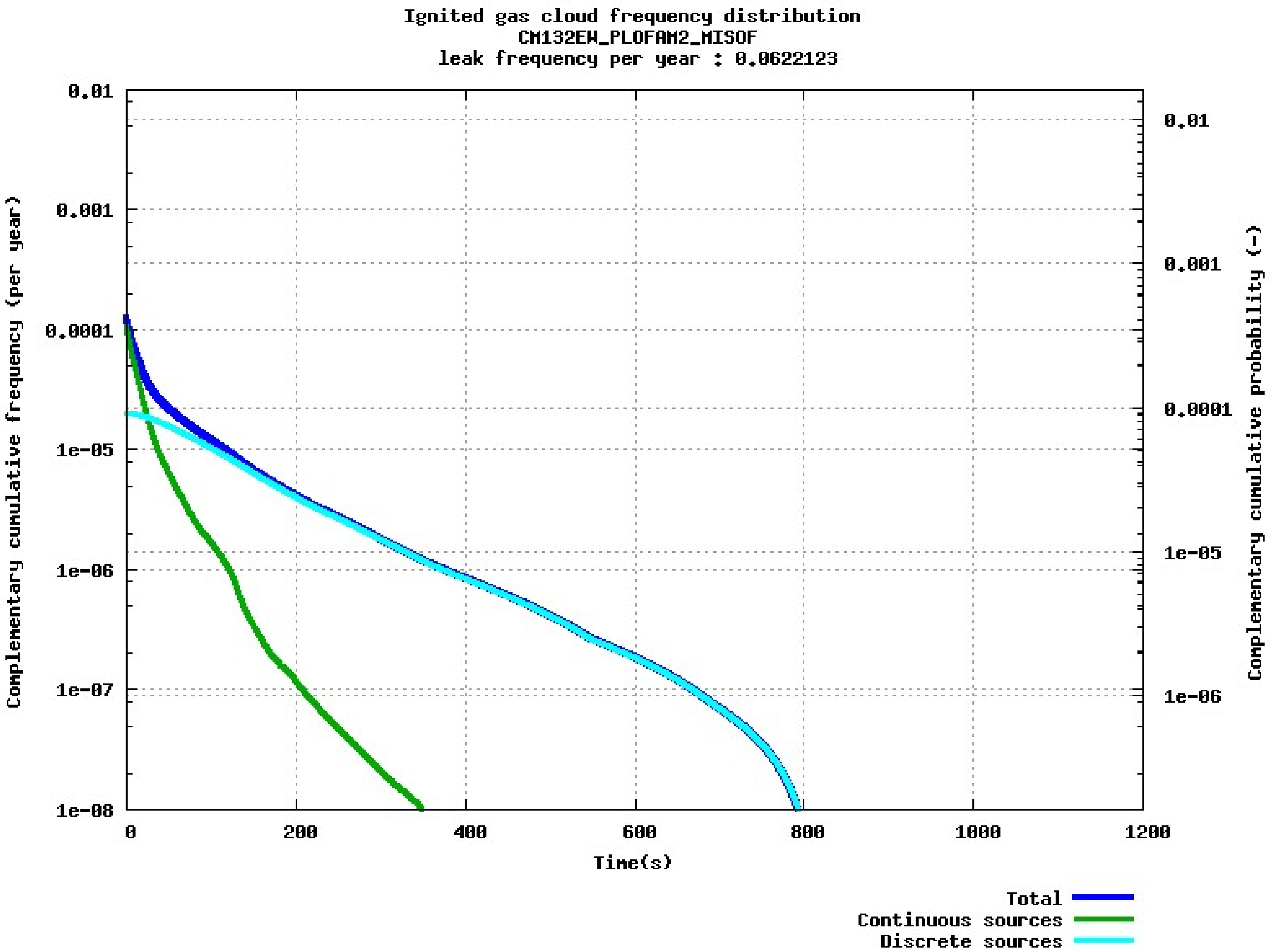


Figure 4-14: CM132EW PLOFAM-MISOF: Complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

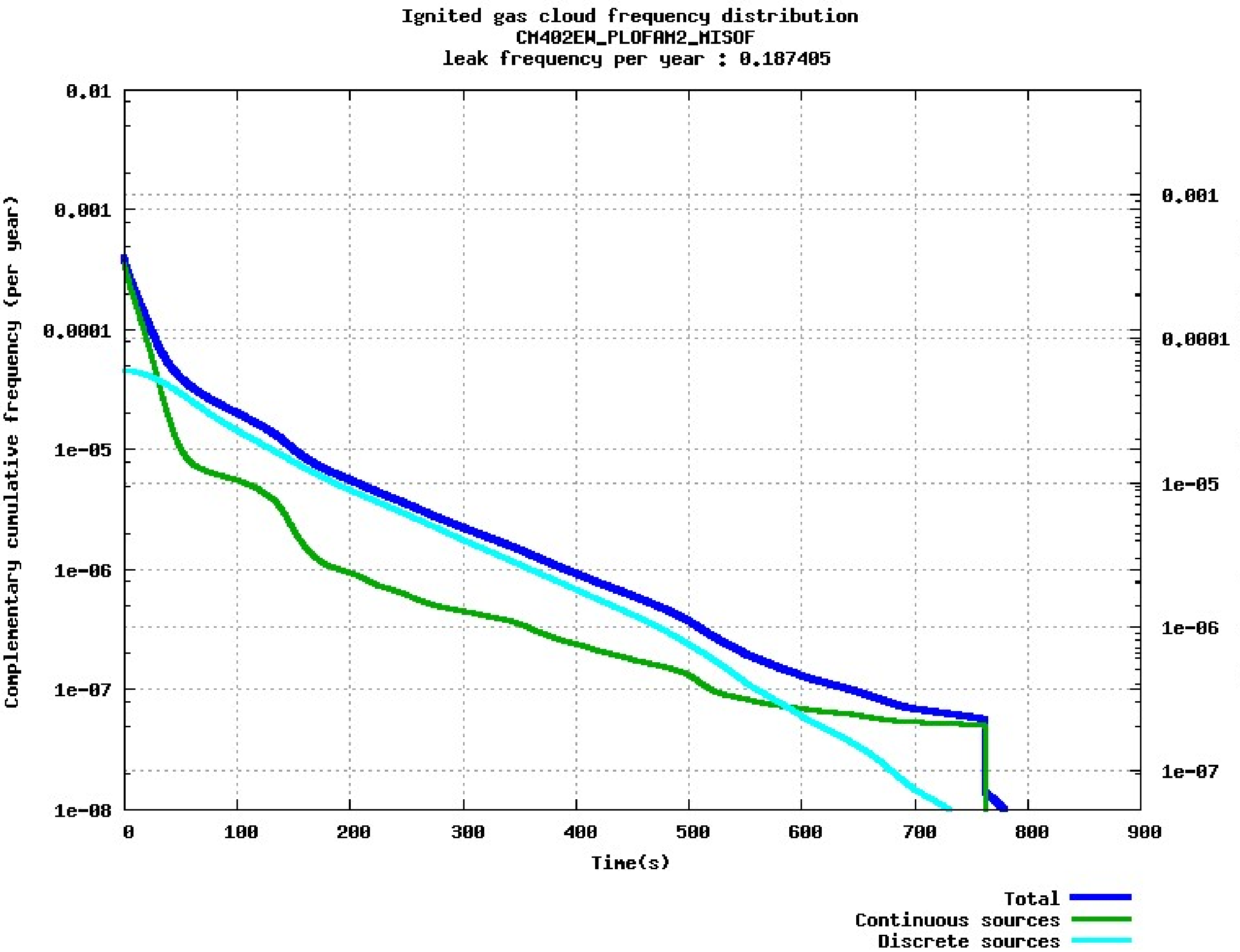


Figure 4-15: CM402EW PLOFAM-MISOF: Complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

4.5 Contribution per equipment category

Figure 4-16 presents the contribution per equipment category for CM42EW. The result shows that the contributor is in the same range. Note the difference in slope of the distributions, which is due to difference in the P_{iso} parameter as well as the varying weight on the discrete and continuous ignition mechanism for the three equipment categories.

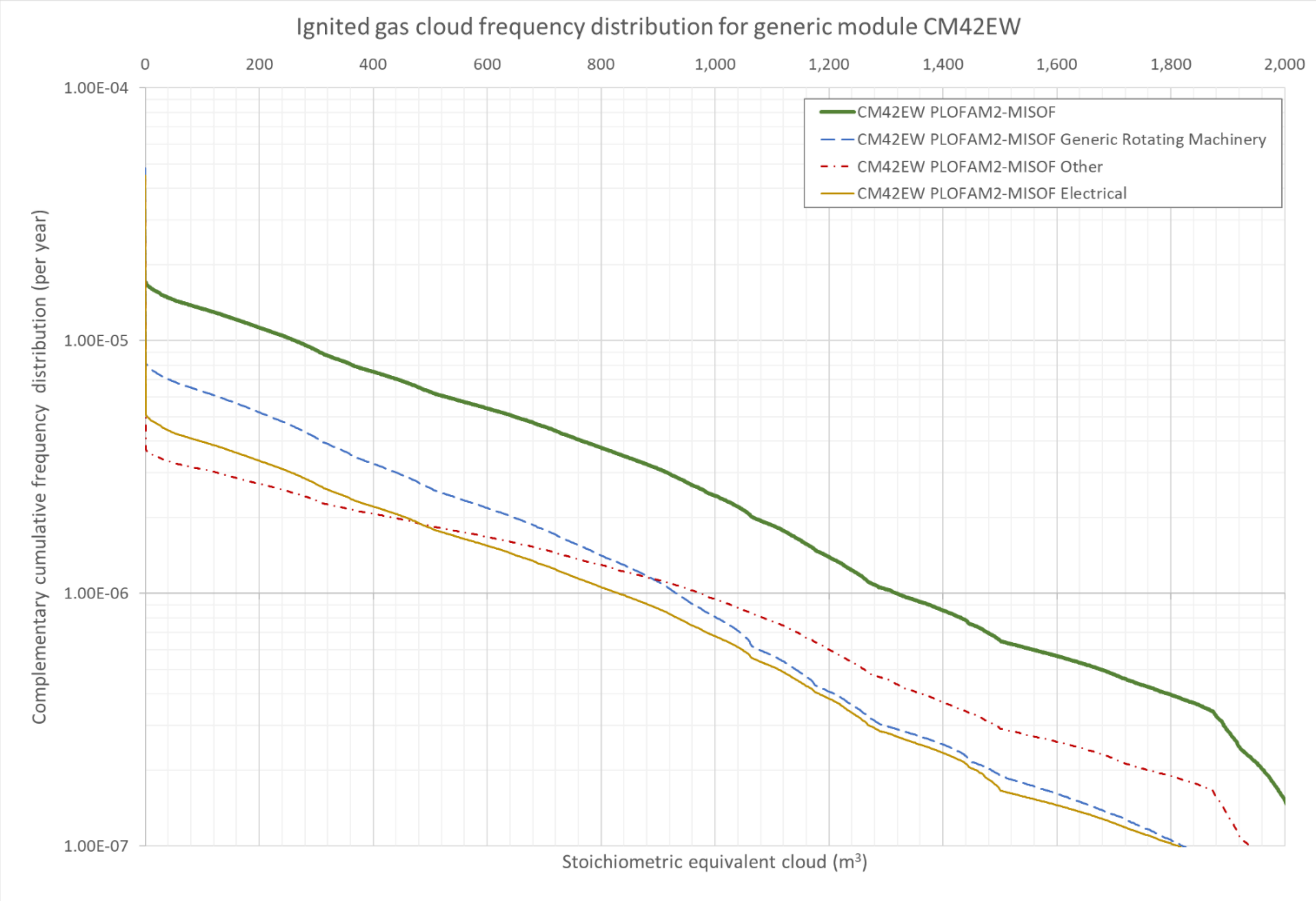


Figure 4-16: CM42EW PLOFAM-MISOF: Complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

4.6 Generic vs. specific modelling of rotating machinery

Figure 4-19 and Figure 4-20 presents the results for CM42EW and CM132EW based on modelling the specific location of the pumps in the modules. The number of pumps in both cases are scaled to approximately equal the average number of operative pumps in an offshore module in the North Sea.

The pumps have been located at the deck level. Their location is shown in Figure 4-17 and Figure 4-18. Note that the pumps quite evenly distributed.

The results demonstrate that the effect of specific modelling of the rotating machinery is not very prominent for the small module. This is explained by that the pumps are evenly distributed and that the module is quite small. In a small module with small ventilation openings, such as CM42EW, massive exposure of potential ignition sources will materialize within a short time interval after start of release. It is highly likely that several of the pumps have been exposed in this initial phase.

In cases where the module is larger and more open (more than two open walls) and the rotating machinery is located in a specific area, the effect may be prominent. For CM132EW, which also is a poorly ventilated module, the results demonstrate a significant effect. The bigger size of the module result in longer time to the first exposure (on average), which allows for shut down of the pumps to take effect (100% of pumps are isolated upon confirmed gas detection). Generic modeling of the contribution from rotating machinery implies that all leaks (even 0.1 kg/s) may expose a unit (the probability given exposure is distributed uniformly in space). When modelling the specific location, small leaks are very unlikely to expose a pump.

