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Process leak for offshore installations frequency assessment model - PLOFAM(2)

Main report

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Summary

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Main report

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Draft A	15.11.2018	This draft version is an update of the report 105586/R1 released 18.03.2016, ref /1/	Ingar Fossan and Are Opstad Sæbø
Final	06.12.2018	Comments from Equinor, Safetec and DNV GL, and Lilleaker Consulting AS are implemented	Ingar Fossan and Are Opstad Sæbø

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

Hydrocarbon process leaks are a major contributor to offshore risk. The last decade the industry has used a model denoted "Offshore QRA - Standardised Hydrocarbon Leak Frequencies" (SHLFM) to estimate leak frequencies for these incidents. This model originates from the JIP project "Standardised Hydrocarbon Leak Frequencies", which was first reported in final version in 2005. Based on experience from use of the model, Equinor has appreciated the need for a thorough revision of the methodology, and initiated a project where the purpose has been to create an updated leak frequency model that can be accepted as an industry standard for the Norwegian Continental Shelf by consultancy companies and operators.

To achieve this, Equinor contracted Lloyd's Register Consulting (LRC), DNV GL, Safetec and Lilleaker Consulting AS to work together. In addition to the four consultancy companies, the operators ConocoPhillips and Lundin were invited to the project. LRC has been the lead contractor while the others have contributed as advisors through workshops, document review and discussions in meetings. The project has been run in two phases during the periods March – December 2015 and June – December 2018. Personnel participating in workshops (in one or both phases) are listed in Table 1.1. Also other subject matter experts have been involved in video conferences and discussions.

This report with technical notes documents the resulting leak frequency model, denoted PLOFAM (Process leak for offshore installations frequency assessment model) that for most situations is expected to be the preferred model by all above mentioned project participants. It is expected that this model will be used for most QRA's for Equinor, ConocoPhillips and Lundin.

PLOFAM is designed to be a tool for estimation of future leak frequencies for use in QRAs. Overall the model is built on a combination of the explanatory variable that shows the strongest correlations with experienced number of leaks, and rational explanations and causalities reflecting known failure modes. The number of equipment (for each equipment type) is concluded to be the best single explanatory variable to build the model on. However, as only one explanatory variable is chosen for the model, there are many factors influencing the leak frequency that are not captured by the model, which will give rise to stochastic effects. The historical leak frequency per installation at the NCS can vary significantly from the NCS average and from the model prediction, as a result of the stochastic effects, and also if the conditions at a particular installation deviates from the normal conditions at installations on NCS.

The leak frequency model covers process leaks occurring during all operation phases, and topside leaks from the well system occurring during normal production. The leak scenarios may have a leak point associated with well, process system (including fuel gas system) or utility systems. The leak frequency for process leaks estimated by the model accounts for leaks occurring both in the process system and utility system fed from the process system. The model does however not give separate leak frequencies for process releases through utility systems and through process system. Three main leak scenarios are defined for the leak frequency model. That is *Process leak*, *Producing well leak* and *Gas lift well leak*. Furthermore, the model distinguishes between leak scenarios where the total released amount of hydrocarbons is ≤10 kg, and >10 kg. These leaks are classified as *Marginal leaks* and *Significant leaks*, respectively. Only the Significant leak scenario is relevant for detailed modelling of consequences and dimensioning accidental loads in a formal QRA. The Marginal leak scenario is only relevant with regard to immediate exposure of personnel in the close vicinity to scene of the leak to accidental loads or for small poorly ventilated enclosures.

The model itself consists of mathematical equations for the frequency hole size distribution per standard equipment type per equipment dimension. Thus, the model is equipment size dependent. A significant effort has been made to build a model where both the total leak frequency and the frequency for ruptures are equipment size dependent, unique for every standard equipment type, and as good as possible reflects the most common failure modes. The model includes the following new equipment types not included in SHLFM; compact flanges, steel piping, flexible piping, gas lift well, producing well and a model for leaks from hoses used in temporary operations.

The strategy has been to build a model that gives a best estimate for future leak frequencies, i.e. to create an unbiased model without built in conservatism. It is observed a significant decreasing trend in historical leak frequency with time for installations on the NCS in the period after year 2000 (actually since 1992). The number of historical leaks in the period 2006-2017 is used as target for the total leak frequency while leak data from the period 2001 – 2017 is used as target for the relative leak rate distribution. Targeting this frequency level would imply that the model will estimate about 30% lower leak frequency than the average leak frequency in the period 2001 – 2017, but also 30% higher leak frequency than seen for any years after 2011, i.e. the chosen target level for the model account for uncertainty in the data material and shifts in underlying causal factors (e.g. emerging unknown degradation mechanisms due to age or changing operational conditions) affecting the future trend in leaks occurring on installations on the NCS. In total the combination of the targeted total leak frequency and the fraction of large leaks will decide the targeted leak frequency for large leaks, and is regarded reasonable and as a best estimate, slightly approached from the conservative side. Note also that conservatism is embedded in the guideline for use of PLOFAM in QRAs.