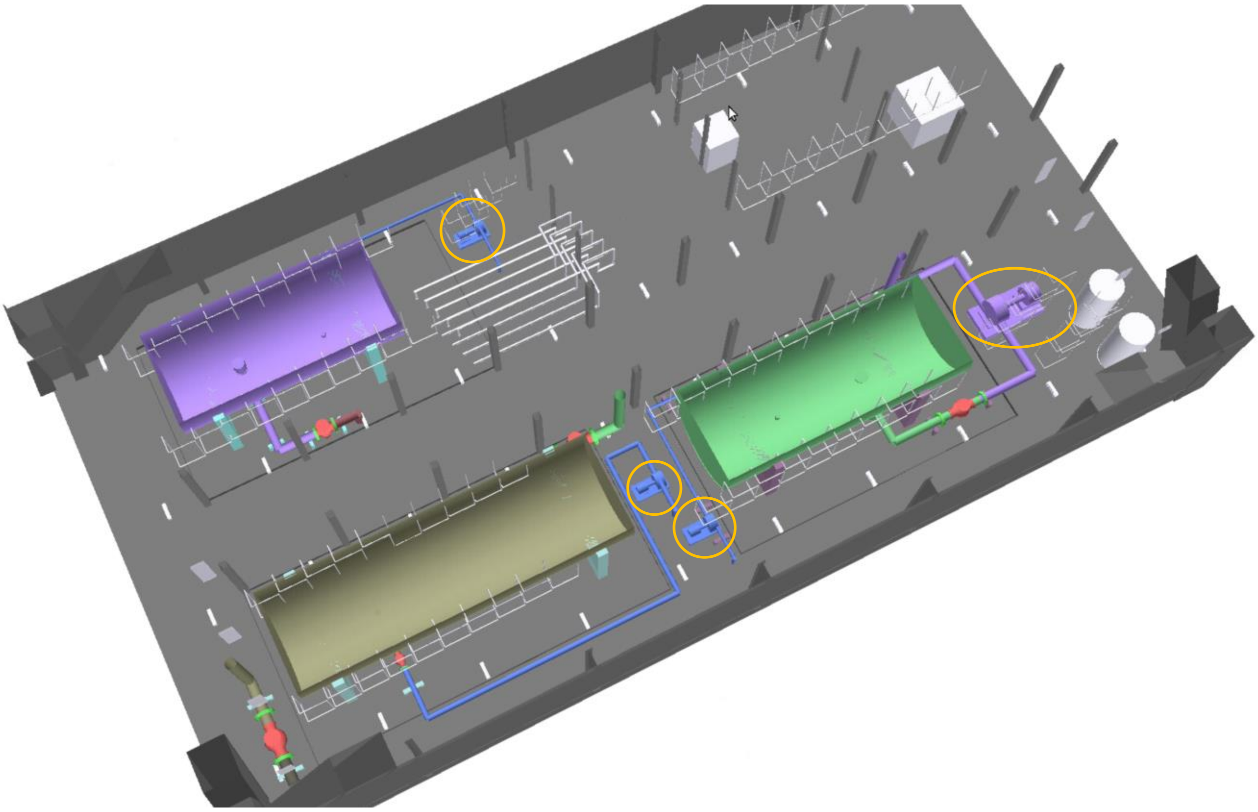


Figure 4-17: CM402EW: Bird's view displaying location of pumps

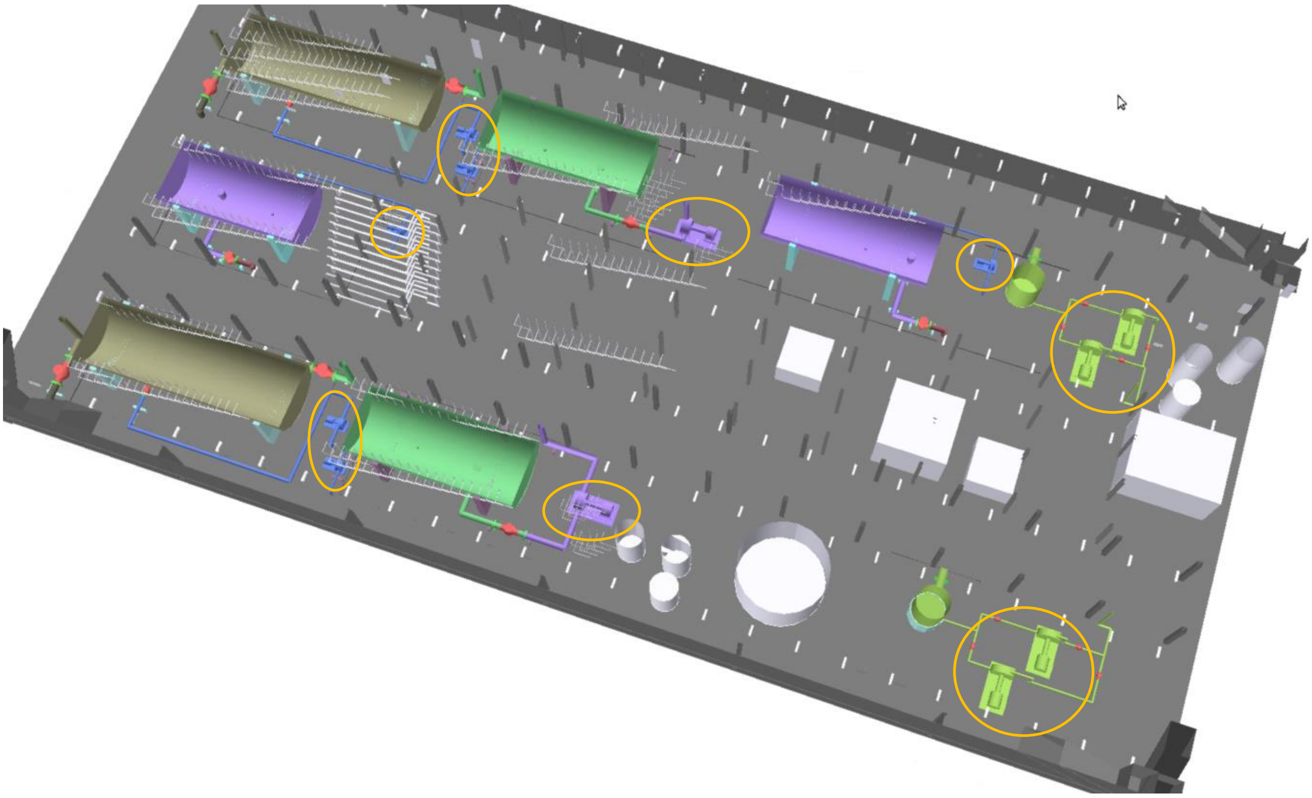


Figure 4-18: CM132EW: Bird's view displaying location of pumps

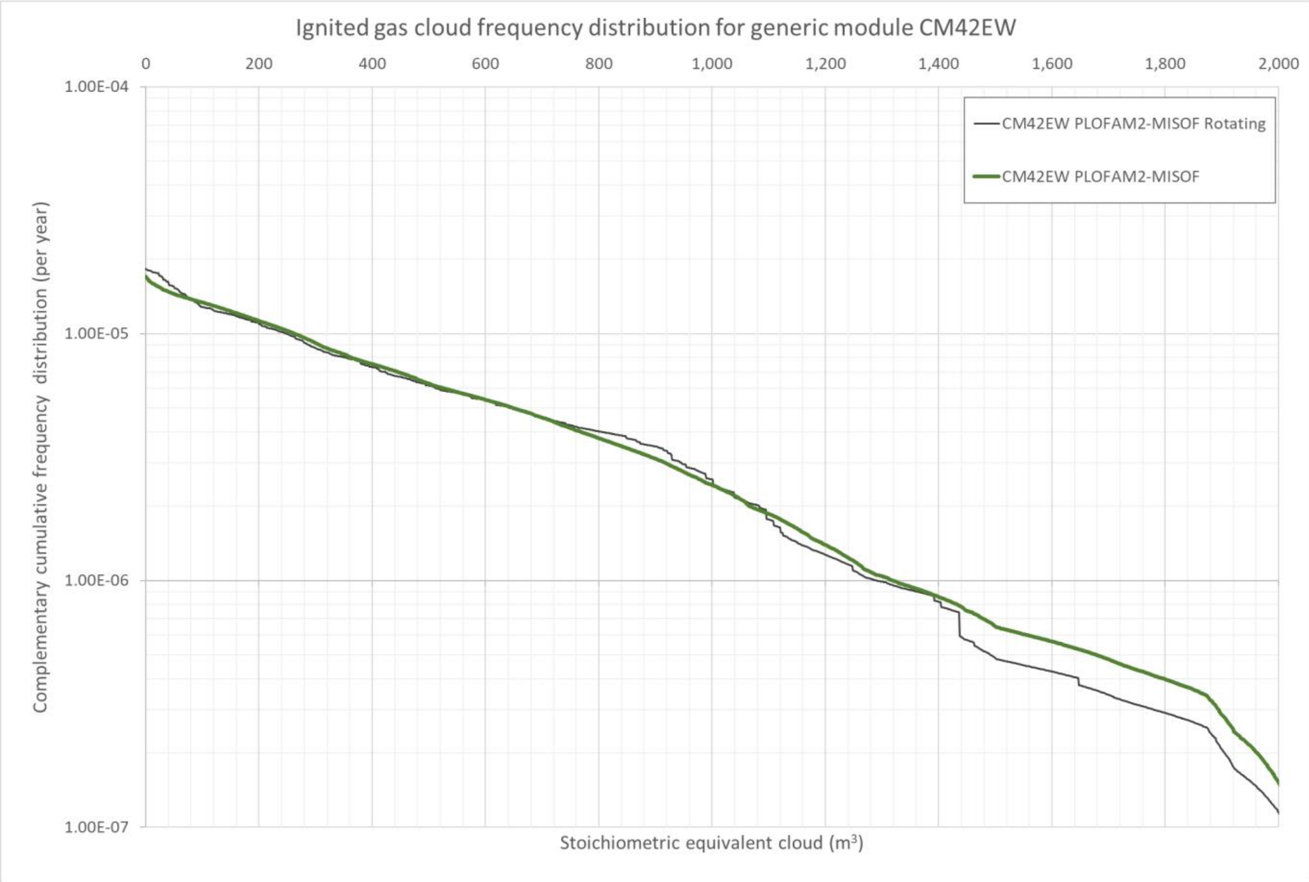


Figure 4-19: CM42EW PLOFAM-MISOF with specific modelling of 4 pumps instead of generic volumetric modelling of rotating machinery; complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

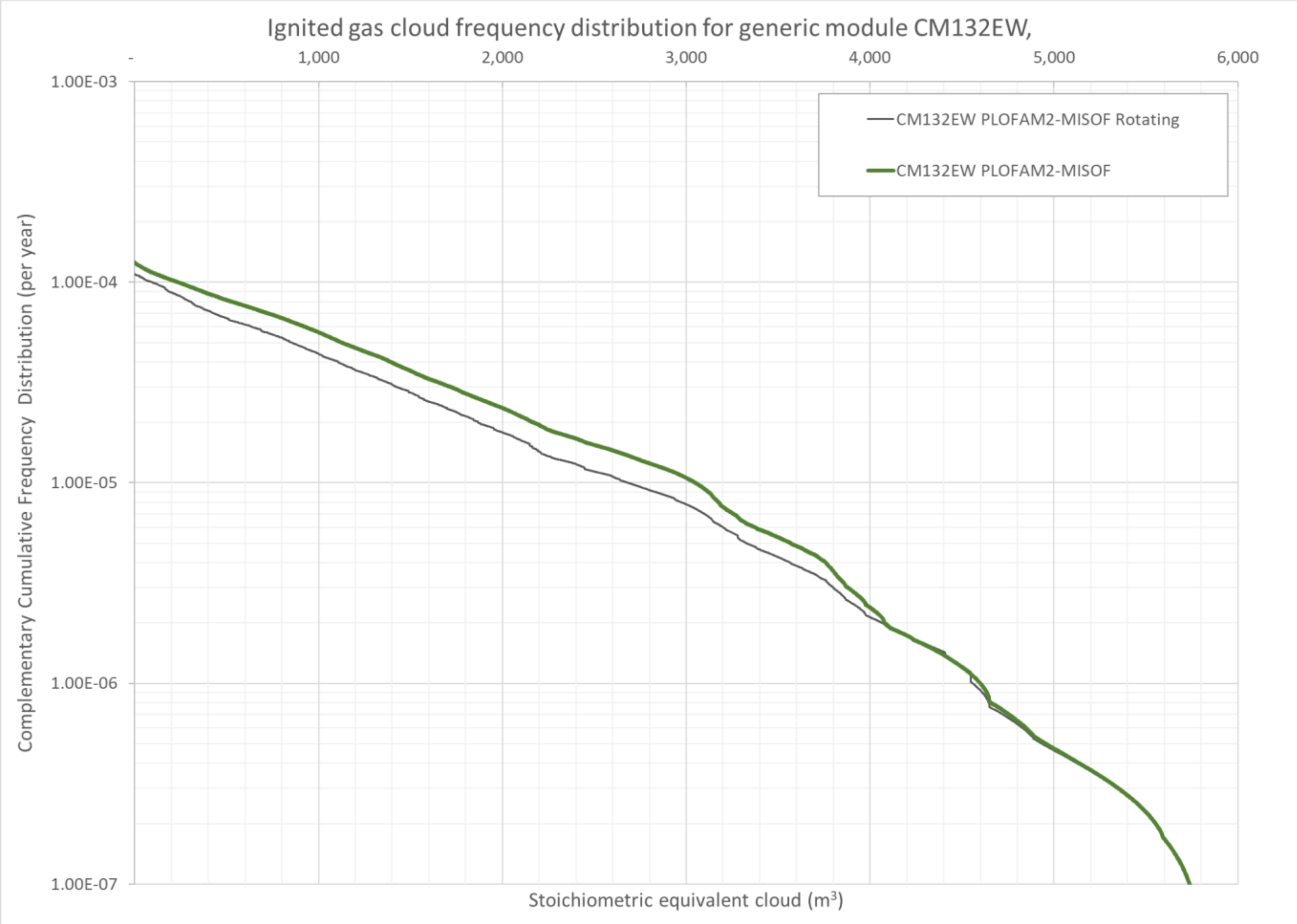


Figure 4-20: CM132EW PLOFAM-MISOF with specific modelling of 12 pumps instead of generic volumetric modelling of rotating machinery; complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

4.7 Importance of external ignition sources

Gas turbine air intakes are expected to generate ignition if external gas is ingested. To demonstrate the potential contribution from gas turbine air intakes in unfavourable situations, sensitivity studies have been performed for CM42EW and CM132EW. The location of the air intakes is shown in Figure 4-21 and Figure 4-24. In Figure 4-21, also an example scenario for an 8 kg/s leak is displayed. The location of the gas turbine air intakes is very unfavourable in these examples, but there are a few installations in industry where such layouts have been implemented. It is important to note that such solutions do not violate the requirements as long as the air intake itself is located outside the hazardous zone.

The results are presented in Figure 4-22 and Figure 4-23. The results demonstrate that in such unfavourable cases, the contribution from gas turbine air intakes may constitute the major contributor to fire and explosion risk. The resulting dimensioning (in the context of 10^{-4} per year) is about 1.5 barg including the gas turbine air intakes and less than 0.5 barg without the turbines (see Figure 4-25 and Figure 5-2).

The potential ignition mechanisms causing ignition when combustible gas is ingested by a gas turbine is not fully understood. A JIP carried out by Lloyd's Register mapped the current understanding of the problem, but is not conclusive in terms of the ignition probability or the potential ignition mechanisms.

A list of potential risk reducing measures is discussed in the JIP report. One potential effective measure is to retrofit a system that inert the ingested atmosphere upon gas detection. More work is required to understand the time window such a system needs to be effective (i.e. for how long time in the gas turbine wind down cycle is the turbine a potential source of ignition). For green fields, risk could be mitigated by smart layout.

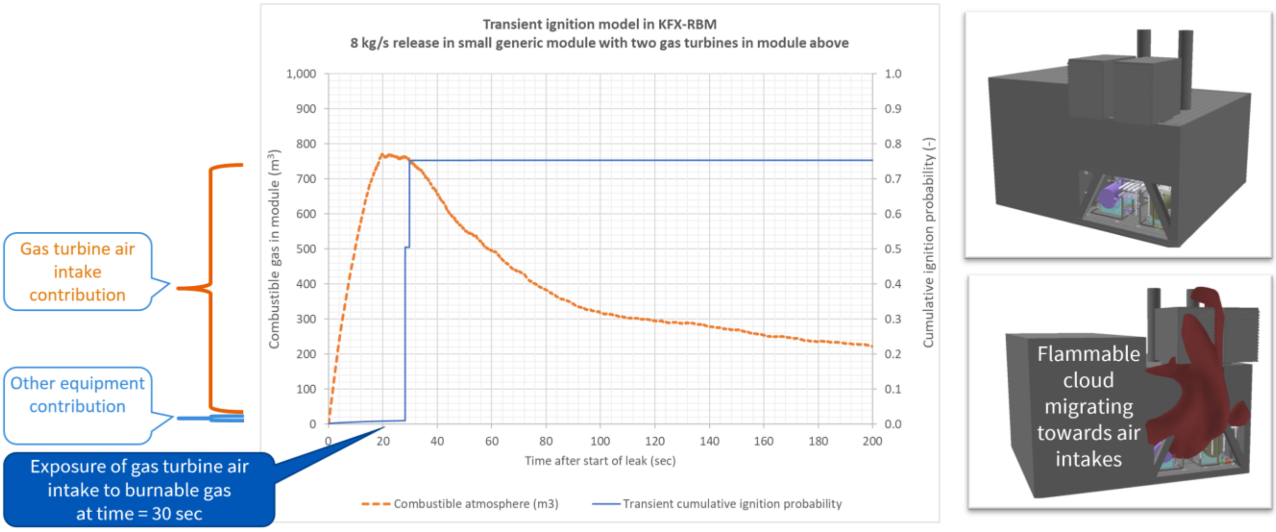


Figure 4-21: CM42EW: example scenario (8 kg/s) by use of KFX-RBM exposing gas turbine air intake and location of gas turbine air intakes relative to the module (directly above)

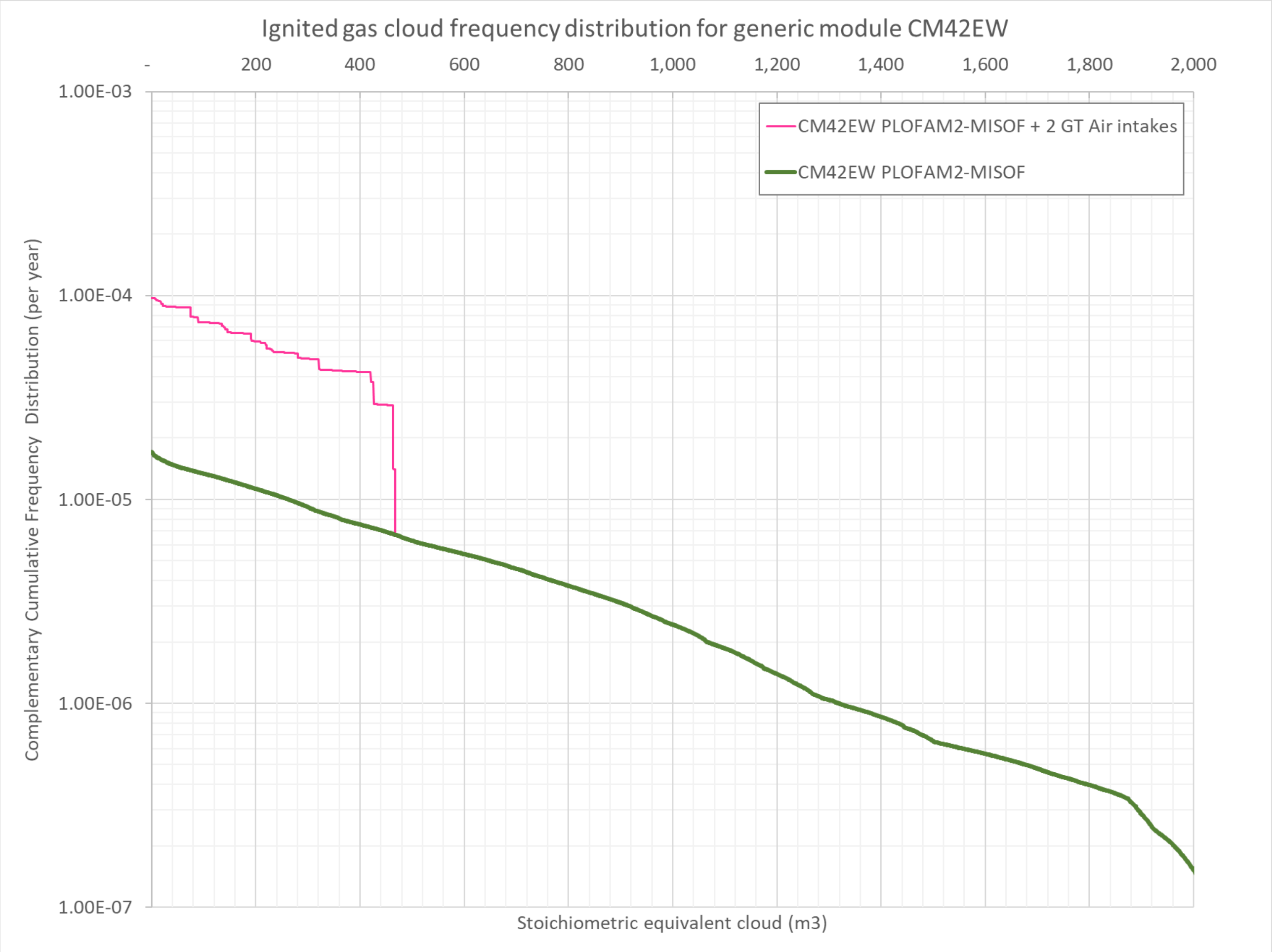


Figure 4-22: CM42EW PLOFAM-MISOF + two gas turbine air intakes located directly above the module (see Figure 4-21); complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

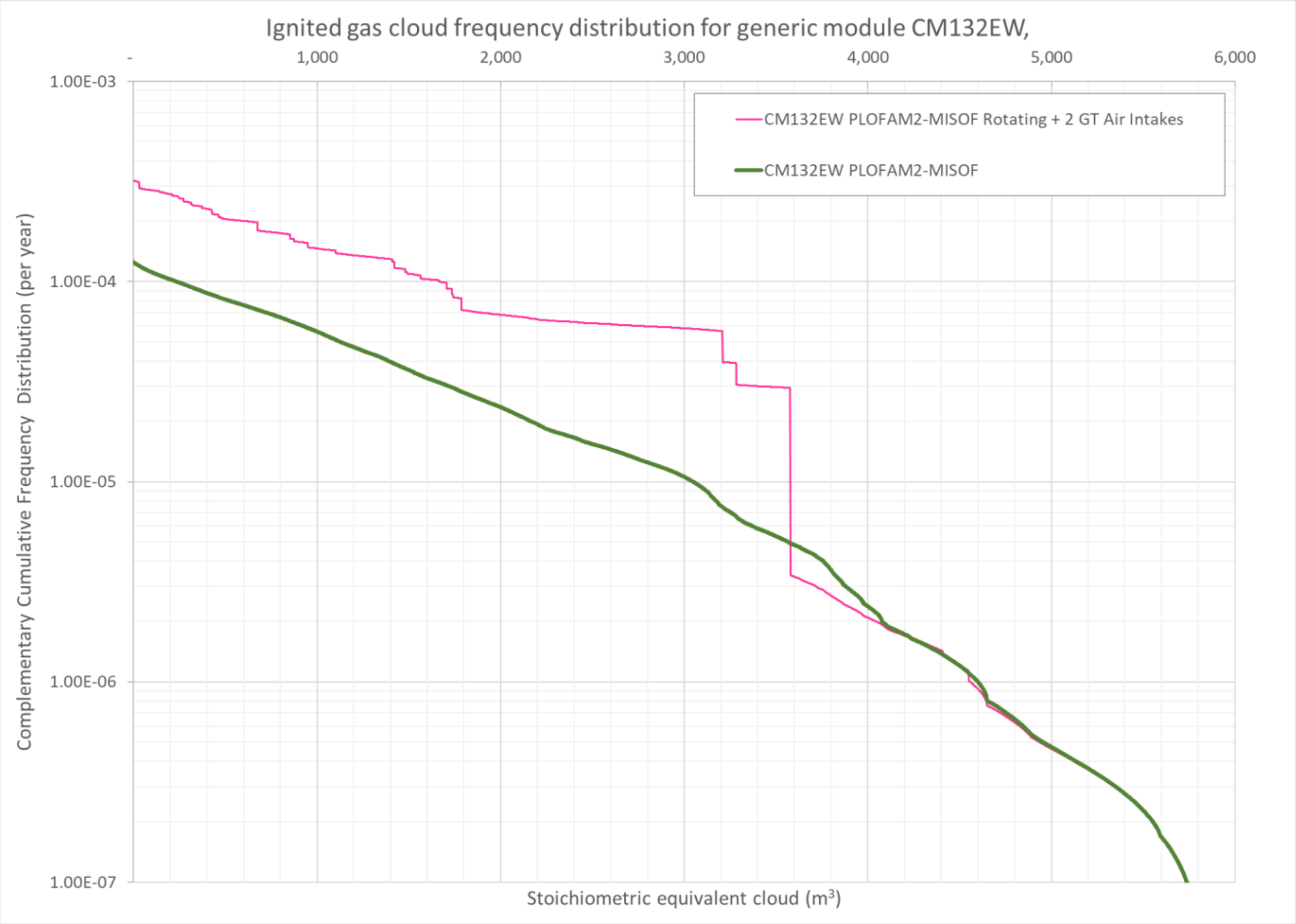


Figure 4-23: CM132EW PLOFAM-MISOF with specific modelling of 12 pumps instead of generic volumetric modelling of rotating machinery + two gas turbine air intakes located directly above the module (see Figure 4-24); complementary cumulative frequency distribution for time of ignition of stoichiometric equivalent gas cloud.