The stochastic uncertainty has been quantified and is larger for large leak rates than for small leak rates. This is important to consider when evaluating the accuracy of a QRA model based on PLOFAM. For leak rates above about 30 kg/s, the relative stochastic uncertainty constitutes a factor in the range 1.5 to 2.5. i.e. based on the historical data it can be argued that the target value used for parametrization of the model can be both a factor 1.5 – 2.5 higher and lower than the target values used in PLOFAM (PLOFAM targets the most likely value). As a consequence it is shown that if two leaks >100 kg/s where one of them is larger than 300kg/s occur tomorrow, the model will still be valid.

The model validation is performed by applying the model to all installations on NCS being in operation in the period 2006 – 2017. The results shows that PLOFAM is able to:

(1) Reproduce the total number of leaks at NCS in the period 2006 – 2017
(2) Reproduce the total cumulative leak rate frequency distribution (i.e. the leak rate distribution) seen in historical data from NCS in the period 2001 – 2017, which is the defined target for the model, when applied to all installations on NCS.
(3) Reproduce the observed contribution to leaks originating from the different equipment types. The model does also reproduce the observed frequency distribution of leaks with respect to initial leak rate for the most dominating equipment types at NCS (*i.e.* valves, flanges, instruments and steel pipes).

The model is mainly validated towards available data of leaks that has occurred at installations on the Norwegian Continental Shelf (NCS), but also data from the United Kingdom Continental Shelf (UKCS) has been utilized where the data material for NCS is scarce. A main overall conclusion 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 UK installations. The differences may be explained by uncertainty related to the datasets (both the leaks and the population data, and the way equipment is counted and leaks are assigned to equipment types). Furthermore, also the total frequency and time trend in the leak frequency at UKCS is similar to the total leak frequency and time trend seen on NCS. The model is therefore regarded as valid for both sectors.

Table 1.1 – Personnel participating in one or more workshops in both project phases. Also other persons have been involved in video conferences, project meetings and discussions

Name	Company	Role
Phase 1 (2015)		
Eli Bech	Equinor	Equinor project manager
Unni Nord Samdal	Equinor	Technical point of contact
Espen Fyhn Nilsen	Equinor	Technical point of contact
Marie Saltkjel	ConocoPhillips	Participant
Espen Skilhagen	Lundin	Participant
Robert Schumacher	Lundin	Participant
Are Opstad Sæbø	Lloyds's Register Consulting	Project manager/participant
Ingar Fossan	Lloyds's Register Consulting	Technical responsible
Erik Odgaard	Lloyds's Register Consulting	Quality assurer
Jan Pappas	Lloyds's Register Consulting	Participant
Jens Garstad	DNV GL	Participant
Andreas Falck	DNV GL	Participant
Jo Wiklund	Lilleaker Consulting AS	Participant
Jens Morten Nilsen	Lilleaker Consulting AS	Participant
Jon Andreas Rismyhr	Safetec	Participant
Geir Drage Berentsen	Safetec	Participant
Morten Skjong	Safetec	Participant
Ole Magnus Nyheim	Safetec	Participant

Name	Company	Role
Phase 2 (2018)		
Eli Bech	Equinor	Equinor project manager
Marie Saltkjel	ConocoPhillips	Participant
Are Opstad Sæbø	Lloyds's Register Consulting	Project manager/participant
Ingar Fossan	Lloyds's Register Consulting	Technical responsible
Jan Pappas	Lloyds's Register Consulting	Quality assurance
Jens Garstad	DNV GL	Participant
Jo Wiklund	Lilleaker Consulting AS	Participant
Jon Andreas Rismyhr	Safetec	Participant

Glossary/abbreviations

Abbreviations and expressions used in the main report and all technical notes are given in TN-1. Abbreviations relevant for the main report are repeated in Table 1.2. An important expression, frequently used in the model, is the *Complementary cumulative hole size frequency distribution.* This expression denotes frequency distributions F(hole size > d), where d is a specific hole size. This expression is throughout the report denoted F, and for simplicity it is referred to as the **hole size frequency distribution**. The complementary cumulative hole size probability distribution for an equipment type multiplied by the total leak frequency for that equipment type, gives the complementary cumulative hole size frequency distribution.

Table 1.2- Abbreviations used in main report and technical notes

Abbreviation	Description
ACH	Air change per hour
ASCV	Annulus safety check valve
ASV	Annulus safety valve
DHSV	Downhole safety valve
ESD	Emergency shut down
HCRD	Hydrocarbon release database
HSE	Health and safety executive
LRC	Lloyd's Register Consulting
MISOF	Modelling of Ignition Sources on Offshore oil and gas Facilities
NCS	Norwegian continental shelf
PLOFAM	Process Leak for Offshore installations Frequency Assessment Model
P&ID	Piping and instrumentation diagram/drawing
Ptil	Petroleumstilsynet (Petroleum safety authority)
PWV	Production wing valve
QRA	Quantitative risk analysis
RNNP	Risikonivå i norsk petroleumsvirksomhet (Risk level in Norwegian petroleum industry)
SHLFM	Standardised hydrocarbon leak frequencies model
TN	Technical note
UKCS	United kingdom continental shelf

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1 Introduction

This report describes the leak frequency model, denoted PLOFAM (Process leak for offshore installations frequency assessment model), and used for estimation of topside process leak frequencies for use in Quantitative Risk Analysis of fire and explosion at installations located on the Norwegian Continental Shelf.