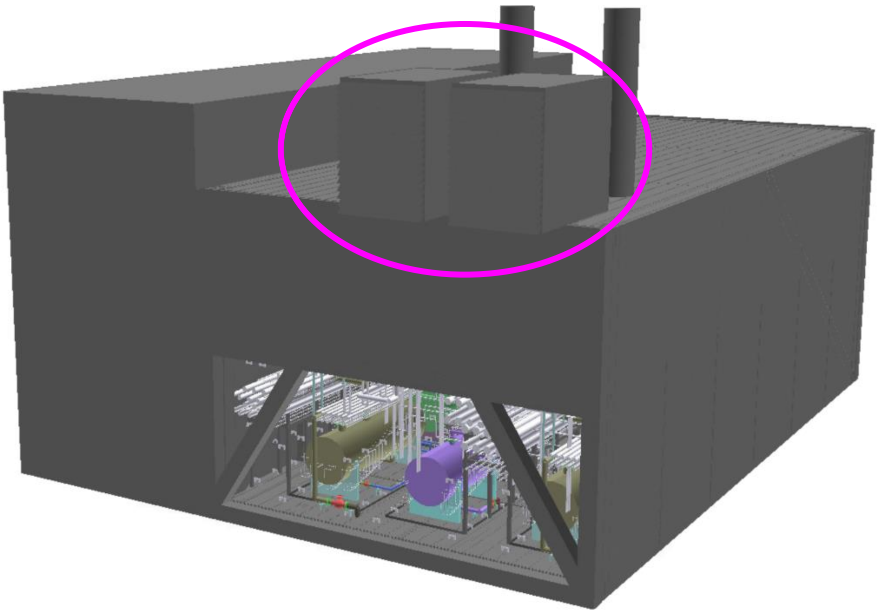


Figure 4-24: CM132EW location of gas turbine air intakes

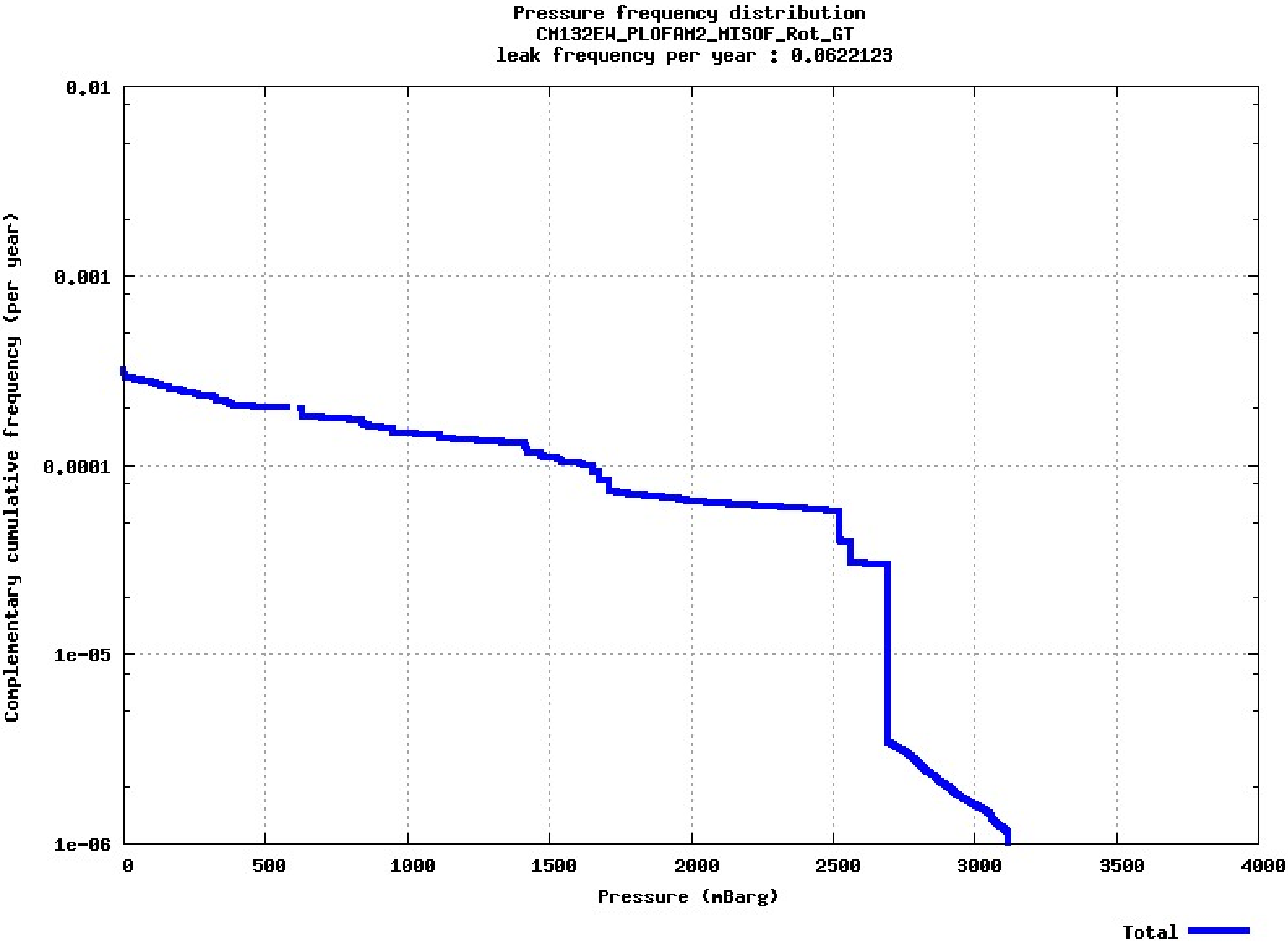


Figure 4-25: CM132EW PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load corresponding to the ignited gas cloud distribution in Figure 4-23. See Figure 5-2 for the result excluding the two gas turbine air intakes.

4.8 Importance of module size

The figure below shows the ignited gas cloud distribution for the three modules with respect to the filling degree of the ignited stoichiometric gas cloud.

The results show that the module size has a profound effect on the shape of the distribution. In a big module, only very large leaks can result in clouds resulting in a high filling fraction. But even such leaks will only in rare scenarios fill the major part of the module. Accounting for the very steep leak frequency distribution with respect to leak rate, a unique shape in terms of filling fraction is expected to emerge for every module design.

The ventilation conditions will have a similar effect. The ignited cloud distribution in modules with one more open wall (three open walls instead of two) will be very different. One element is the enhanced natural ventilation in a 3-way ventilated module, but the most important aspect is that the a much bigger fraction of the leaks will not be impinged by walls. In such cases the impulse of the leak will drive the gas out of module. If impinged, the gas will recirculate back into the module leading to accumulation of combustible gas in the module.

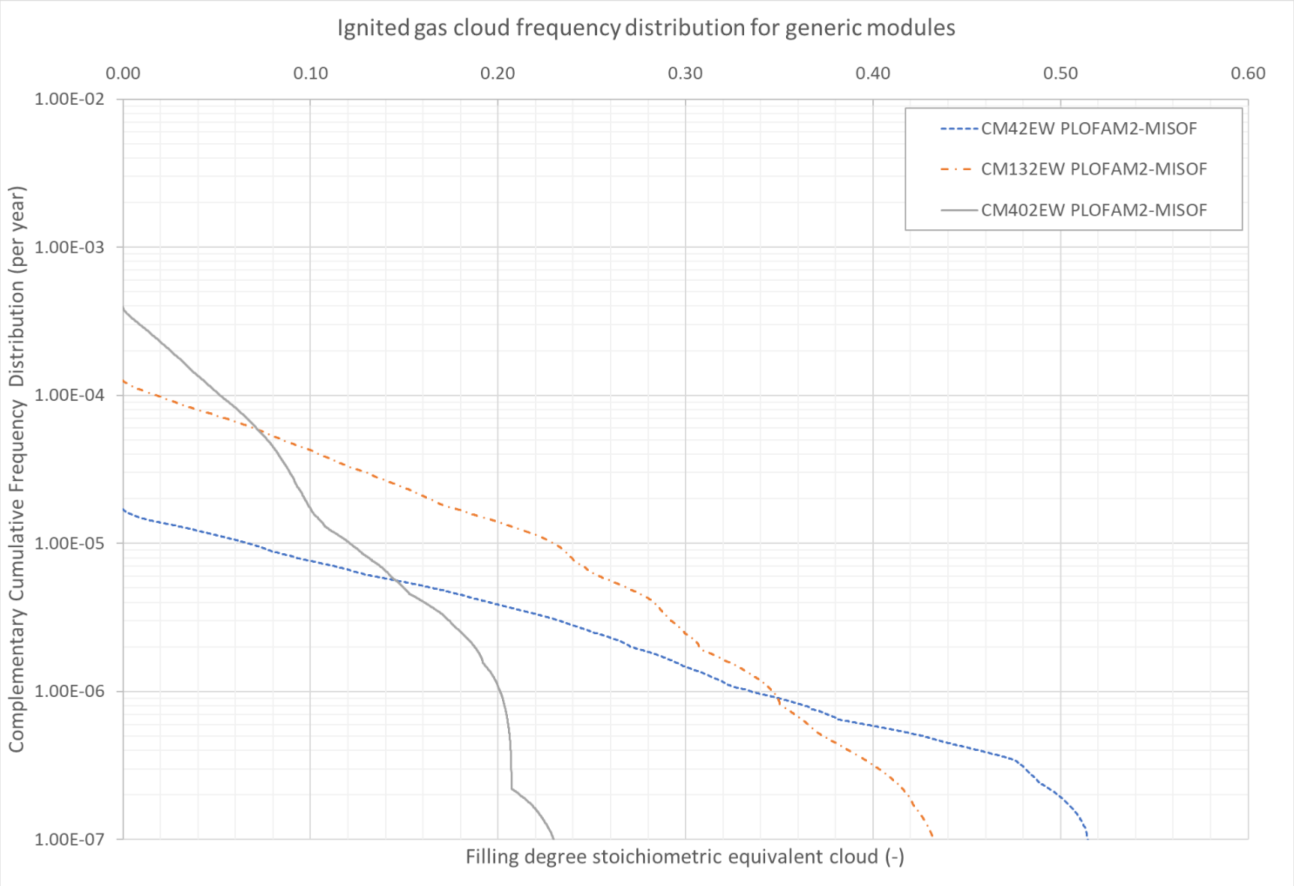


Figure 4-26: PLOFAM-MISOF: Complementary cumulative frequency distribution for filling degree of ignited stoichiometric equivalent gas cloud for the different generic modules.

4.9 Importance of ventilation conditions

An initial test applying the same generic modules and the same methodology was executed to analyse the effect of the global ventilation conditions of the modules. This initial test was run based on 50 CFD simulations (in KFX-RBM) that were on average more conservative in terms of wind conditions and leak directions. Hence, the result from this initial study is not directly comparable with the result for the final study presented in this report. However, the overall result in terms of the relative effects of ventilation conditions provides valuable insight into the effect of the openness of the modules.

In this initial study, the 50 scenarios where run with and without one of the two walls removed. The geometrical layout for the situation with 3 open walls is shown in Figure 4-28, Figure 4-29 and Figure 4-30.

The resulting reduction in delayed ignition probability is shown in Figure 4-27. The results demonstrate that removal of one wall has a profound effect on the ignition probability. A reduction of 25% can be expected for typical offshore module sizes. For a big module it is expected that the effect is smaller, which is explained by:

- the relative effect on the average ventilation conditions decrease with module size
- the average distance from the leak points in the module to the edge of the module decrease with increasing module size. An important effect of removal of a wall is that fewer leaks will be impinged by walls/decks. The impulse of leaks that it is not obstructed will push combustible atmosphere effectively out of the module.

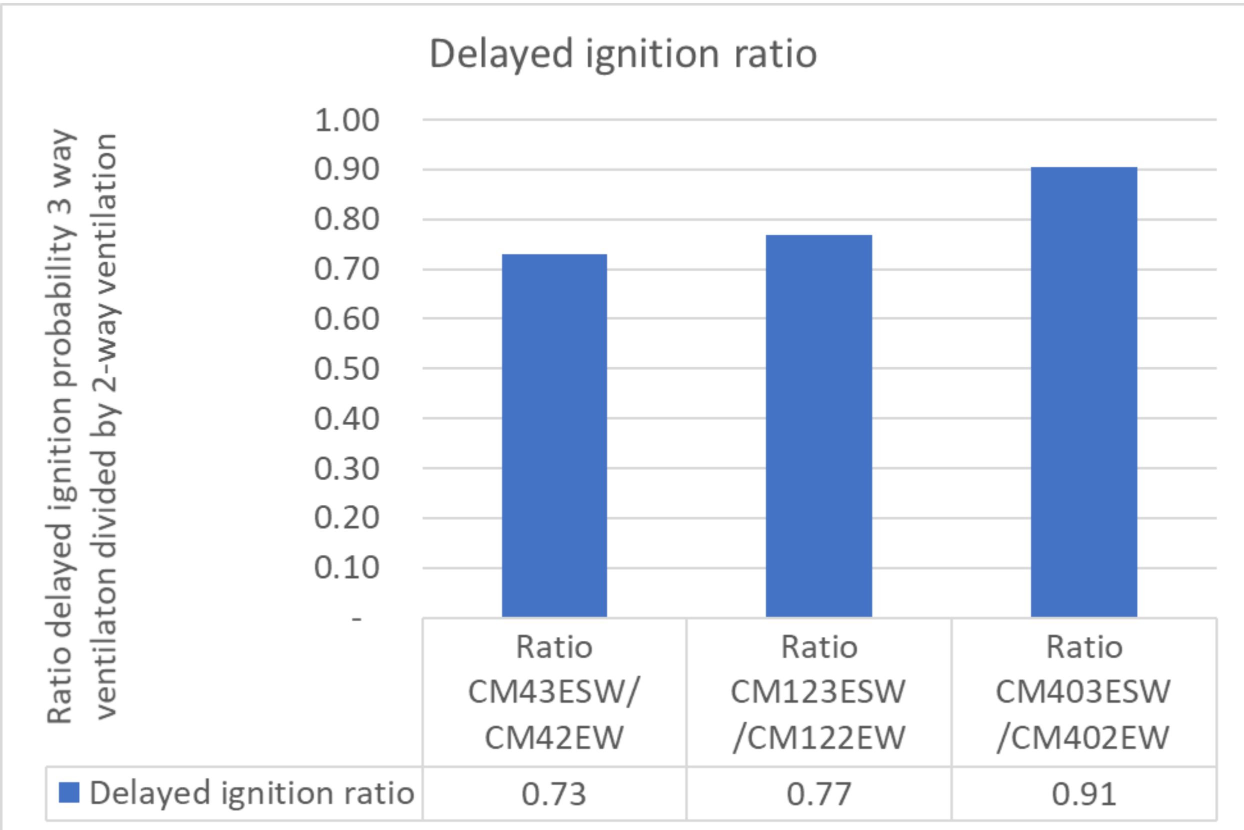


Figure 4-27: Ratio delayed ignition probability for initial sensitivity study of effect of global ventilation conditions.

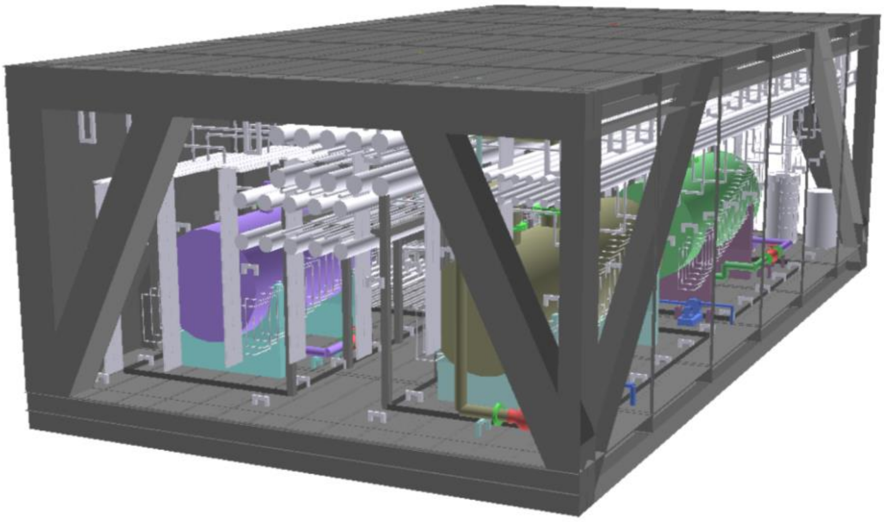


Figure 4-28: CM43ESW; 4 000 gross m^3, three open walls

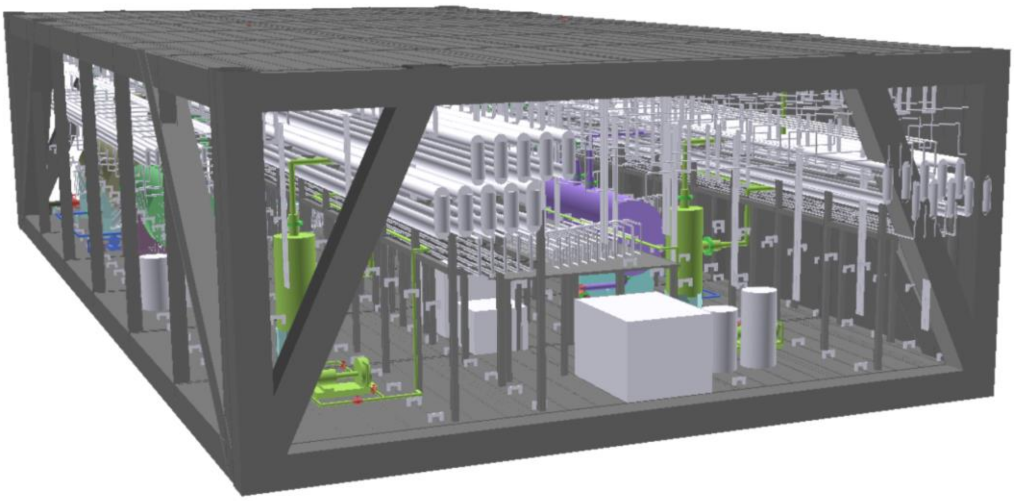


Figure 4-29 CM123ESW; 13 300 gross m^3 (net volume: HOLD), three open walls

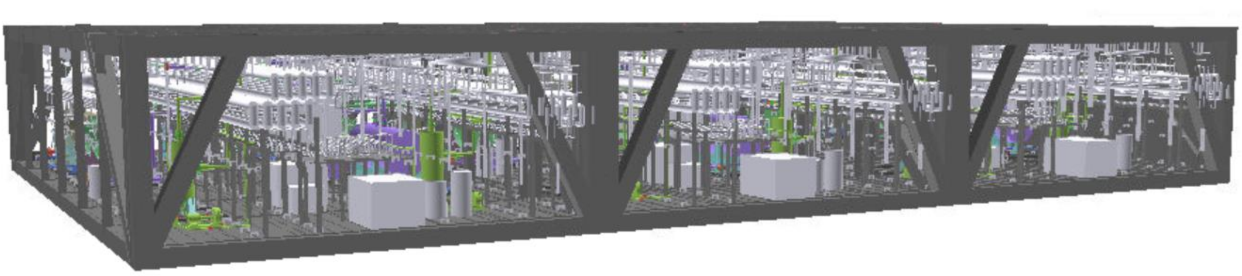


Figure 4-30: CM403ESW; 40 000 gross m^3, three open walls (open end wall at left side)

4.10 Sensitivity study MISOF model parameters

The derivation of the parameters in the MISOF model is quite uncertain. In order to study the sensitivity to key parameters, the probabilistic models for the three modules have been rerun varying the parameter values. The sensitivity cases are described in Table 4-1.

Table 4-1: OLF ignition model parameters used in the study. The caption 'PLOFAM2' is used in the figures to denote that rev. 2 of the PLOFAM model issued in December 2018 has been applied.

ID	Caption	Description
A	PLOFAM2-MISOF-Piso*0.5	P_{iso} values for 'Electrical equipment' and 'Other' is shifted from 0.25 to 0.5 and 0.3 to 0.6 respectively.
B	PLOFAM2-MISOF-Discrete*2	The weight on discrete sources is doubled and the corresponding weight on continuous sources is reduced with a factor of two to ensure consistency with the statistical basis.
C	PLOFAM2-MISOF-Pif_El*0.5	The contribution from 'Electrical equipment' is reduced with a factor of 2 (both discrete and continuous sources).
D	PLOFAM2-MISOF-Piso*0.5+Discrete*2	A + B.

The results show that all sensitivity cases affect the frequency distribution significantly. In particular, note the profound effect of P_{iso} reflecting isolation of equipment upon exposure. Hence, it is crucial that applied value for P_{iso} is representative for the installation being studied.

The significant effect of shifting the weight on discrete vs. continuous sources demonstrate the underlying uncertainty in the modelling approach. The discrete and continuous ignition mechanism implemented in the model is far from perfect idealisations of what is going in practice. More effort should be put in understanding actual failure modes to improve the basis for the applied idealisation in the model. Acquired knowledge on this issue in the future will hopefully provide basis for reducing the uncertainty with respect to how to idealise the actual ignition mechanisms in the ignition model.