The model is in general fully documented in the technical notes (TN) listed in Chapter 1.1. This main report presents the most important aspects of the model, without presenting all details, but with a sufficient level of detail to gain an overview of the model. For further details it is referred to the TNs throughout the report.

The project has been run in two phases during the periods March – December 2015 and June – December 2018. The first version was issued in March 2016, Ref. /1/, and documents the concluded model in the first phase. This report is the second version of PLOFAM and documents the model after the revision in the second phase. The main changes from the first phase are:

- Data for the period 2015 – 2017 included in the database
- Relative leak rate distribution reassessed based on leaks on NCS in the period 2001 – 2017 as opposed to 2001 – 2015 In the first version. Relative leak rate distributions including data from the period 1992 - 2000 has also been assessed.
- Population data base used for validation/parametrization increased from 62 to 109 installations, including all installations that have been in operation on NCS.
- Failure modes for valves, flanges and instruments are discussed together with experts in Equinor. This resulted in an updated mathematical model for leak frequency distribution and reduced rupture fraction for valves and flanges, and updated guidelines for instruments.
- The model for hose leaks is re-assessed giving reduced leak frequency for leaks giving large released quantities
- The data base and hence the model is now fully aligned with the MISOF model, Ref. /2/. The models are based on the same assessment of the historical leak scenarios and are therefore interlinked. In particular, the number of large leaks has a significant effect on both models. Note however that if the number of large leaks is misinterpreted in the data material and should have been higher (i.e. that the leak frequency for large leaks should have been higher) then the ignition probability would have been lower in MISOF. This demonstrates why the two models should be used together and not combined with other models. Using the models together ensures consistent interpretation of scenarios having impact on both models, ensuring a best estimate for the fire and explosion frequency as well as a consistent estimate the uncertainties in these frequencies

1.1 Report structure

The report consists of the following technical notes:

- TN-1 Expressions and abbreviations
- TN-2 NCS data
- TN-3 UKCS data
- TN-4 Leak scenarios
- TN-5 Leak frequency model and Guideline for use of PLOFAM in QRAs
- TN-6 Model parametrization and validation

1.2 Objective

The objective of the leak frequency model is to serve as a tool for prediction of the future leak frequency for topside process leaks at installations located on the Norwegian Continental Shelf (NCS) for use in QRAs. The model should be unbiased, i.e. it should aim at a best estimate. However the best estimate should be approached slightly from the conservative side.

2 Philosophy for model development and expectations to the model

The reasons for leaks occurring from process systems at offshore installations are diverse and many, and hence there is a large number of factors that influence the leak frequency. Such factors may be the components that the process system consists of, the equipment size distribution, the process conditions, the environment around the process system, the maintenance scheme, training of personnel, work culture and time and cost requirements. Many of these factors will be different from installation to installation and some will strongly influence the leak frequency, while other will only to some extent have implications on the leak frequency.

When building a model serving as a tool for prediction of future leak frequency for topside process leaks in QRAs, it is obvious that all factors influencing the leak frequency cannot be included. Building a model for such a complex phenomenon will be a trade-off between model complexity, user friendliness of the model, and the model's ability to predict good overall estimates for single installations. The model should therefore capture the "most important" contributing factors to topside process leaks in order to reflect the most important differences between the installations. The "less important" contributing factors, not included in the model, will give rise to stochastic effects, i.e. comparing the predicted number of leaks (by the model) and historical leaks for every single installation must be expected to show stochastic behaviour.

The reasons for leaks occurring are many and normally all factors that resulted in an observed leak cannot be fully understood. However, some failure modes can be understood, and in such cases these known failure modes should be aimed reflected in the model.

Based on the above, and a more thorough discussion given in TN-5, the following important philosophy for building the model is established: Overall the model should be built on a combination of the parameter that shows the strongest correlations with experienced number of leaks, and rational explanations and causalities reflecting known failure modes.

In PLOFAM the number of equipment (for each equipment type) is the only explanatory variable assumed in the model. In addition, known failure modes are reflected in the parametrization of the model. Note that this does not mean that it is concluded that the number of equipment is the only factor having implications on the leak frequency, but it is concluded to be the best single explanatory variable. However, as only one explanatory variable is chosen for the model, there will be many factors influencing the leak frequency that are not captured by the model, which will give rise to stochastic effects.

3 Leak scenarios covered by the model

The leak frequency model covers process leaks and topside leaks from the well system occurring during normal production. A detailed description of system boundaries and scenarios covered by the model is given in TN-4.

The leak scenarios covered by the model may have a leak point associated with well, process system (including fuel gas system) or utility systems, and are described in Table 3.1. Other leak scenarios, such as leaks from utility systems fed from utility systems (for example diesel from diesel tanks and MEG from MEG-system) are not included.

Note that the leak frequency for process leaks estimated by the model does also account for leaks occurring in the utility system, but being fed from the process system. This is done by including process leaks fed through utility systems, but not equipment counts from utility systems as basis for the model validation. This implies that utility equipment should not be counted as basis for estimation of process leak frequencies. Furthermore the model does not give separate leak frequencies for process releases through utility systems and through process system. This means that a QRA based on PLOFAM will not reflect the potential location of the leak sources in utility systems. Furthermore, the leak frequency contribution from utility systems will scale with the number of equipment counts for process system. This contribution will in practice vary somewhat with the system at hand, but this cannot be quantified based on PLOFAM. A detailed risk assessment of leaks in utility systems, if found required, should hence be covered by special evaluations. Figure 3.2 gives an illustration of leak scenarios normally considered in a QRA. The figure shows which scenarios that are covered by the model and which that are not.

Incidents occurring during well interventions/operations, such as wire line and coiled tubing, are defined as blowouts or well releases, and are covered by Ref. /3/ that is based on the SINTEF Offshore Blowout Database. These incidents are not covered by the model.

Table 3.1 - Leak scenarios covered by the model. They occur in well system, process system or utility system (process leaks fed through utility systems). Scenarios that are not listed in this table are not covered by the 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. d. Produced water

Three main leak scenarios for modelling in QRAs are defined in PLOFAM. That is *Process leak*, *Producing well leak* and *Gas lift well leak*.

For all leak scenarios, 0.1 kg/s is recommended as the general leak rate threshold for estimation of leak duration (both in terms of calculation of fluid dispersion and fire duration) in a QRA, for all leak scenarios in open areas and leaks in enclosures having a net volume more than 1,000 m^3 and with ventilation rate of 12 ach or higher (see TN-4). The lower leak rate threshold is put as basis for the lower boundary with regard to aggregated released amount of hydrocarbons (10 kg). The model distinguishes between leak scenarios (rate > 0.1 kg/s) where the total released amount of hydrocarbons is ≤10 kg, and >10 kg. These leaks are classified as *Marginal leaks* and *Significant leaks,* respectively.

In a QRA, the risk in terms of fire- and explosion load exposure to vulnerable equipment and structures such as safety systems, pressurized equipment, load carrying structures and main safety functions, associated with Marginal leaks can normally be neglected. However, the risk to personnel associated with Marginal leaks should not be neglected.

The three main leak scenarios for modelling in QRAs are summarized in Table 3.2, and in Figure 3.1. The table shows how the three main leak scenarios for modelling in QRAs relate to the leak scenarios in Table 3.1. The figure shows how the leak scenarios in PLOFAM relate to the leak scenarios in SHLFM, Ref. /4/.

Table 3.2 - Leak scenarios suggested for QRAs at NCS

Modelled leak scenario		Leak scenarios included
Process leak	Significant	Scenario 4-7 in Table 3.1, released quantity >10 kg
	Marginal	Scenario 4-7 in Table 3.1, released quantity ≤10 kg
Production well leak[1]	Significant	Scenario 1 and 3 in Table 3.1, released quantity >10 kg
	Marginal	Scenario 1 and 3 in Table 3.1, released quantity ≤10 kg
Gas lift well leak	Significant	Scenario 2 and 3 in Table 3.1, released quantity >10 kg
	Marginal	Scenario 2 and 3 in Table 3.1, released quantity ≤10 kg