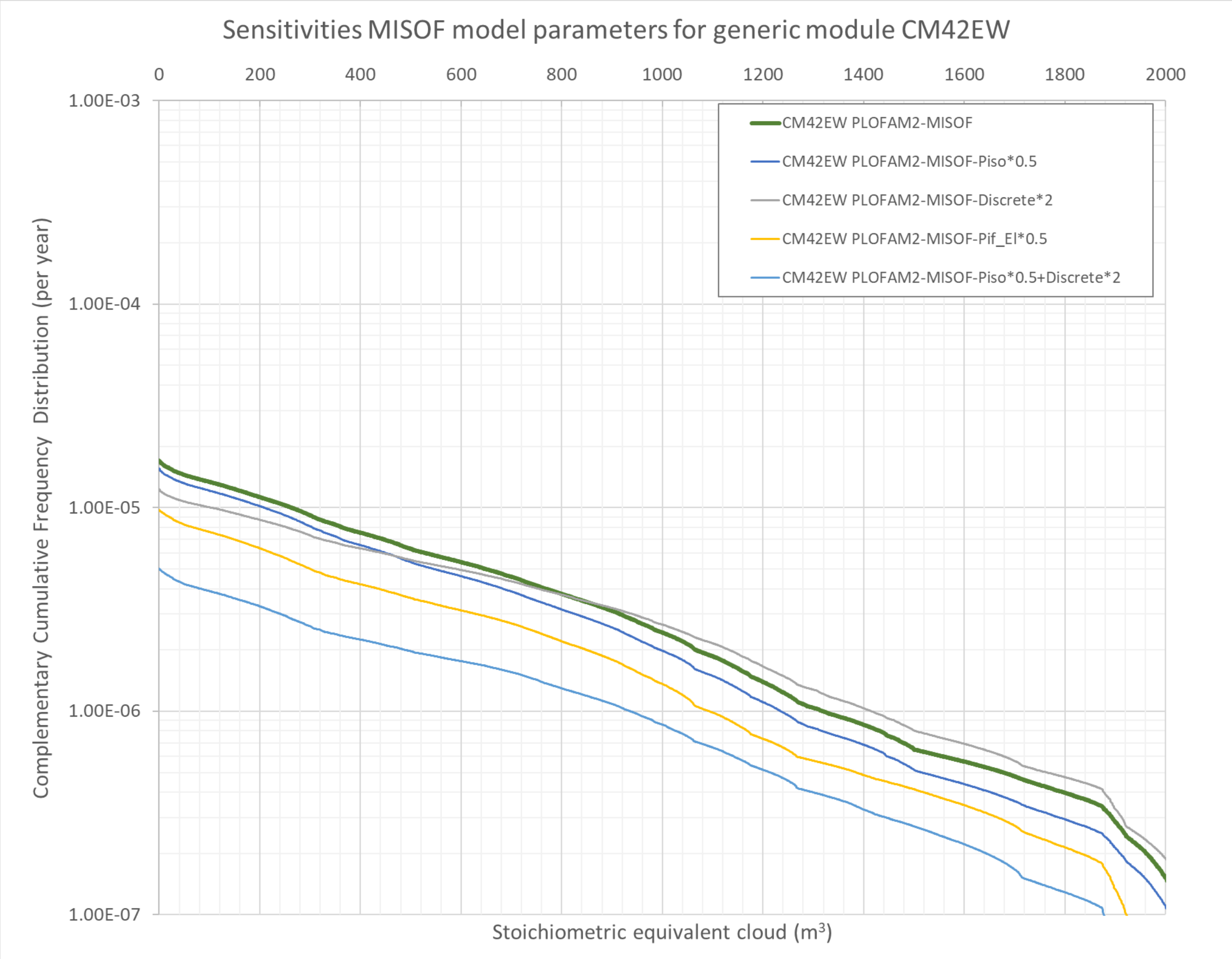


Figure 4-31: Sensitivities MISOF model parameters: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM42EW.

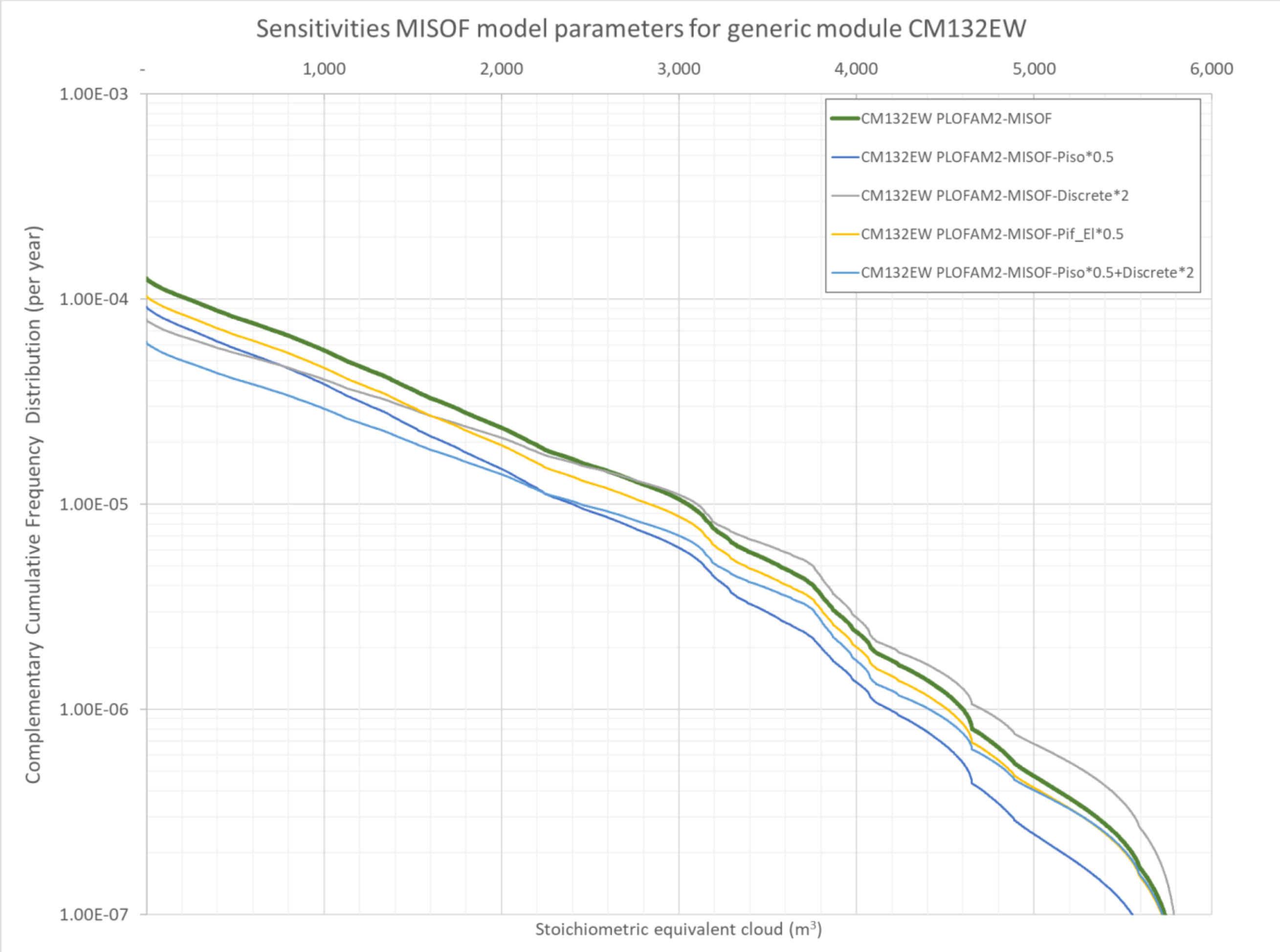


Figure 4-32: Sensitivities MISOF model parameters: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM132EW.

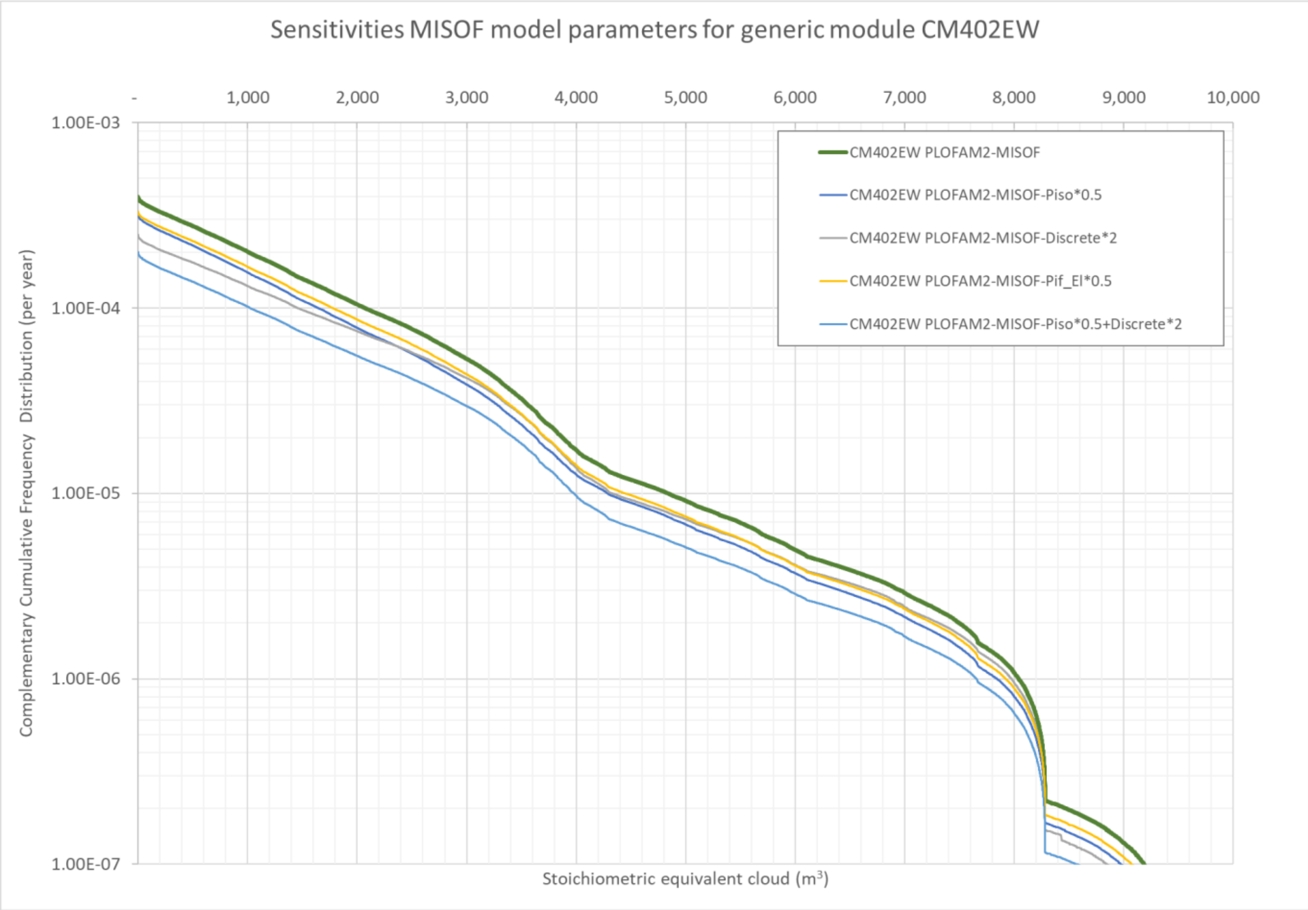


Figure 4-33: Sensitivities MISOF model parameters: Complementary cumulative frequency distribution for ignited stoichiometric equivalent gas cloud for the generic module CM402EW.

5 Pressure frequency distributions

The complementary cumulative distribution for the dimensioning explosion pressure (mbarg) is obtained by combining the relevant complementary cumulative distribution for the ignited stoichiometric equivalent gas cloud with equation (5.1).

The applied model for the explosion pressure is a coarse correlation between gas cloud size and dimensioning explosion pressure for the global structure in the modules (*e.g.* average pressure for a blast wall or the entire deck).

The results based on the PLOFAM and MISOF models are presented in the following figures. The results demonstrate according to a 10^{-4} per year criterion that:

- Explosions are not a dimensioning event for the smallest module (CM42EW).

- The dimensioning explosion load is about 0.25 barg for M132EW.

- The dimensioning explosion load is about 1.5 barg for M402EW.

The result shows the module size is important for the resulting design pressure, *i.e.* increasing design pressure with module size. In addition to the increased leak frequency in bigger modules (more process equipment in a bigger module), the driving parameter is due that a gas cloud is allowed to expand more freely in a large module. This is however only the case for leak rates where the expansion of the gas cloud is hampered in the smaller module). A larger gas cloud will expose more potential ignition sources (*e.g.* additional electrical units and/or running pumps), which lead to a higher accumulated ignition probability in the MISOF model (and also the OLF model).

The effect that a bigger module result in higher explosion risk than a smaller module is not a general argument for dividing a big module in smaller modules. Such a design will in many cases reduce the ventilation rate in the smaller modules relative to the big module generating larger gas clouds for smaller leaks. A larger cloud generates higher exposure probability to potential ignition sources. Combined with that the leak frequency increase steeply with decreasing initial leak rate, the resulting exposure probability may increase. Moreover, the explosion load generated from an equally sized cloud is significantly larger in smaller module. In total these effects may outweigh the benefit from isolating leak sources from the potential ignition sources in a large area. This is illustrated in Figure 5-5. The sensitivity case represents a layout where the CM402EW module is split into three identical CM132EW modules. The aggregated pressure frequency distribution for all three modules established by combining the estimated cloud distribution shown in Figure 5-4 with the explosion model for CM402EW (see Figure 3-9). The aggregated ignited cloud distribution for all three modules is established by multiplying the distribution for CM132EW (see Figure 4-11) with a factor of 3.

It should be noted that the modules studied are considered to on average represent rather unfavorable designs in terms of explosion risk, *i.e.* due to quite poor global ventilation conditions. The estimated explosion risk using PLOFAM and MISOF is therefore expected to be less for many equally sized modules in the North Sea.