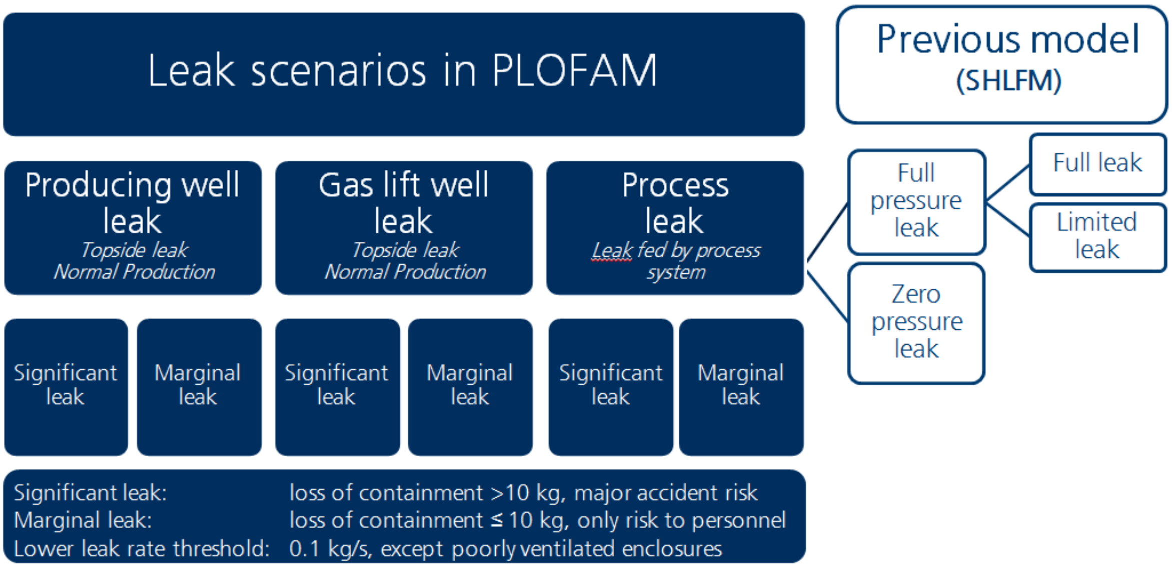


Figure 3.1 - Illustration and summary of the leak scenarios to be modelled in a QRA based on PLOFAM, together with the leak scenarios Full pressure leaks (Limited leaks and Full leaks) and Zero pressure leaks defined in the SHLFM Ref. /4/

[1] The frequency for production wells and injection wells are considered to be identical. The leak scenario is denoted production well only

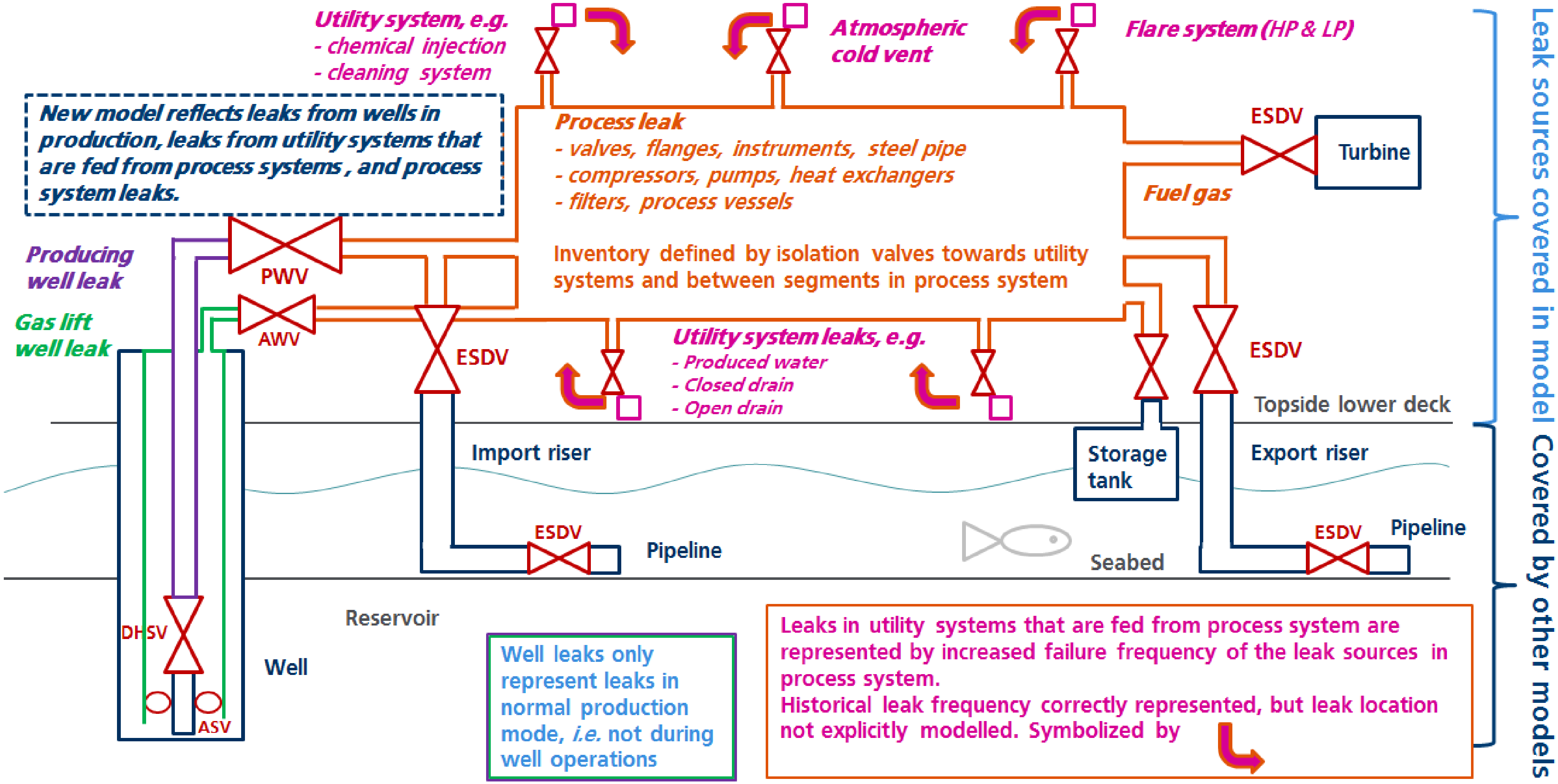


Figure 3.2 - Illustration of leak scenarios normally considered in a QRA. The figure shows which scenarios that are covered by the model and which that are not