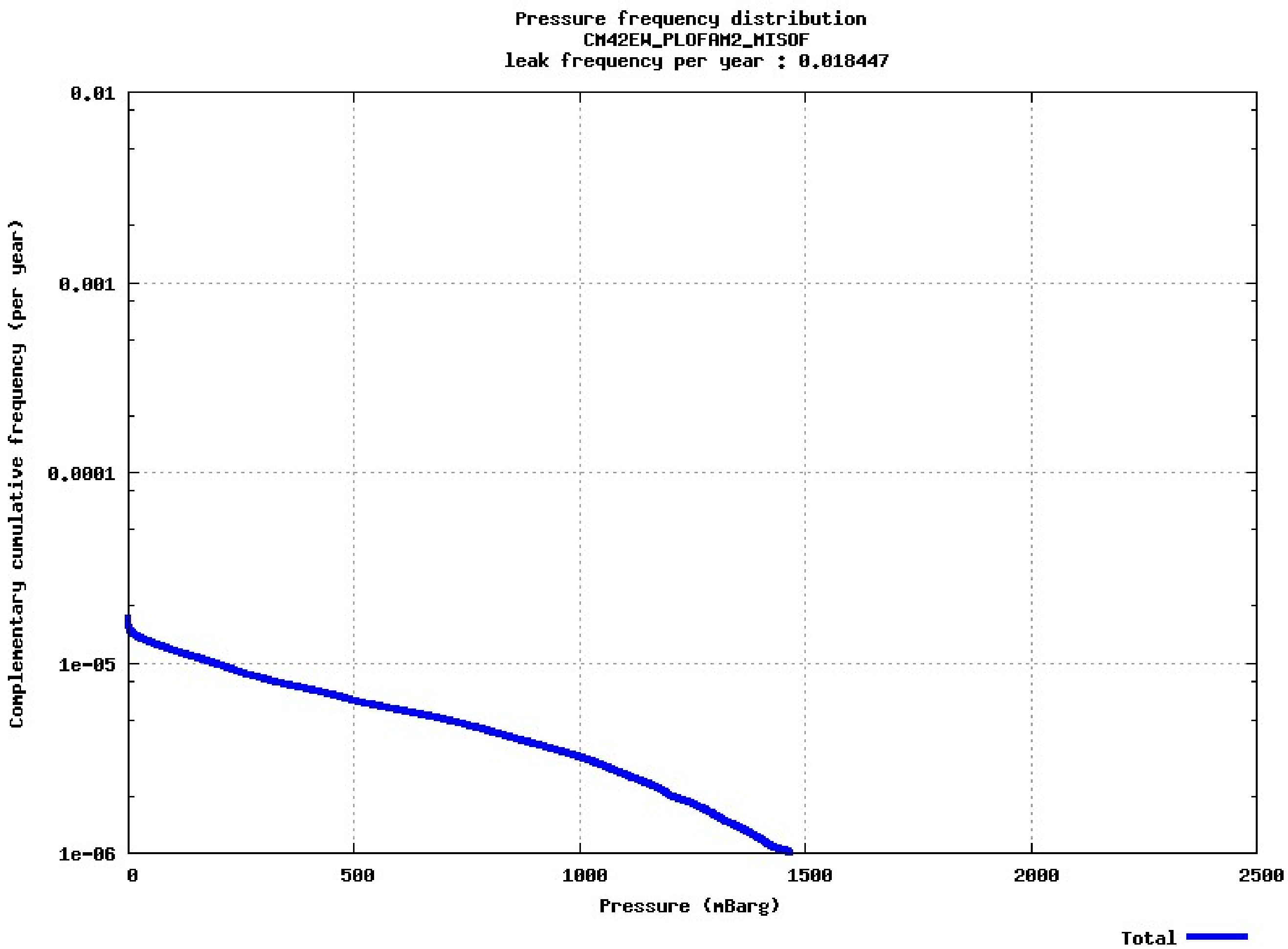


Figure 5-1: CM42EW PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load

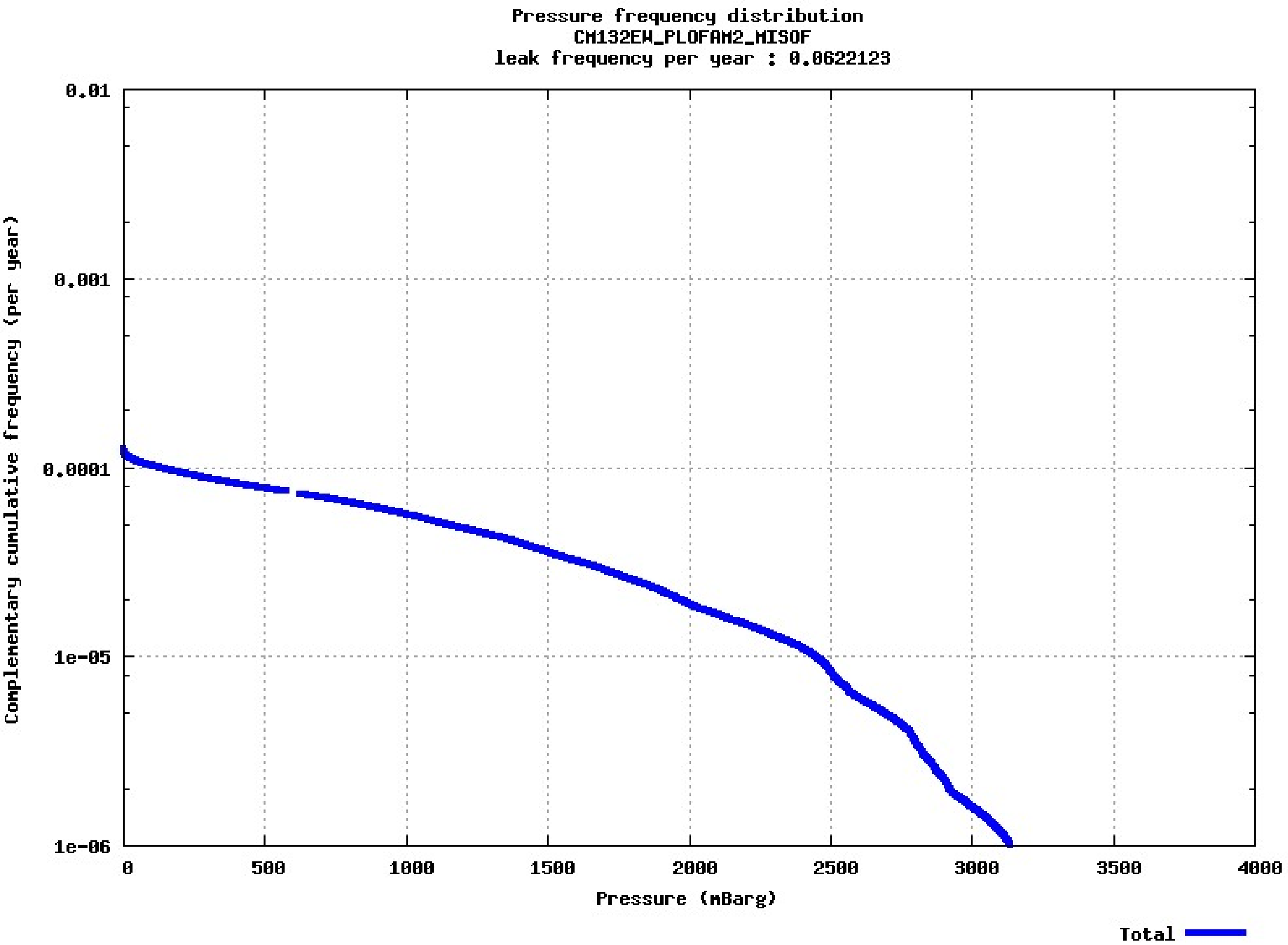


Figure 5-2: CM132EW PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load

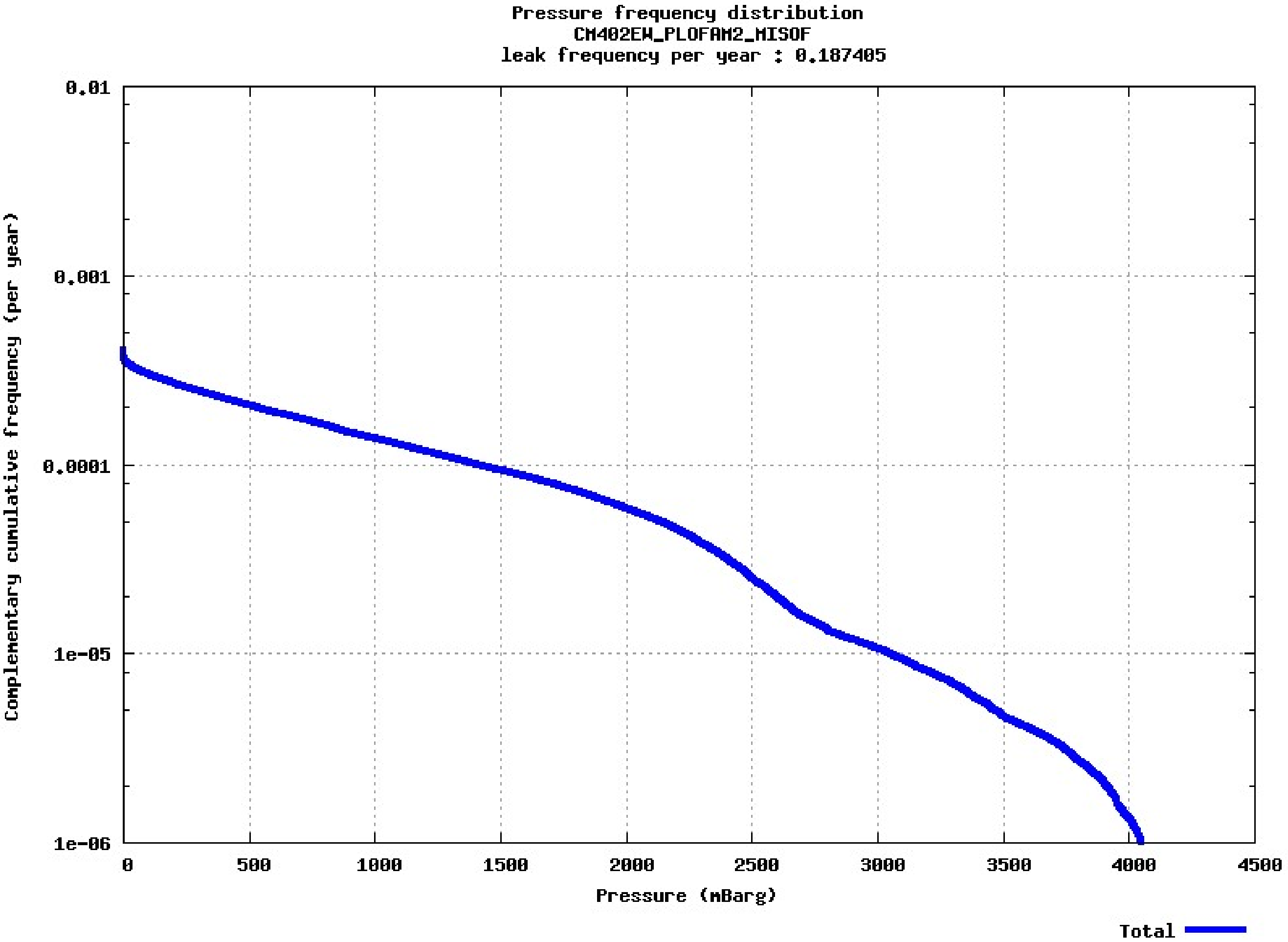


Figure 5-3: CM402EW PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load

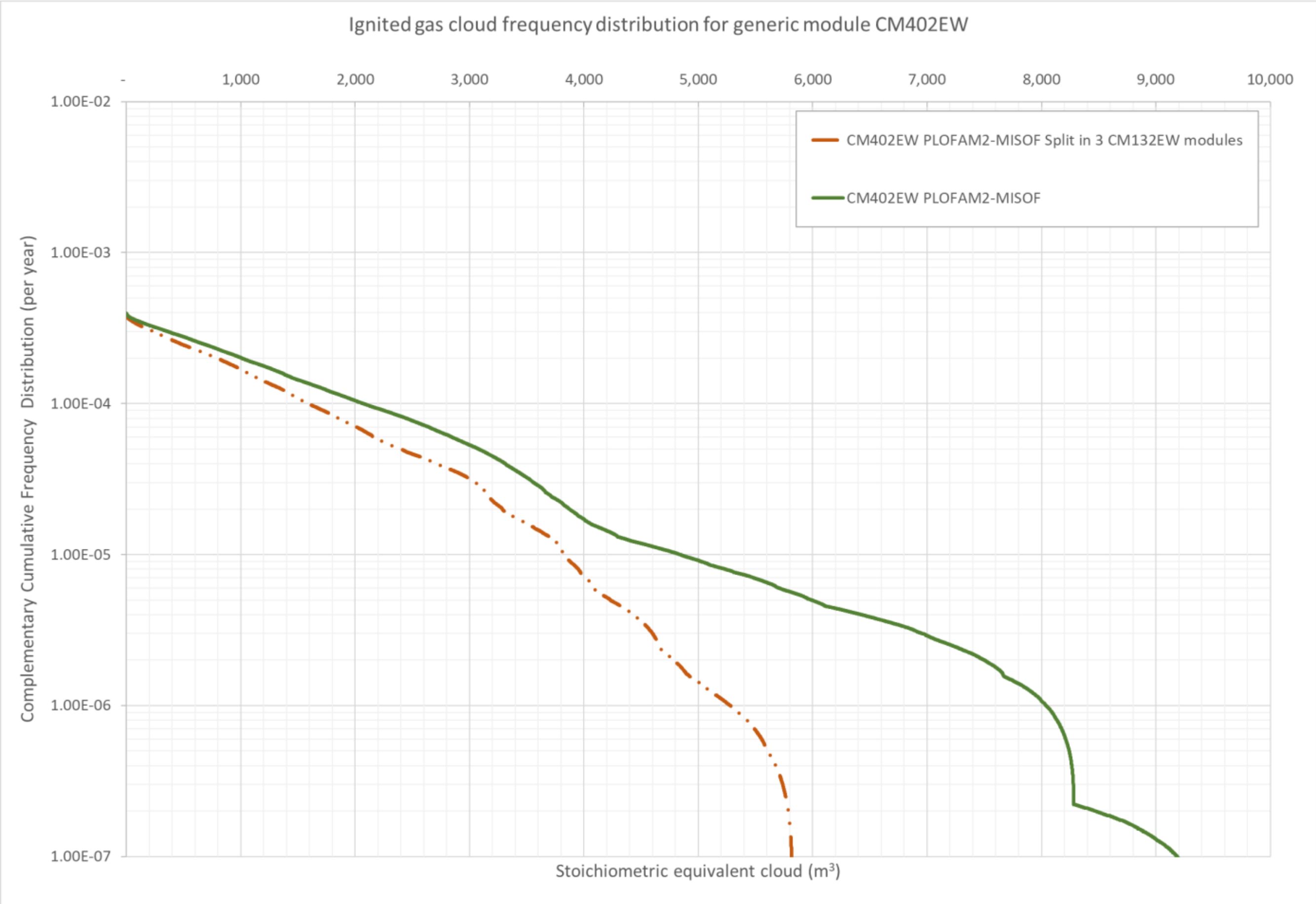


Figure 5-4: PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load. Sensitivity case representing a design where the CM402EW module is split into three identical CM132EW modules. The aggregated ignited cloud distribution for all three modules is established by multiplying the distribution for CM132EW (see Figure 4-11) with a factor of 3.

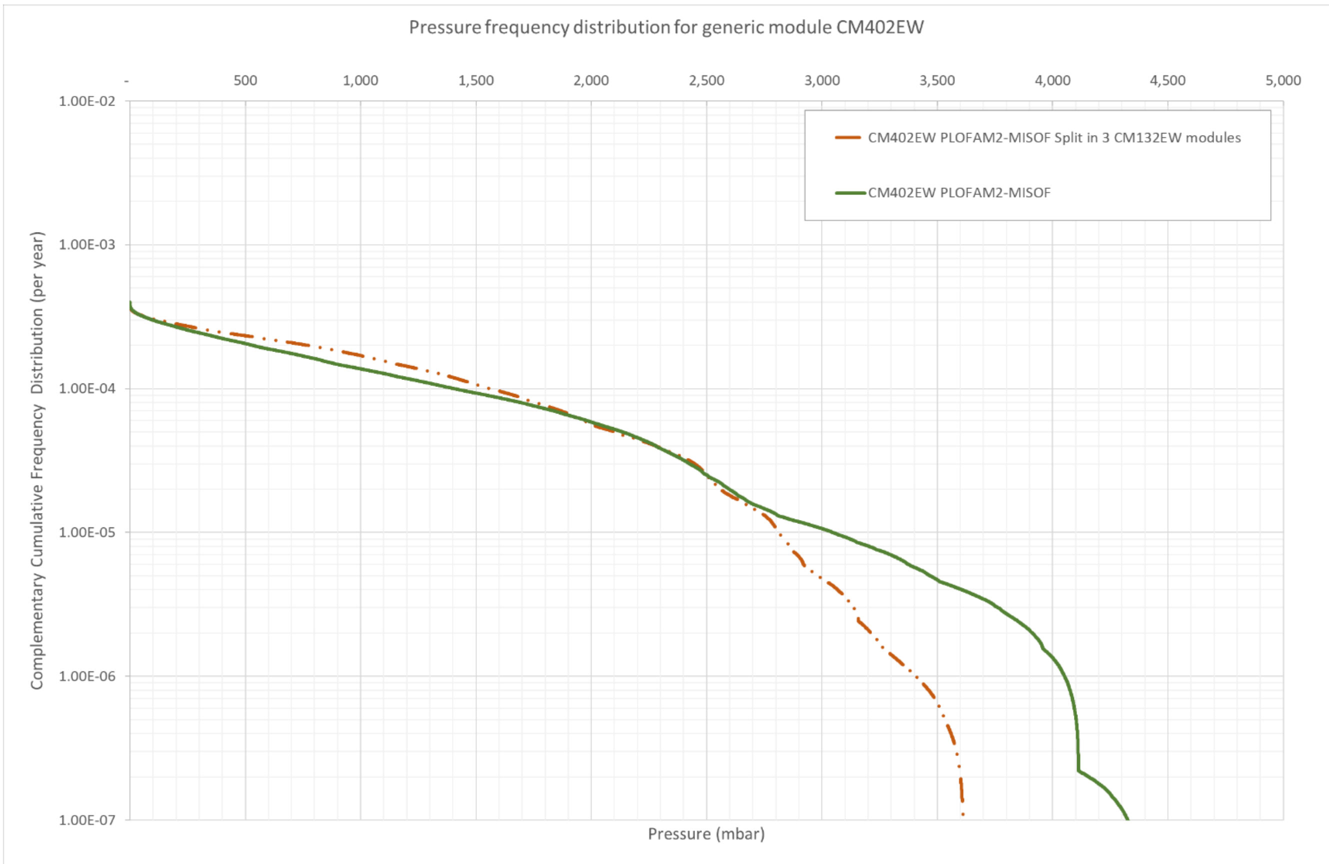


Figure 5-5: CM402EW PLOFAM-MISOF: Complementary cumulative frequency distribution for dimensioning explosion load. Sensitivity case representing a design where the CM402EW module is split into three identical CM132EW modules. The aggregated pressure frequency distribution for all three modules established by combining the estimated cloud distribution shown in Figure 5-4 with the explosion model for CM402EW (see Figure 3-9).

6 Trends in fire and explosion frequency with module size

6.1 General

In this section the total fire and explosion frequencies and the total ignition probabilities are discussed.

6.2 Leak and fire frequency

The resulting leak frequency, modelled based on the volume of the modules (see section 3.3), is displayed in Figure 6-1.

The resulting fire frequency generates a linear trend looking at the response in terms of module size (see Figure 6-2.).

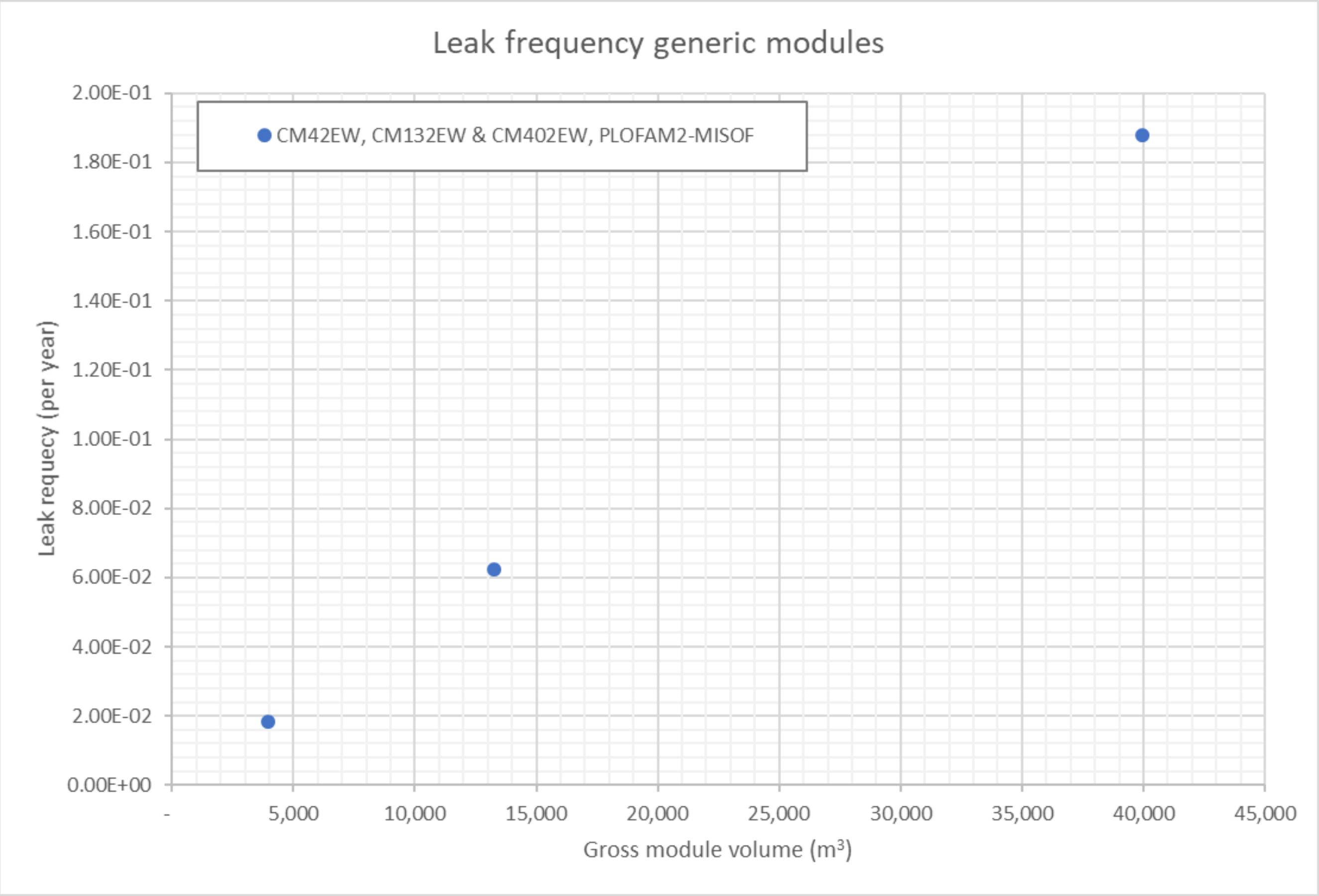


Figure 6-1: Total leak frequency vs. module volume for the various modules

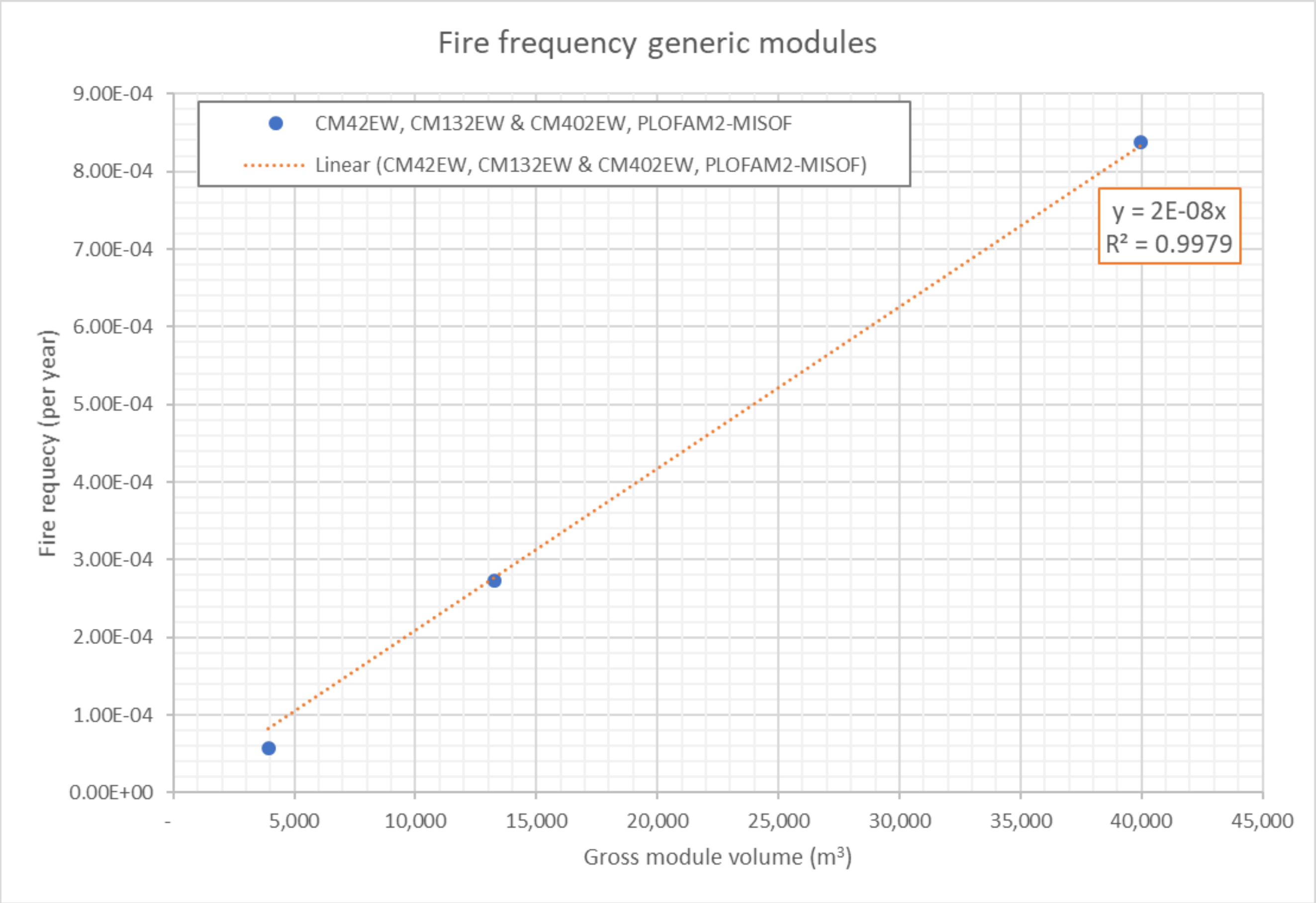


Figure 6-2: Fire frequency vs. module volume for the various modules

6.3 Ignition probability

The trend with respect to ignition probability is shown in the following figures.