4 Model summary and application of the model

PLOFAM is based on the assumption that the leak frequency is proportional to the number of each type of equipment. This assumption is justified in TN-5, where it is also assessed to what extent the level of operational activity on an installation contributes to leaks. However, for reasons presented in TN-5 (Chapter 3 and 4), the number of equipment (for each equipment type) is the only explanatory variable implemented in the model.

This chapter summarizes the concluded mathematical formulation of the model. Furthermore, equipment types included in the model and a description of how to use the model, including an example is given. Further details including the rationale and detailed description of the model is given in Chapter 2 in TN-5.

4.1 Mathematical formulation

The general formulation of the mathematical equations for the complementary cumulative hole size frequency distribution F (i.e. the frequency for hole diameter equal to or larger than d millimetres, given equipment diameter D in millimetres, see also TN-1 for definition) valid for a unique equipment type, which for simplicity is referred to as the hole size frequency distribution, is:

$$F(d,D) = \begin{cases} [F_0(D) - \alpha \cdot F_D(D)] \cdot d^{m(D)} + \alpha \cdot F_D(D) & , \ 1 \leq d \leq D \\ 0 & , \ d > D \end{cases} \tag{1}$$

$$F_0(D) = F_{hist} \cdot (A_0 \cdot D^{M_0}) \tag{2}$$

$$F_D(D) = F_0(D) \cdot (A_D \cdot D^{M_D} + B_D) \tag{3}$$

$$m\,(D) = \frac{\log(F_\mathrm{D} - \alpha \cdot F_\mathrm{D}) - \log(F_0 - \alpha \cdot F_\mathrm{D})}{\log(D)} \tag{4}$$

The parameters in the equations above are described in Table 4.1. Note that except for the parameters d and D, all parameters are in general unique for every equipment type, even though this is not reflected in the mathematical formulation above. A list of unique parameter values for F_{hist}, A_0, M_0, A_D, M_D, B_D and α necessary to estimate leak frequencies for every equipment type included in the model are given in Table 7.1. F_{hist} is the historical leak frequency (given in leaks per year per piece of equipment), for the relevant equipment. The other parameters are dimensionless model parameters. The subscript "0" is used to indicate the total leak frequency for an equipment and hence the "starting point" on the y-axis. The subscript D is used to indicate the frequency for getting a hole diameter equal to the equipment diameter D. Both F_0 and $F_D$are in general dependent on the equipment diameter D, which is indicated in the parenthesis:

$$F_0(D) = F(d = 1, D) \tag{5}$$

$$F_D(D) = F(d = D, D) \tag{6}$$

In short the model described above can be summarized to be built up of the following parts

1. Modelling of the total leak frequency per equipment, F_0. To model the equipment diameter dependency of F_0, the parameters F_{hist}, A_0 and M_0 are used.
2. Modelling of the full bore hole frequency F_D. To model the equipment diameter dependency of F_D, the parameters A_D, M_D and B_D are used.
3. Modelling of the cumulative frequency for hole diameters d in the interval $1 < d < D$. This model is built up of a power law modelling the hole size dependency, and an additional frequency for full bore hole leaks:
   a. The model assumes that the hole size dependent part of the hole size frequency distribution follows a power law, that "starts" at $(F_0(D) - \alpha \cdot F_D(D))$ for d=1and "ends" at $(F_D(D) - \alpha \cdot F_D(D))$ for $d = D$. The formula for the slope parameter $m(D)$ in Eq. (4) follows from the assumption that the hole size dependent part of the hole size frequency distribution (becoming the first part in Eq. (1)) follows a power law with "start" and" end" points as described.
   b. The last term in Eq. (1), which is the product of $F_D$and the parameter $\alpha \in [0, 1\rangle$, is introduced to capture the effect that the frequency for hole diameters close to the equipment diameter is expected to be even lower than estimated by the normal power law for some failure modes. The parameter α is the fraction of the full bore hole frequency that is added in the second term in Eq. (1). This parameter only influences the frequency for hole diameter in the interval $1 < d < D$, while the total leak frequency F_0 and the full bore hole frequency $F_D$are unaffected. The net effect of a non-zero α is to shift more of the leak frequency towards smaller holes compared to $\alpha = 0$.