A significant positive trend with module size is observed, which is due the number of potential ignition sources is increasing with module size.

The relatively small increase from CM132EW to CM402EW is explained that the ventilation conditions in CM132EW is much poorer. The contribution from discrete sources are more prominent in CM132EW due to the lower ventilation rate.

The ignition probability is in line with the observed historical ignition probability (total about 0.3%).

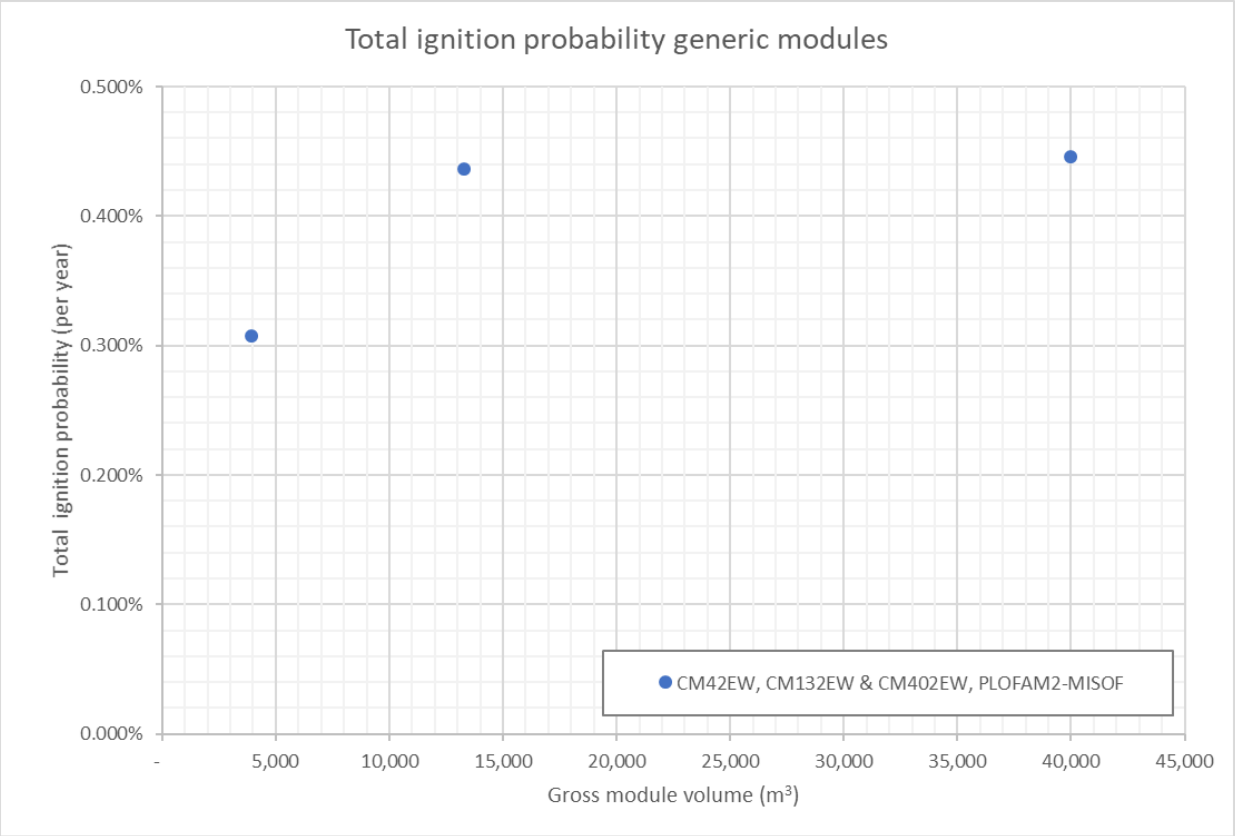


Figure 6-3: Total ignition probability vs. module volume for the various modules

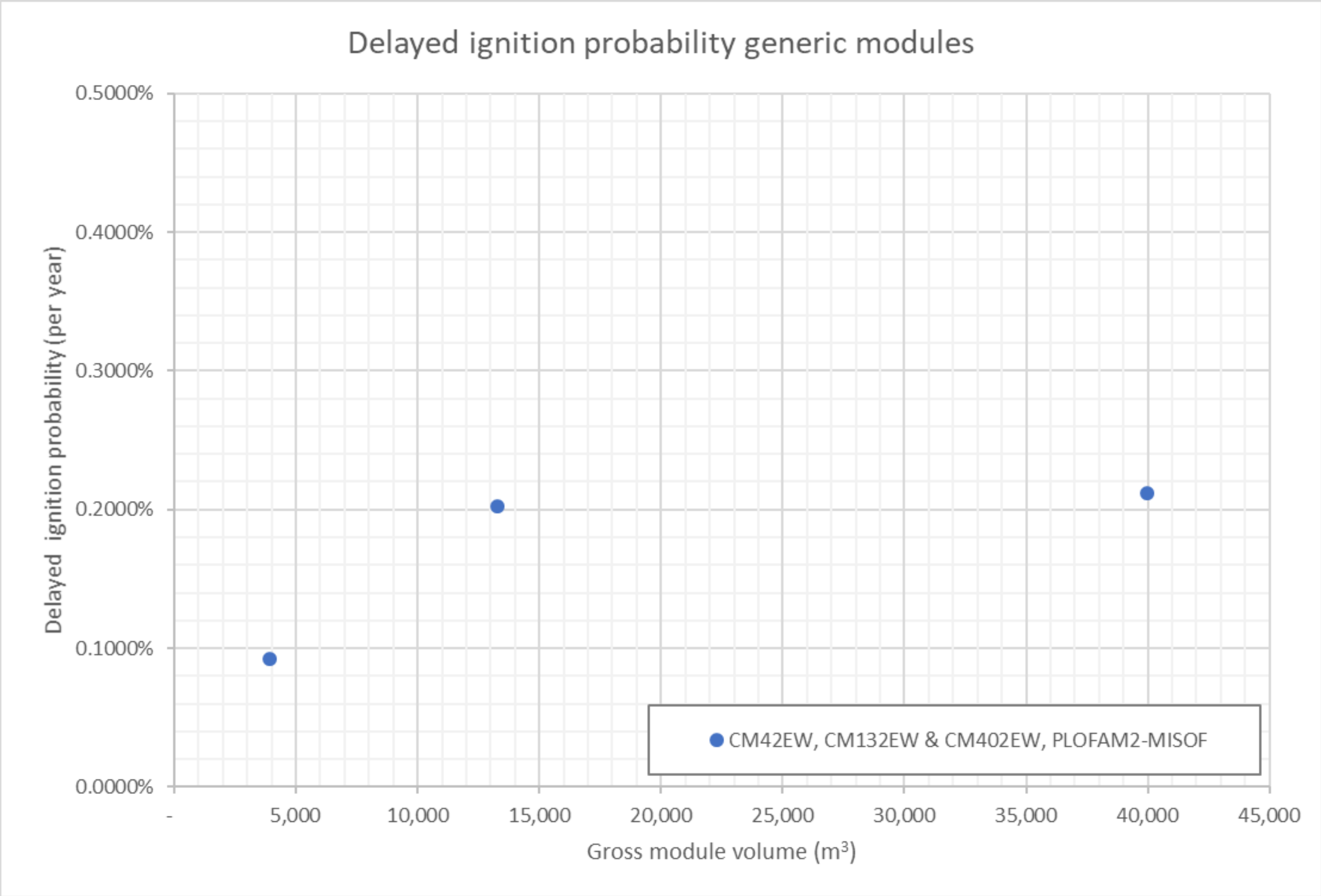


Figure 6-4: Delayed ignition probability vs. module volume for the various modules

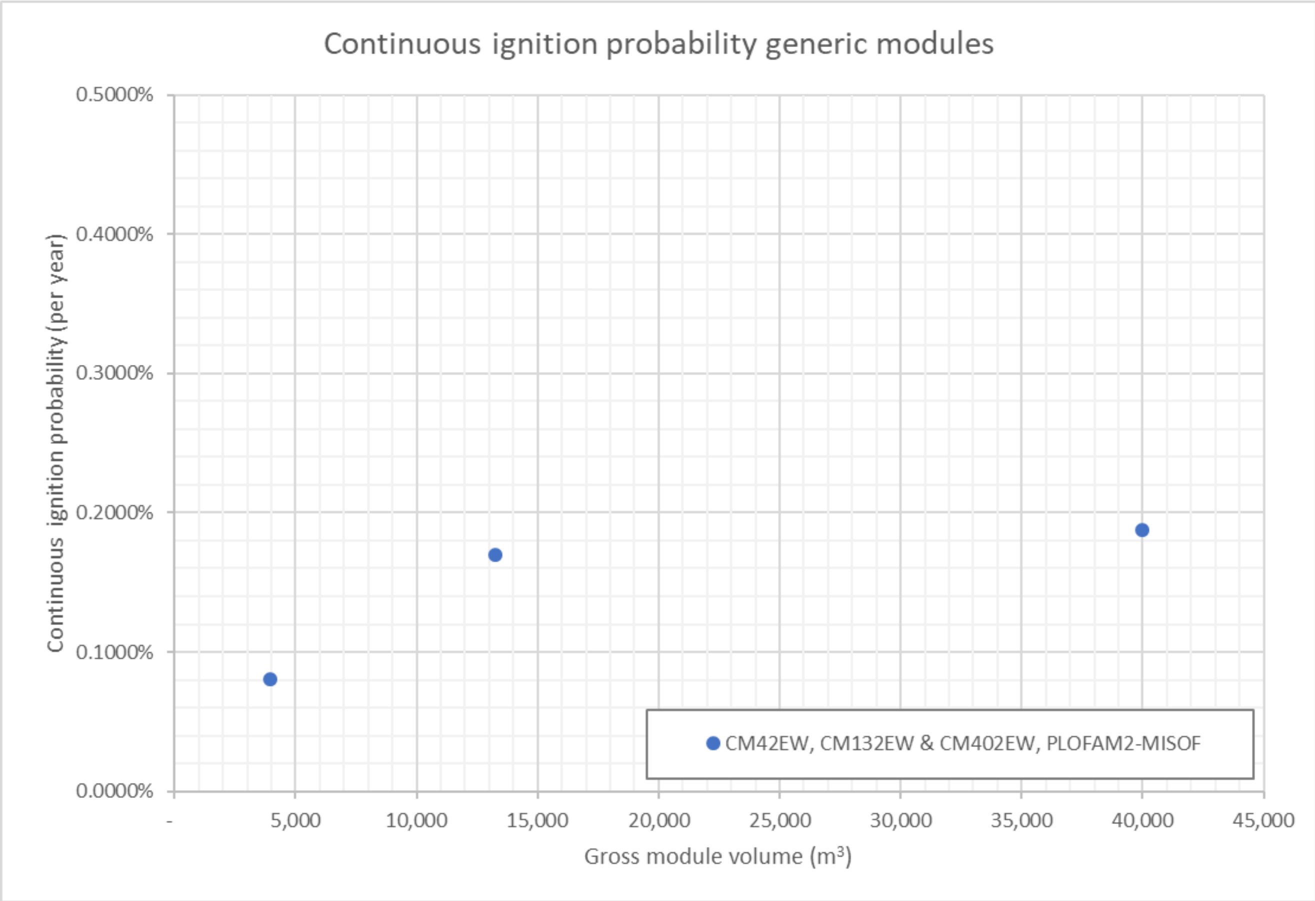


Figure 6-5: Continuous ignition probability vs. module volume for the various modules

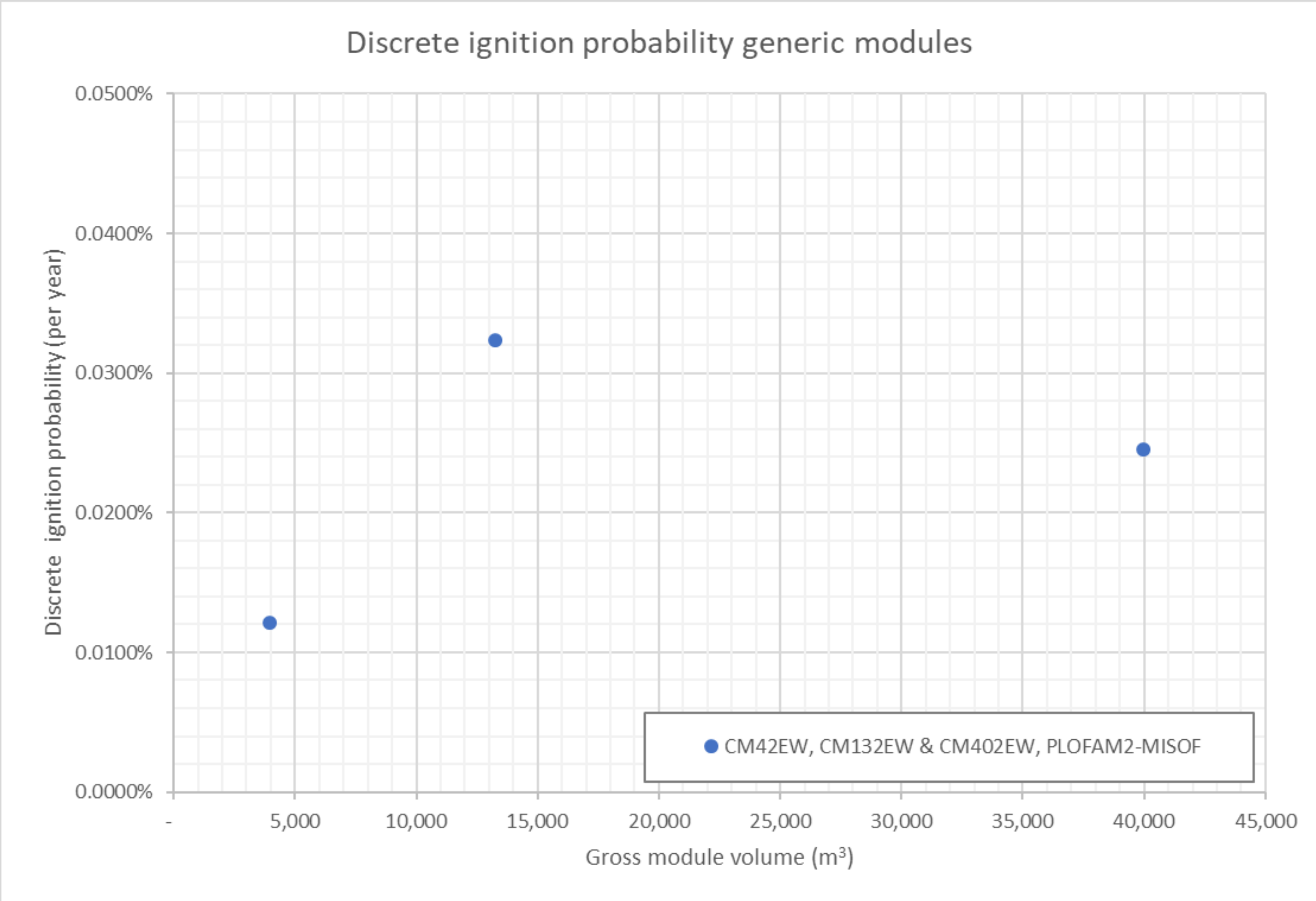


Figure 6-6: Discrete ignition probability vs. module volume for the various modules

6.4 Critical explosion frequency

The trend with respect to the gas cloud corresponding to a cumulative frequency of 10^{-4} and 10^{-5} per year is presented in the following figures.

The results demonstrate a significant trend with module size.

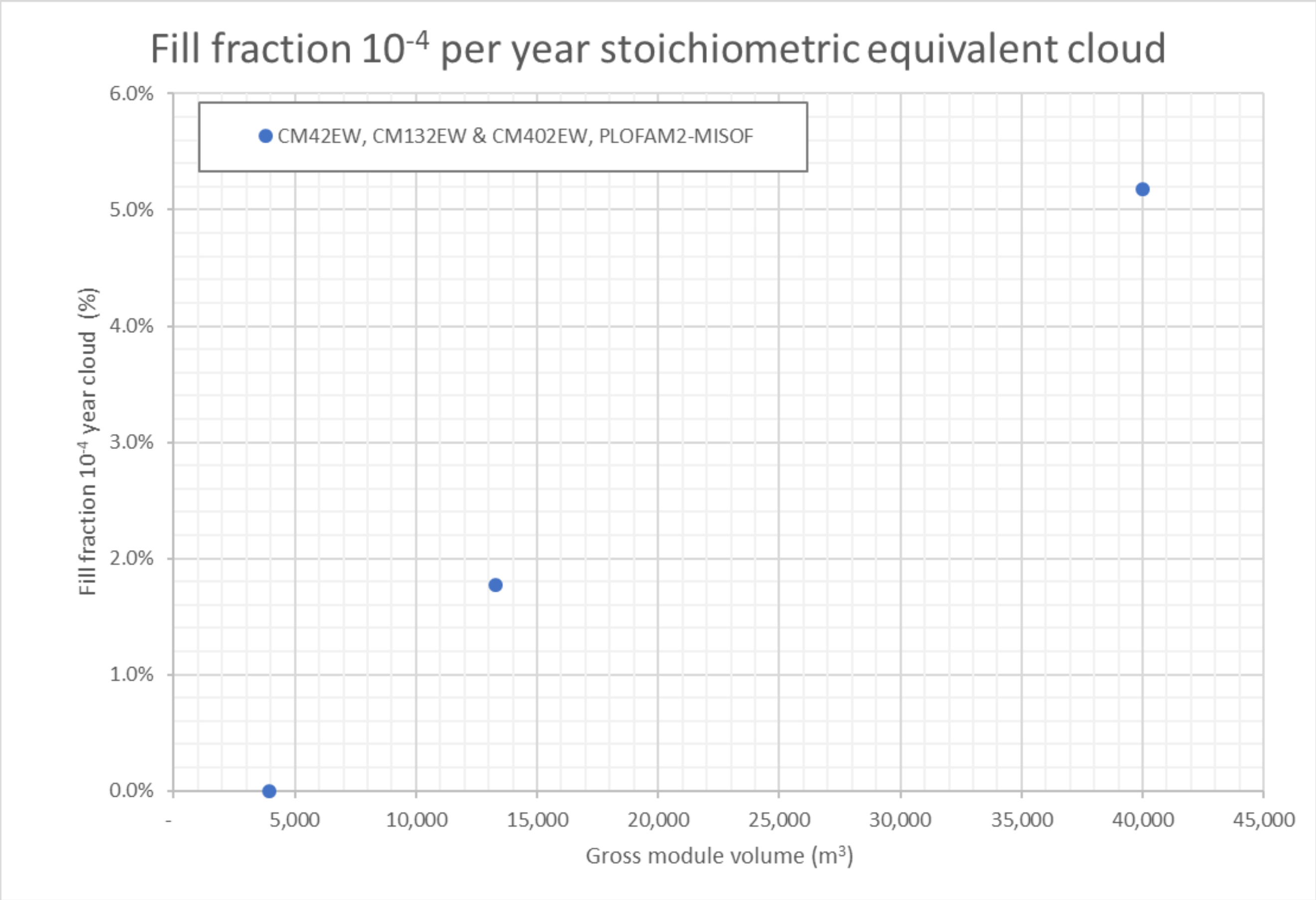


Figure 6-7: Fill fraction 10^{-4} per year stoichiometric equivalent volume vs. module volume for the three modules

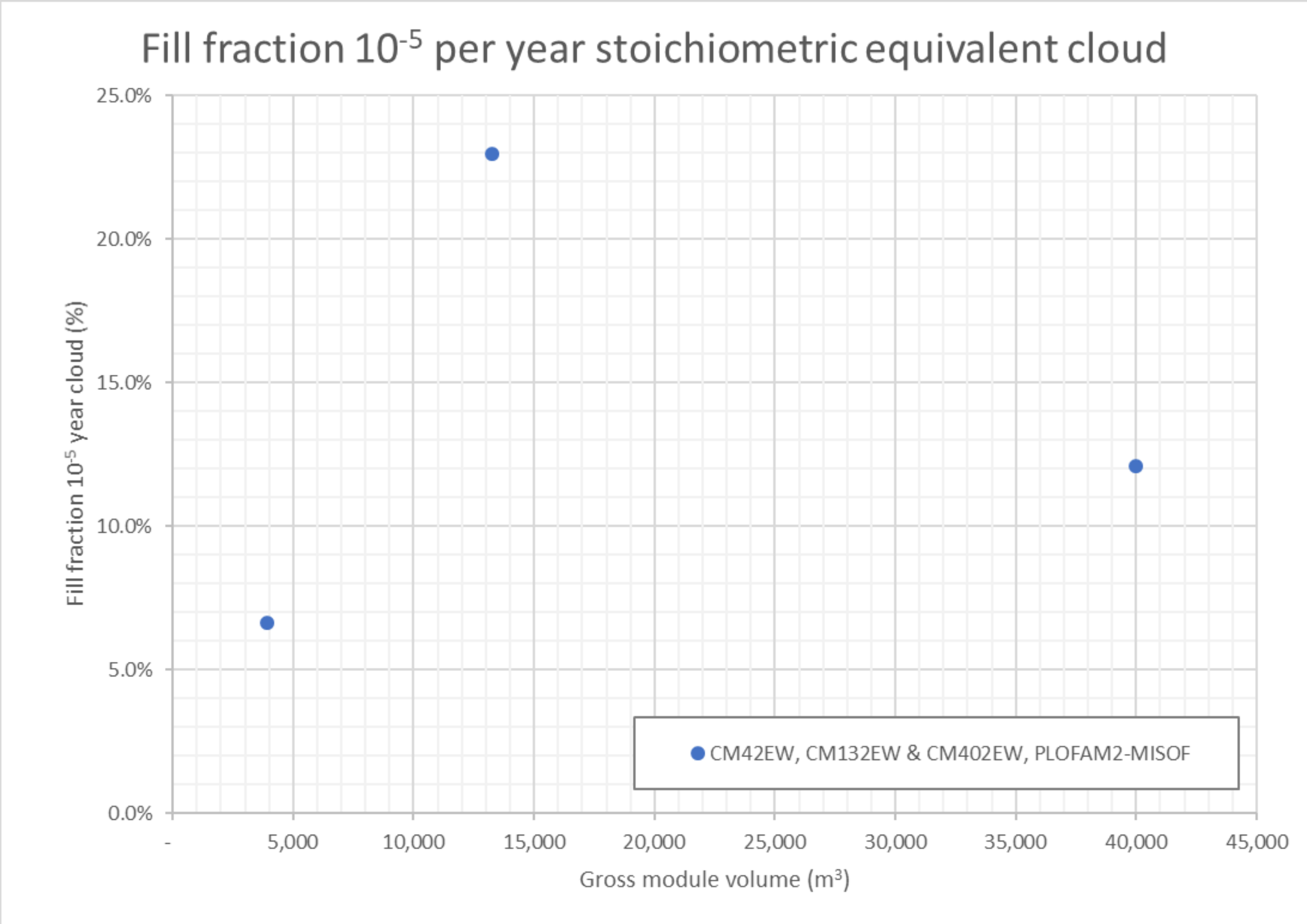


Figure 6-8: Fill fraction 10^{-5} per year stoichiometric equivalent volume vs. module volume for the three modules

7 Main conclusions

- The frequency distribution for ignited gas clouds is shifted towards much smaller gas clouds using the PLOFAM-MISOF models compared to the SHLFM and OLF models. Here it must be emphasized that the applied OLF model parameters corresponds to a module set in operation in the 80's. The correction factors in the OLF model favour new installations, and the distributions are shown to be similar for green fields. Hence, it is expected that the PLOFAM-MISOF models will generate a similar explosion risk picture as the SHLFM-OLF models for new installations.
- The generated total fire frequency will be considerably less using the upgraded models. The leak frequency generated by the PLOFAM model is considerably less than the leak frequency estimate provided by the SHLFM model, especially for large leaks. The large reduction in leak frequency outweighs the significant increase in ignition probability generated by MISOF. Based on these results, it is expected that the new models will generate lower fire frequencies in most cases. Exceptions could be modules with many pumps and/or compressors. Hence, PLOFAM-MISOF is expected to produce considerably lower risk figures in terms of risk metrics measuring consequences due to fires, for example impairment of escape ways due to smoke and escalation to pressurized equipment or structures.
- The generated fire frequency using PLOFAM and MISOF is in line with the observed historical frequency. The SHLFM-OLF models generated excessive estimates of the fire frequency.
- The SHLFM and the OLF model is not recommended for estimation of the fire and explosion risk at offshore installations. Both models deviate much from the observed historical data and our understanding of the performance of the barriers affecting the risk. Hence, the SHLFM and OLF models are to be considered obsolete.
- The dominant contribution is expected to result from large leaks generating a rapidly expanding gas cloud materialising ignition due to continuous sources within short time after start of the leak.
- The results show that most ignitions tend to occur before 1 minute after start of the leak. This is related to that the continuous ignition mechanisms are the dominant idealisation of ignition mechanisms in the MISOF model. Large leaks that generates big gas clouds within a few seconds drives the explosion risk according to the model. The continuous ignition mechanism is materialized upon first time exposure, and the effect of the safety functions are relatively small within the initial half a minute or so. The late ignitions are typically stemming from long duration liquid leaks in low wind conditions. The dominant fraction early ignition is consistent with the aim of the MISOF model in this regard. Generally, it is expected that ignitions will occur early in a leak scenario (see main report).
- in unfavourable cases, the contribution from gas turbine air intakes may constitute the major contributor to fire and explosion risk. The potential ignition mechanisms causing ignition when combustible gas is ingested by a gas turbine is not fully understood. A JIP carried out by Lloyd's Register mapped the current understanding of the problem, but is not conclusive in terms of the ignition probability or the potential ignition mechanisms. A list of potential risk reducing measures are discussed in the JIP report. One potential effective measure is to retrofit

a system that inert the ingested atmosphere upon gas detection. More work is required to understand the time window such a system needs to be effective (i.e. for how long time in the gas turbine wind down cycle is the turbine a potential source of ignition). For green fields, risk could be mitigated by smart layout.

- Specific modelling of the location of special ignition sources, such as pumps, compressors and gas turbine air intakes, may have a significant effect on the resulting distribution of ignited gas clouds. This can in particular be important for large open areas where the rotating machinery is located in one distinct area. Then there is dependency between the location of the leak sources and the dominant ignition sources.
- The fraction of equipment isolated upon gas detection has a profound effect on the result. Hence, it is crucial that applied value for P_{iso} is representative for the installation being studied.
- It is important to be aware of that MISOF will tend to lead to ignitions at an early stage of the unfolding scenario. This result may lead to the conclusion that the safety functions controlling the duration of the leak has little importance for the explosion safety. The idealization of ignition mechanisms in MISOF is uncertain, and the result from MISOF in this regard should not be used to compromise the performance of systems in place to control ignition and loss of containment. The main objective of the MISOF model is to generate a reasonable distribution of ignited gas clouds on line with the historical data. Further work should address the uncertainty related to the idealization of ignition mechanisms in MISOF.
- It should be noted that the modules studied are considered to represent rather unfavorable designs in terms of explosion risk, i.e. due to quite poor global ventilation conditions. The estimated explosion risk using PLOFAM and MISOF is therefore expected to be less for many equally sized modules in the North Sea.

8 References

/1/ Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", report no: 107566/R1, Rev: Final, Date: December 2018.

/2/ DNV, Offshore QRA – Standardised Hydrocarbon Leak Frequencies, report number 2009-1768, rev. 1, 16.01.2009.

/3/ Scandpower AS: "Ignition modelling in risk analysis", report no. 89.390.008/R1, March 2007

Appendix A

List of simulated scenarios per module

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
30	CM42EW	p01	yp	265	4	Liquid	0.5
31	CM42EW	p01	yp	265	4	Liquid	1
32	CM42EW	p01	yp	265	4	Liquid	2
33	CM42EW	p01	yp	265	4	Liquid	4
34	CM42EW	p01	yp	265	4	Liquid	8
35	CM42EW	p01	yp	265	4	Liquid	16
36	CM42EW	p01	yp	265	4	Liquid	32
37	CM42EW	p01	yp	265	4	Liquid	64
38	CM42EW	p01	yp	265	4	Liquid	128
39	CM42EW	p01	yp	265	4	Liquid	256
40	CM42EW	p01	yp	265	4	Liquid	512
41	CM42EW	p01	yp	265	4	Liquid	999
42	CM42EW	p01	yp	265	12	Liquid	64
43	CM42EW	p01	yp	265	12	Liquid	128
44	CM42EW	p01	yp	265	12	Liquid	256
45	CM42EW	p01	yp	265	12	Liquid	512
46	CM42EW	p01	yp	265	12	Liquid	999
47	CM42EW	p01	xn	265	4	Gas	0.5
48	CM42EW	p01	xn	265	4	Gas	1
49	CM42EW	p01	xn	265	4	Gas	2
50	CM42EW	p01	xn	265	4	Gas	4
51	CM42EW	p01	xn	265	4	Gas	8
53	CM42EW	p01	xn	265	4	Gas	16
55	CM42EW	p01	xn	265	4	Gas	32
57	CM42EW	p01	xn	265	4	Gas	64
59	CM42EW	p01	xn	265	4	Gas	128
61	CM42EW	p01	xn	265	4	Gas	256
63	CM42EW	p01	xn	265	4	Gas	512
65	CM42EW	p01	xn	265	4	Gas	999
78	CM42EW	p01	xp	265	12	Gas	4
79	CM42EW	p01	xp	265	12	Gas	8
80	CM42EW	p01	xp	265	12	Gas	16
81	CM42EW	p01	xp	265	12	Gas	32
82	CM42EW	p01	xp	265	12	Gas	64
83	CM42EW	p01	xp	265	12	Gas	128
84	CM42EW	p01	xp	265	12	Gas	256
85	CM42EW	p01	xp	265	12	Gas	512
86	CM42EW	p01	xp	265	12	Gas	999
100	CM42EW	p01	yp	265	4	Gas	0.5
105	CM42EW	p01	yp	265	4	Gas	1
110	CM42EW	p01	yp	265	4	Gas	2
115	CM42EW	p01	yp	265	4	Gas	4
120	CM42EW	p01	yp	265	4	Gas	8
138	CM42EW	p01	yp	265	4	Gas	16
143	CM42EW	p01	yp	265	4	Gas	32
148	CM42EW	p01	yp	265	4	Gas	64
153	CM42EW	p01	yp	265	4	Gas	128
158	CM42EW	p01	yp	265	4	Gas	256
163	CM42EW	p01	yp	265	4	Gas	512
168	CM42EW	p01	yp	265	4	Gas	999

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
177	CM42EW	p01	yp	265	4	Liquid	64
179	CM42EW	p01	yp	265	4	Liquid	128
181	CM42EW	p01	yp	265	4	Liquid	256
183	CM42EW	p01	yp	265	4	Liquid	512
185	CM42EW	p01	yp	265	4	Liquid	999
186	CM42EW	p01	yp	265	12	Gas	0.5
187	CM42EW	p01	yp	265	12	Gas	1
188	CM42EW	p01	yp	265	12	Gas	2
189	CM42EW	p01	yp	265	12	Gas	4
190	CM42EW	p01	yp	265	12	Gas	8
192	CM42EW	p01	yp	265	12	Gas	16
194	CM42EW	p01	yp	265	12	Gas	32
196	CM42EW	p01	yp	265	12	Gas	64
198	CM42EW	p01	yp	265	12	Gas	128
200	CM42EW	p01	yp	265	12	Gas	256
202	CM42EW	p01	yp	265	12	Gas	512
204	CM42EW	p01	yp	265	12	Gas	999
207	CM42EW	p01	yp	265	12	Liquid	64
209	CM42EW	p01	yp	265	12	Liquid	128
211	CM42EW	p01	yp	265	12	Liquid	256
213	CM42EW	p01	yp	265	12	Liquid	512
215	CM42EW	p01	yp	265	12	Liquid	999
216	CM42EW	p01	zn	170	8	Gas	0.5
217	CM42EW	p01	zn	170	8	Gas	1
218	CM42EW	p01	zn	170	8	Gas	2
219	CM42EW	p01	zn	170	8	Gas	4
220	CM42EW	p01	zn	170	8	Gas	8
221	CM42EW	p01	zn	170	8	Gas	16
222	CM42EW	p01	zn	170	8	Gas	32
223	CM42EW	p01	zn	170	8	Gas	64
224	CM42EW	p01	zn	170	8	Gas	128
225	CM42EW	p01	zn	170	8	Gas	256
227	CM42EW	p01	zn	170	8	Gas	512
228	CM42EW	p01	zn	170	8	Gas	999
229	CM42EW	p01	zn	265	4	Gas	0.5
230	CM42EW	p01	zn	265	4	Gas	1
232	CM42EW	p01	zn	265	4	Gas	2
234	CM42EW	p01	zn	265	4	Gas	4
236	CM42EW	p01	zn	265	4	Gas	8
238	CM42EW	p01	zn	265	4	Gas	16
240	CM42EW	p01	zn	265	4	Gas	32
242	CM42EW	p01	zn	265	4	Gas	64
244	CM42EW	p01	zn	265	4	Gas	128
246	CM42EW	p01	zn	265	4	Gas	256
248	CM42EW	p01	zn	265	4	Gas	512
250	CM42EW	p01	zn	265	4	Gas	999

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
251	CM42EW	p01	zn	265	12	Gas	0.5
252	CM42EW	p01	zn	265	12	Gas	1
253	CM42EW	p01	zn	265	12	Gas	2
254	CM42EW	p01	zn	265	12	Gas	4
255	CM42EW	p01	zn	265	12	Gas	8
256	CM42EW	p01	zn	265	12	Gas	16
257	CM42EW	p01	zn	265	12	Gas	32
258	CM42EW	p01	zn	265	12	Gas	64
259	CM42EW	p01	zn	265	12	Gas	128
260	CM42EW	p01	zp	170	2	Gas	0.5
261	CM42EW	p01	zp	170	2	Gas	1
262	CM42EW	p01	zp	170	2	Gas	2
263	CM42EW	p01	zp	170	2	Gas	4
264	CM42EW	p01	zp	170	2	Gas	8
265	CM42EW	p01	zp	170	2	Gas	16
266	CM42EW	p01	zp	170	2	Gas	32
267	CM42EW	p01	zp	170	2	Gas	64
268	CM42EW	p01	zp	170	2	Gas	128
269	CM42EW	p01	zp	170	2	Gas	256
270	CM42EW	p01	zp	170	2	Gas	512
271	CM42EW	p01	zp	170	2	Gas	999
309	CM42EW	p01	yp	265	4	Gas	4
312	CM42EW	p01	yp	265	4	Gas	8
315	CM42EW	p01	yp	265	4	Gas	16
318	CM42EW	p01	yp	265	4	Gas	32
321	CM42EW	p01	yp	265	4	Gas	64
324	CM42EW	p01	yp	265	4	Gas	128
327	CM42EW	p01	yp	265	4	Gas	256
330	CM42EW	p01	yp	265	4	Gas	512
333	CM42EW	p01	yp	265	4	Gas	999
334	CM42EW	p01	yp	265	4	Liquid	64
335	CM42EW	p01	yp	265	4	Liquid	128
336	CM42EW	p01	yp	265	4	Liquid	256
337	CM42EW	p01	yp	265	4	Liquid	512
338	CM42EW	p01	yp	265	4	Liquid	999
339	CM42EW	p01	yp	265	12	Gas	2
340	CM42EW	p01	yp	265	12	Gas	4
341	CM42EW	p01	yp	265	12	Gas	16
342	CM42EW	p01	yp	265	12	Gas	32
343	CM42EW	p01	yp	265	12	Gas	128
344	CM42EW	p01	yp	265	12	Gas	256
345	CM42EW	p01	yp	265	12	Gas	512
346	CM42EW	p01	yp	265	12	Gas	999
347	CM42EW	p01	yp	265	12	Liquid	64
348	CM42EW	p01	yp	265	12	Liquid	128
349	CM42EW	p01	yp	265	12	Liquid	256
350	CM42EW	p01	yp	265	12	Liquid	512

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
351	CM42EW	p01	yp	265	12	Liquid	999
352	CM42EW	p01	yp	265	4	Gas	0.5
353	CM42EW	p01	yp	265	4	Gas	1
354	CM42EW	p01	yp	265	4	Gas	2
355	CM42EW	p01	yp	265	4	Gas	4
356	CM42EW	p01	yp	265	4	Gas	8
357	CM42EW	p01	yp	265	4	Gas	16
358	CM42EW	p01	yp	265	4	Gas	32
359	CM42EW	p01	yp	265	4	Gas	64
360	CM42EW	p01	yp	265	4	Gas	128
361	CM42EW	p01	yp	265	4	Gas	256
362	CM42EW	p01	yp	265	4	Gas	512
363	CM42EW	p01	yp	265	4	Gas	999
364	CM42EW	p01	yp	265	12	Gas	0.5
365	CM42EW	p01	yp	265	12	Gas	1
366	CM42EW	p01	yp	265	12	Gas	2
367	CM42EW	p01	yp	265	12	Gas	4
368	CM42EW	p01	yp	265	12	Gas	8
369	CM42EW	p01	yp	265	12	Gas	16
370	CM42EW	p01	yp	265	12	Gas	32
371	CM42EW	p01	yp	265	12	Gas	64
372	CM42EW	p01	yp	265	12	Gas	128
373	CM42EW	p01	yp	265	12	Gas	256
374	CM42EW	p01	yp	265	12	Gas	512
375	CM42EW	p01	yp	265	12	Gas	999
376	CM42EW	p01	yp	265	4	Gas	4
377	CM42EW	p01	yp	265	4	Gas	8
378	CM42EW	p01	yp	265	4	Gas	16
379	CM42EW	p01	yp	265	4	Gas	32
380	CM42EW	p01	yp	265	4	Gas	64
381	CM42EW	p01	yp	265	4	Gas	128
382	CM42EW	p01	yp	265	4	Gas	256
383	CM42EW	p01	yp	265	4	Gas	512
384	CM42EW	p01	yp	265	4	Gas	999
385	CM42EW	p01	yp	265	4	Liquid	64
386	CM42EW	p01	yp	265	4	Liquid	128
387	CM42EW	p01	yp	265	4	Liquid	256
388	CM42EW	p01	yp	265	12	Gas	4
389	CM42EW	p01	yp	265	12	Gas	8
390	CM42EW	p01	yp	265	12	Gas	16
391	CM42EW	p01	yp	265	12	Gas	32
392	CM42EW	p01	yp	265	12	Gas	64
393	CM42EW	p01	yp	265	12	Gas	128
394	CM42EW	p01	yp	265	12	Gas	256
395	CM42EW	p01	yp	265	12	Gas	512
396	CM42EW	p01	yp	265	12	Gas	999
397	CM42EW	p01	yp	265	4	Liquid	128
398	CM42EW	p01	yp	265	4	Liquid	256

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
1	CM132EW	p01	yp	265	4	Liquid	128
2	CM132EW	p01	yp	265	4	Liquid	256
3	CM132EW	p01	yp	265	4	Liquid	512
4	CM132EW	p01	yp	265	4	Liquid	999
6	CM132EW	p01	xn	265	4	Gas	4
8	CM132EW	p01	xn	265	4	Gas	8
10	CM132EW	p01	xn	265	4	Gas	16
12	CM132EW	p01	xn	265	4	Gas	32
14	CM132EW	p01	xn	265	4	Gas	64
16	CM132EW	p01	xn	265	4	Gas	128
18	CM132EW	p01	xn	265	4	Gas	256
20	CM132EW	p01	xn	265	4	Gas	512
22	CM132EW	p01	xn	265	4	Gas	999
23	CM132EW	p01	xn	265	12	Liquid	128
24	CM132EW	p01	xn	265	12	Liquid	256
25	CM132EW	p01	xn	265	12	Liquid	512
26	CM132EW	p01	xn	265	12	Liquid	999
28	CM132EW	p01	xp	265	4	Gas	4
30	CM132EW	p01	xp	265	4	Gas	8
32	CM132EW	p01	xp	265	4	Gas	16
34	CM132EW	p01	xp	265	4	Gas	32
36	CM132EW	p01	xp	265	4	Gas	64
38	CM132EW	p01	xp	265	4	Gas	128
40	CM132EW	p01	xp	265	4	Gas	256
42	CM132EW	p01	xp	265	4	Gas	512
44	CM132EW	p01	xp	265	4	Gas	999
45	CM132EW	p01	xp	265	8	Liquid	128
46	CM132EW	p01	xp	265	8	Liquid	256
47	CM132EW	p01	xp	265	8	Liquid	512
48	CM132EW	p01	xp	265	8	Liquid	999
50	CM132EW	p01	yn	265	4	Gas	4
52	CM132EW	p01	yn	265	4	Gas	8
54	CM132EW	p01	yn	265	4	Gas	16
56	CM132EW	p01	yn	265	4	Gas	32
58	CM132EW	p01	yn	265	4	Gas	64
60	CM132EW	p01	yn	265	4	Gas	128
62	CM132EW	p01	yn	265	4	Gas	256
64	CM132EW	p01	yn	265	4	Gas	512
65	CM132EW	p01	yn	265	4	Gas	999
73	CM132EW	p01	yp	265	2	Liquid	0.5
74	CM132EW	p01	yp	265	2	Liquid	1
75	CM132EW	p01	yp	265	2	Liquid	2
76	CM132EW	p01	yp	265	2	Liquid	16
77	CM132EW	p01	yp	265	2	Liquid	32
78	CM132EW	p01	yp	265	2	Liquid	64
80	CM132EW	p01	yp	265	4	Gas	0.5
82	CM132EW	p01	yp	265	4	Gas	1
84	CM132EW	p01	yp	265	4	Gas	2
86	CM132EW	p01	yp	265	4	Gas	4
88	CM132EW	p01	yp	265	4	Gas	8
90	CM132EW	p01	yp	265	4	Gas	16