In addition to the equations described above, the parameter F_1 is introduced and expressed as a function of F_D as follows, and can be substituted in the equations above when convenient:

$$F_1(D) = \alpha \cdot F_D(D) \qquad , \alpha \in [0, 1\rangle \tag{7}$$

F_1 is useful both when implementing the model and when describing the rationale for the model (see TN-5 Appendix A).

For a further detailed description of the rationale for the model, derivation of the expression for the slope parameter and illustrations, it is referred to TN-5 Appendix A. The appendix also compares the model with the previous leak frequency model used in the industry, denoted SHLFM, Ref. /4/, and explains the difference.

Table 4.1 - Summary of all parameters used for each equipment type in the model. Except for the parameters d and D, all parameters are in general unique for every equipment type. Note that not all parameters are included in the above equations. Some are introduced later in the report.

Parameter	Description
$F(d, D)$	Hole size frequency distribution (see TN-1) [year-1 equipment-1].
F_0	Total leak frequency [year-1 equipment-1]. The subscript 0 is used to indicate the total leak frequency for an equipment and hence the "starting point" on the y-axis. $F_0 = F(d = 1, D)$.
F_D	The total full bore hole frequency [year-1 equipment-1]. The subscript D is used to indicate the frequency for getting a hole equal to the equipment diameter D. $F_D = F(d = D, D)$.

Parameter	Description
$\theta(D)$	The full bore fraction of total leak frequency $$\theta(D) = \frac{F_D(D)}{F_0(D)}$$
d	Hole diameter in millimetres
D	Equipment diameter in millimetres
m	Slope parameter
F_{hist}	The average leak frequency (independent of equipment diameter) for the relevant equipment type [year^{-1} equipment^{-1}]
A_0	Parameter in equation for total leak frequency, F_0
M_0	Parameter in equation for total leak frequency, F_0
A_D	Parameter in equation for full bore hole frequency, F_D
M_D	Parameter in equation for full bore hole frequency, F_D
B_D	Parameter in equation for full bore hole frequency, F_D
α	Dimensionless parameter, independent of equipment diameter D, $\alpha \in [0, 1\rangle$. The fraction of the full bore frequency that comes from the second term in Eq. (1)
F_1	Additional full bore hole frequency [year^{-1} equipment^{-1}]

4.2 Equipment types covered by the model

In total 20 different equipment types are covered by the model, including Gas lift well and Production well, which belongs to the well system. The other equipment types included in the model are the most common process equipment types at offshore installations. All equipment types covered by the model are given in Table 4.2.

Table 4.2 - Equipment types included in the model

Equipment type	Additional description
Air-cooled heat exchanger	
Atmospheric vessel	Vessels with atmospheric pressure
Centrifugal compressor	
Centrifugal pump	
Compact flange	
Filter	
Flexible pipe	Permanently installed hose
Hose	Temporary hoses
Instrument	

Equipment type	Additional description
Pig trap	Pig launchers and pig receivers
Plate heat exchanger	
Process vessel	Pressurized process vessels
Reciprocating compressor	
Reciprocating pump	
Shell and tube side heat exchanger	Includes equipment where the hydrocarbon is on the shell side and/or tube side of the heat exchanger
Standard flange	Includes all flange types, except compact flanges
Steel pipe	Process steel pipe
Valve	Includes all types of valves
Gas lift well	Well head with gas lift.
Producing well	Well head with or without gas lift

4.3 Application of the model

When applying the model on a specific installation the first step is to define the desired leak rate intervals defined by the leak rates $q_1 < q_2 < \cdots < q_N$, or the desired hole size intervals defined by $d_1 < d_2 < \cdots < d_N$. Next the following procedure is suggested for all equipment types on the installation:

1. Calculate $F_0(D)$ for the relevant equipment types and dimensions using equation (2)
2. Calculate $F_D(D)$ for the relevant equipment types and dimensions using equation (3)
3. Calculate $F_1(D) = \alpha \cdot F_D(D)$ for the relevant equipment using equation (7). This step is not necessary, but may be convenient.
4. Calculate $m(D)$ for the relevant equipment using equation (4)
5. If leak frequencies are calculated for leak rate intervals: For each piece of equipment (or group of equipment with the same process conditions) calculate the hole size intervals defined by $d_1 < d_2 < \cdots < d_N$ corresponding to the defined leak rate intervals $q_1 < q_2 < \cdots < q_N$ based on appropriate equations for modelling of leak rate. The models used for estimating release rates should be carefully chosen based on fluid composition and process conditions (e.g. pressure, composition and temperature). TN-5 Appendix B gives relations for gas and liquid leak rate estimations. Since the leak frequency model is defined for hole diameters >1 mm only, it is recommended to set d_i to 1 if the calculated hole size is < 1mm. Thus leak frequencies for hole diameters less than 1 mm is not included. This will in general not affect results in most QRA's as leaks around 1 mm will produce small release rates (< 0.1 kg/s). In some cases, leaks having a release rate less than 0.1 kg/s ought to be assessed in the QRA to model the risk picture with adequate precision (*e.g.* enclosures with poor ventilation, and release of poisonous gases). A special assessment of leaks with an initial leak rate less than 0.1 kg/s has to be performed in such cases.
6. Calculate leak frequencies for all hole diameters d_1, d_2 … d_N, for the relevant equipment based on the equation (1) given in Chapter 4.1.
7. Calculate the frequency $F(d_i < d < d_{i+1}) = F(d_i) - F(d_{i+1})$ for the relevant equipment for the hole size intervals and/or leak rate intervals