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
92	CM132EW	p01	yp	265	4	Gas	32
94	CM132EW	p01	yp	265	4	Gas	64
96	CM132EW	p01	yp	265	4	Gas	128
98	CM132EW	p01	yp	265	4	Gas	256
100	CM132EW	p01	yp	265	4	Gas	512
101	CM132EW	p01	yp	265	4	Gas	999
110	CM132EW	p01	yp	265	4	Liquid	128
112	CM132EW	p01	yp	265	4	Liquid	256
114	CM132EW	p01	yp	265	4	Liquid	512
116	CM132EW	p01	yp	265	4	Liquid	999
124	CM132EW	p01	zn	265	4	Gas	4
125	CM132EW	p01	zn	265	4	Gas	8
126	CM132EW	p01	zn	265	4	Gas	16
127	CM132EW	p01	zn	265	4	Gas	32
128	CM132EW	p01	zn	265	4	Gas	64
129	CM132EW	p01	zn	265	4	Gas	128
130	CM132EW	p01	zn	265	4	Gas	256
131	CM132EW	p01	zn	265	4	Gas	512
132	CM132EW	p01	zn	265	4	Gas	999
133	CM132EW	p01	zp	265	4	Gas	4
134	CM132EW	p01	zp	265	4	Gas	8
135	CM132EW	p01	zp	265	4	Gas	16
136	CM132EW	p01	zp	265	4	Gas	32
137	CM132EW	p01	zp	265	4	Gas	64
138	CM132EW	p01	zp	265	4	Gas	128
139	CM132EW	p01	zp	265	4	Gas	256
140	CM132EW	p01	zp	265	4	Gas	512
141	CM132EW	p01	zp	265	4	Gas	999
142	CM132EW	p02	yp	265	2	Liquid	64
150	CM132EW	p01	yp	265	8	Liquid	128
151	CM132EW	p01	yp	265	8	Liquid	256
152	CM132EW	p01	yp	265	8	Liquid	512
153	CM132EW	p01	yp	265	8	Liquid	999
154	CM132EW	p01	yp	100	8	Liquid	128
155	CM132EW	p01	yp	100	8	Liquid	256
156	CM132EW	p01	yp	100	8	Liquid	512
157	CM132EW	p01	yp	100	8	Liquid	999
158	CM132EW	p01	yp	265	2	Liquid	128
159	CM132EW	p01	yp	265	2	Liquid	256
160	CM132EW	p01	yp	265	2	Liquid	512
161	CM132EW	p01	yp	265	2	Liquid	999
162	CM132EW	p01	yp	265	8	Liquid	128
163	CM132EW	p01	yp	265	8	Liquid	256
164	CM132EW	p01	yp	265	8	Liquid	512
165	CM132EW	p01	yp	265	8	Liquid	999
169	CM132EW	p01	yp	265	4	Liquid	128
171	CM132EW	p01	yp	265	4	Liquid	256
173	CM132EW	p01	yp	265	4	Liquid	512
175	CM132EW	p01	yp	265	4	Liquid	999
176	CM132EW	p01	xn	265	4	Gas	4
177	CM132EW	p01	xn	265	4	Gas	8
178	CM132EW	p01	xn	265	4	Gas	16

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
179	CM132EW	p01	xn	265	4	Gas	32
180	CM132EW	p01	xn	265	4	Gas	64
181	CM132EW	p01	xn	265	4	Gas	128
182	CM132EW	p01	xn	265	4	Gas	256
183	CM132EW	p01	xn	265	4	Gas	512
184	CM132EW	p01	xn	265	4	Gas	999
185	CM132EW	p01	xn	265	12	Liquid	128
186	CM132EW	p01	xn	265	12	Liquid	256
187	CM132EW	p01	xn	265	12	Liquid	512
188	CM132EW	p01	xn	265	12	Liquid	999
197	CM132EW	p01	xp	265	4	Gas	4
198	CM132EW	p01	xp	265	4	Gas	8
199	CM132EW	p01	xp	265	4	Gas	16
200	CM132EW	p01	xp	265	4	Gas	32
201	CM132EW	p01	xp	265	4	Gas	64
202	CM132EW	p01	xp	265	4	Gas	128
203	CM132EW	p01	xp	265	4	Gas	256
204	CM132EW	p01	xp	265	4	Gas	512
205	CM132EW	p01	xp	265	4	Gas	999
206	CM132EW	p01	xp	265	8	Liquid	128
207	CM132EW	p01	xp	265	8	Liquid	256
208	CM132EW	p01	xp	265	8	Liquid	512
209	CM132EW	p01	xp	265	8	Liquid	999
210	CM132EW	p01	yn	265	4	Gas	4
211	CM132EW	p01	yn	265	4	Gas	8
212	CM132EW	p01	yn	265	4	Gas	16
213	CM132EW	p01	yn	265	4	Gas	32
214	CM132EW	p01	yn	265	4	Gas	64
215	CM132EW	p01	yn	265	4	Gas	128
216	CM132EW	p01	yn	265	4	Gas	256
217	CM132EW	p01	yn	265	4	Gas	512
218	CM132EW	p01	yn	265	4	Gas	999
248	CM132EW	p01	yp	265	2	Liquid	0.5
249	CM132EW	p01	yp	265	2	Liquid	1
250	CM132EW	p01	yp	265	2	Liquid	2
251	CM132EW	p01	yp	265	2	Liquid	16
253	CM132EW	p01	yp	265	2	Liquid	32
255	CM132EW	p01	yp	265	2	Liquid	64
260	CM132EW	p01	yp	265	4	Gas	0.5
261	CM132EW	p01	yp	265	4	Gas	1
262	CM132EW	p01	yp	265	4	Gas	2
263	CM132EW	p01	yp	265	4	Gas	4
264	CM132EW	p01	yp	265	4	Gas	8
265	CM132EW	p01	yp	265	4	Gas	16
266	CM132EW	p01	yp	265	4	Gas	32
267	CM132EW	p01	yp	265	4	Gas	64
268	CM132EW	p01	yp	265	4	Gas	128
269	CM132EW	p01	yp	265	4	Gas	256
270	CM132EW	p01	yp	265	4	Gas	512
271	CM132EW	p01	yp	265	4	Gas	999
272	CM132EW	p01	yp	265	4	Liquid	128
273	CM132EW	p01	yp	265	4	Liquid	256

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
274	CM132EW	p01	yp	265	4	Liquid	512
275	CM132EW	p01	yp	265	4	Liquid	999
276	CM132EW	p01	zn	265	4	Gas	4
277	CM132EW	p01	zn	265	4	Gas	8
278	CM132EW	p01	zn	265	4	Gas	16
279	CM132EW	p01	zn	265	4	Gas	32
280	CM132EW	p01	zn	265	4	Gas	64
281	CM132EW	p01	zn	265	4	Gas	128
282	CM132EW	p01	zn	265	4	Gas	256
283	CM132EW	p01	zn	265	4	Gas	512
284	CM132EW	p01	zn	265	4	Gas	999
285	CM132EW	p01	zp	265	4	Gas	4
286	CM132EW	p01	zp	265	4	Gas	8
287	CM132EW	p01	zp	265	4	Gas	16
288	CM132EW	p01	zp	265	4	Gas	32
289	CM132EW	p01	zp	265	4	Gas	64
290	CM132EW	p01	zp	265	4	Gas	128
291	CM132EW	p01	zp	265	4	Gas	256
292	CM132EW	p01	zp	265	4	Gas	512
293	CM132EW	p01	zp	265	4	Gas	999
294	CM132EW	p02	yp	265	2	Liquid	64
301	CM132EW	p01	yp	265	8	Liquid	128
302	CM132EW	p01	yp	265	8	Liquid	256
303	CM132EW	p01	yp	265	8	Liquid	512
304	CM132EW	p01	yp	265	8	Liquid	999
305	CM132EW	p01	yp	100	8	Liquid	128
306	CM132EW	p01	yp	100	8	Liquid	256
307	CM132EW	p01	yp	100	8	Liquid	512
308	CM132EW	p01	yp	100	8	Liquid	999
309	CM132EW	p01	yp	265	2	Liquid	128
310	CM132EW	p01	yp	265	2	Liquid	256
311	CM132EW	p01	yp	265	2	Liquid	512
312	CM132EW	p01	yp	265	2	Liquid	999
318	CM132EW	p01	yp	265	8	Liquid	128
319	CM132EW	p01	yp	265	8	Liquid	256
320	CM132EW	p01	yp	265	8	Liquid	512
321	CM132EW	p01	yp	265	8	Liquid	999

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
1	CM402EW	p01	zn	265	4	Liquid	128
2	CM402EW	p01	zn	265	4	Liquid	256
3	CM402EW	p01	zn	265	4	Liquid	512
4	CM402EW	p01	zn	265	4	Liquid	999
5	CM402EW	p01	zn	265	12	Liquid	128
6	CM402EW	p01	zn	265	12	Liquid	256
7	CM402EW	p01	zn	265	12	Liquid	512
8	CM402EW	p01	zn	265	12	Liquid	999
9	CM402EW	p01	xn	265	4	Gas	64
10	CM402EW	p01	xn	265	4	Gas	128
11	CM402EW	p01	xn	265	4	Gas	256
12	CM402EW	p01	xn	265	4	Gas	512
13	CM402EW	p01	xn	265	4	Gas	999
14	CM402EW	p01	xn	265	4	Liquid	128
15	CM402EW	p01	xn	265	4	Liquid	256
16	CM402EW	p01	xn	265	4	Liquid	512
17	CM402EW	p01	xn	265	4	Liquid	999
18	CM402EW	p01	xp	265	4	Gas	64
19	CM402EW	p01	xp	265	4	Gas	128
20	CM402EW	p01	xp	265	4	Gas	256
21	CM402EW	p01	xp	265	4	Gas	512
22	CM402EW	p01	xp	265	4	Gas	999
23	CM402EW	p01	yn	265	4	Gas	0.5
24	CM402EW	p01	yn	265	4	Gas	1
25	CM402EW	p01	yn	265	4	Gas	2
26	CM402EW	p01	yn	265	4	Gas	4
27	CM402EW	p01	yn	265	4	Gas	8
28	CM402EW	p01	yn	265	4	Gas	16
29	CM402EW	p01	yn	265	4	Gas	32
30	CM402EW	p01	yn	265	4	Gas	64
31	CM402EW	p01	yn	265	4	Gas	128
32	CM402EW	p01	yn	265	4	Gas	256
33	CM402EW	p01	yn	265	4	Gas	512
34	CM402EW	p01	yn	265	4	Gas	999
35	CM402EW	p01	yp	265	4	Gas	4
36	CM402EW	p01	yp	265	4	Gas	8
37	CM402EW	p01	yp	265	4	Gas	16
38	CM402EW	p01	yp	265	4	Gas	32
39	CM402EW	p01	yp	265	4	Gas	64
40	CM402EW	p01	yp	265	4	Gas	128
41	CM402EW	p01	yp	265	4	Gas	256
42	CM402EW	p01	yp	265	4	Gas	512
43	CM402EW	p01	yp	265	4	Gas	999
44	CM402EW	p01	zn	265	4	Gas	64
45	CM402EW	p01	zn	265	4	Gas	128
46	CM402EW	p01	zn	265	4	Gas	256
47	CM402EW	p01	zn	265	4	Gas	512
48	CM402EW	p01	zn	265	4	Gas	999
49	CM402EW	p01	zn	265	4	Liquid	128
50	CM402EW	p01	zn	265	4	Liquid	256

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
51	CM402EW	p01	zn	265	4	Liquid	512
52	CM402EW	p01	zn	265	4	Liquid	999
53	CM402EW	p01	zn	265	12	Gas	64
54	CM402EW	p01	zn	265	12	Gas	128
55	CM402EW	p01	zn	265	12	Gas	256
56	CM402EW	p01	zn	265	12	Gas	512
57	CM402EW	p01	zn	265	12	Gas	999
58	CM402EW	p01	zp	265	4	Gas	64
59	CM402EW	p01	zp	265	4	Gas	128
60	CM402EW	p01	zp	265	4	Gas	256
61	CM402EW	p01	zp	265	4	Gas	512
62	CM402EW	p01	zp	265	4	Gas	999
63	CM402EW	p01	zp	265	12	Gas	64
64	CM402EW	p01	zp	265	12	Gas	128
65	CM402EW	p01	zp	265	12	Gas	256
66	CM402EW	p01	zp	265	12	Gas	512
67	CM402EW	p01	zp	265	12	Gas	999
68	CM402EW	p03	xn	265	4	Gas	0.5
69	CM402EW	p03	xn	265	4	Gas	1
70	CM402EW	p03	xn	265	4	Gas	2
71	CM402EW	p03	xn	265	4	Gas	4
72	CM402EW	p03	xn	265	4	Gas	8
73	CM402EW	p03	xn	265	4	Gas	16
74	CM402EW	p03	xn	265	4	Gas	32
75	CM402EW	p03	xn	265	4	Gas	64
76	CM402EW	p03	xn	265	4	Gas	128
77	CM402EW	p03	xn	265	4	Gas	256
78	CM402EW	p03	xn	265	4	Gas	512
79	CM402EW	p03	xn	265	4	Gas	999
80	CM402EW	p03	xp	265	4	Gas	4
81	CM402EW	p03	xp	265	4	Gas	8
82	CM402EW	p03	xp	265	4	Gas	16
83	CM402EW	p03	xp	265	4	Gas	32
84	CM402EW	p03	xp	265	4	Gas	64
85	CM402EW	p03	xp	265	4	Gas	128
86	CM402EW	p03	xp	265	4	Gas	256
87	CM402EW	p03	xp	265	4	Gas	512
88	CM402EW	p03	xp	265	4	Gas	999
89	CM402EW	p03	yn	265	2	Liquid	0.5
90	CM402EW	p03	yn	265	2	Liquid	1
91	CM402EW	p03	yn	265	2	Liquid	2
92	CM402EW	p03	yn	265	2	Liquid	4
93	CM402EW	p03	yn	265	2	Liquid	8
94	CM402EW	p03	yn	265	2	Liquid	16
95	CM402EW	p03	yn	265	2	Liquid	32
96	CM402EW	p03	yn	265	2	Liquid	64
97	CM402EW	p03	yn	265	2	Liquid	128
98	CM402EW	p03	yn	265	2	Liquid	256
99	CM402EW	p03	yn	265	2	Liquid	512
100	CM402EW	p03	yn	265	2	Liquid	999

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
101	CM402EW	p03	yn	265	4	Liquid	16
102	CM402EW	p03	yn	265	4	Liquid	32
103	CM402EW	p03	yn	265	4	Liquid	64
104	CM402EW	p03	yn	265	4	Liquid	128
105	CM402EW	p03	yn	265	4	Liquid	256
106	CM402EW	p03	yn	265	4	Liquid	512
107	CM402EW	p03	yn	265	4	Liquid	999
108	CM402EW	p03	yn	265	8	Liquid	16
109	CM402EW	p03	yn	265	8	Liquid	32
110	CM402EW	p03	yn	265	8	Liquid	128
111	CM402EW	p03	yn	265	8	Liquid	256
112	CM402EW	p03	yn	265	8	Liquid	512
113	CM402EW	p03	yn	265	8	Liquid	999
114	CM402EW	p03	yn	265	12	Liquid	16
115	CM402EW	p03	yn	265	12	Liquid	32
116	CM402EW	p03	yn	265	12	Liquid	64
117	CM402EW	p03	yn	265	12	Liquid	128
118	CM402EW	p03	yn	265	12	Liquid	256
119	CM402EW	p03	yn	265	12	Liquid	512
120	CM402EW	p03	yn	265	12	Liquid	999
121	CM402EW	p11	xn	265	4	Gas	8
122	CM402EW	p11	xn	265	4	Gas	16
123	CM402EW	p11	xn	265	4	Gas	32
124	CM402EW	p11	xp	265	4	Gas	64
125	CM402EW	p11	xp	265	4	Gas	128
126	CM402EW	p11	xp	265	4	Gas	256
127	CM402EW	p11	xp	265	4	Gas	512
128	CM402EW	p11	xp	265	4	Gas	999
129	CM402EW	p11	yn	265	4	Gas	64
130	CM402EW	p11	yn	265	4	Gas	128
131	CM402EW	p11	yn	265	4	Gas	256
132	CM402EW	p11	yn	265	4	Gas	512
133	CM402EW	p11	yn	265	4	Gas	999
134	CM402EW	p11	zn	265	4	Gas	128
135	CM402EW	p11	zn	265	4	Gas	256
136	CM402EW	p11	zn	265	4	Gas	512
137	CM402EW	p11	zn	265	4	Gas	999
138	CM402EW	p11	zp	265	4	Gas	64
139	CM402EW	p11	zp	265	4	Gas	128
140	CM402EW	p11	zp	265	4	Gas	256
141	CM402EW	p11	zp	265	4	Gas	512
142	CM402EW	p11	zp	265	4	Gas	999
143	CM402EW	p11	zp	265	12	Gas	512
144	CM402EW	p11	zp	265	12	Gas	999
145	CM402EW	p01	yn	265	4	Gas	8
146	CM402EW	p01	yn	265	4	Gas	16
147	CM402EW	p01	yn	265	4	Gas	32
148	CM402EW	p01	yp	265	4	Gas	4
149	CM402EW	p01	yp	265	4	Gas	8
150	CM402EW	p01	yp	265	4	Gas	16

ID	Module	Leak point	Leak direction	WindDir	Wind Speed (m/s)	Fluid	Leak Rate (kg/s)
151	CM402EW	p01	yp	265	4	Gas	32
152	CM402EW	p01	zn	265	4	Liquid	128
153	CM402EW	p01	zn	265	4	Liquid	256
154	CM402EW	p01	zn	265	4	Liquid	512
155	CM402EW	p01	zn	265	4	Liquid	999
156	CM402EW	p01	zn	265	12	Liquid	128
157	CM402EW	p01	zn	265	12	Liquid	256
158	CM402EW	p01	zn	265	12	Liquid	512
159	CM402EW	p01	zn	265	12	Liquid	999
160	CM402EW	p11	xp	265	4	Gas	64
161	CM402EW	p11	xp	265	4	Gas	128
162	CM402EW	p11	xp	265	4	Gas	256
163	CM402EW	p11	xp	265	4	Gas	512
164	CM402EW	p11	xp	265	4	Gas	999
165	CM402EW	p11	yp	265	4	Gas	4
166	CM402EW	p11	yp	265	4	Gas	8
167	CM402EW	p11	yp	265	4	Gas	16
168	CM402EW	p11	yp	265	4	Gas	32
169	CM402EW	p11	zn	265	4	Gas	64
170	CM402EW	p11	zn	265	4	Gas	128
171	CM402EW	p11	zn	265	4	Gas	256
172	CM402EW	p11	zn	265	4	Gas	512
173	CM402EW	p11	zn	265	4	Gas	999
174	CM402EW	p01	zn	265	4	Liquid	128
175	CM402EW	p01	zn	265	4	Liquid	256
176	CM402EW	p01	zn	265	4	Liquid	512
177	CM402EW	p01	zn	265	4	Liquid	999
178	CM402EW	p11	xp	265	4	Gas	64
179	CM402EW	p11	xp	265	4	Gas	128
180	CM402EW	p11	xp	265	4	Gas	256
181	CM402EW	p11	xp	265	4	Gas	512
182	CM402EW	p11	xp	265	4	Gas	999