8. Multiply the leak frequencies with the number of equipment for the relevant equipment type and dimension with the same process conditions. The number of equipment on an installation should be estimated based on equipment counting on P&ID's or similar. The exception is hoses where the frequency is multiplied with the number of hose operations, and steel pipe and flexible pipe where the frequency is multiplied with the number of steel pipe meters/flexible pipe meters (see also item 9 below). The number of hose operations must be clarified with the operator of the installation. A guideline for use of PLOFAM in QRAs is given in TN-5 Appendix B.
9. In cases where the contribution from steel pipes is not assessed based on the length of steel pipes in the process system, but rather on a general assessment of the expected fraction of leaks stemming from steel pipes, this fraction must be added to the estimated leak frequency. See Appendix B for guidance. It is also referred to TN-2 for an assessment of the fraction of leaks at NCS stemming from steel pipes.

4.4 Example of application of the model

This example is given to illustrate the recipe given in Chapter 4.3. The frequencies for a "Significant leak" (see Chapter 2) from a 4" standard flange, containing gas with density 132 kg/m3 at pressure 156 bara is calculated. Steps 1-7 are followed to estimate the leak frequency distribution for this piece of equipment.

The model parameters for Standard flange are given in Table 4.3. Following step 1- 4 in Chapter 4.3, gives $F_0(D)$, $F_D(D)$, $F_1(D)$ and $m(D)$ as given in Table 4.4.

By using the relation between hole size and leak rate the given in TN-5 Appendix B, the hole diameters corresponding to 0.1, 0.5, 1, 5, 10 and 30 kg/s can be calculated as in step 5 in Chapter 4.3. The results are given in Table 4.5 together with the corresponding cumulative leak frequency calculated following step 6 in Chapter 4.3.

Next the leak frequency for the leak rate intervals and corresponding hole size intervals can be calculated following step 7 in Chapter 4.3. The results are given in Table 4.6.

Table 4.3 – Model parameters for Standard flange

Equipment type	A_0	M_0	A_D	M_D	B_D	α	$F_{hist,sign}$
Standard flange	1	0	18	-1.45	0.005	0.5	2.50E-05

Table 4.4 – Calculated total leak frequency $F_0(D = 101.6)$, rupture frequency $F_D(D = 101.6)$, $F_1(D = 101.6) = \alpha \cdot F_D(D = 101.6)$ and slope parameter $m(D = 101.6)$ for the 4" standard flange.

Equipment type	F_0	F_D	F_1	m
Standard flange	2.50E-05	6.79E-07	3.39E-07	-0.93

Table 4.5 – Leak rates, corresponding hole sizes and cumulative leak frequency

	Leak rate [kg/s]					
Parameter	**0.1**	**0.5**	**1**	**5**	**10**	**30**
Hole size [mm]	2.22	4.97	7.02	15.71	22.21	38.47
Cumulative leak frequency, F(d> hole size) [per year per equipment]	1.21E-05	5.92E-06	4.38E-06	2.26E-06	1.73E-06	1.17E-06

Table 4.6 - Leak rate intervals, corresponding hole size intervals and leak frequency

	Leak rate interval [kg/s]					
Parameter	**0.1 - 0.5**	**0.5 - 1**	**1 - 5**	**5 - 10**	**10 - 30**	**>30**
Hole size interval [mm]	2.22 - 4.97	4.97 - 7.02	7.02 - 15.71	15.71 - 22.21	22.21 - 38.47	>38.47
Leak frequency [per year per equipment]	6.19E-06	1.53E-06	2.13E-06	5.27E-07	5.55E-07	1.17E-06

5 Data basis

The model has been developed, parameterised and validated towards data gathered from two sources of data:

- NCS data: 254 incidents recorded at all installations located on the NCS in the period 01.01.2001 – 31.12.2017
- UKCS data: 4561 incidents at installations on the UKCS recorded in HCR database in the period Q3 1992 - Q1 2015

The NCS and UKCS databases are described in detail in TN-2 and TN-3, respectively. A short review is given in Chapter 5.1 and 5.2.

5.1 NCS data

Population data has been collated for 85 installations based on equipment counts extracted from the QRAs for the installations. 6 out of the 85 installations had not been set in operation by 31.12.2017. Hence, population data is available for 79 installations being in operation in the period 01.01.2001 – 31.12.2017 (full period or part of it).

For the remaining 25 installations, where equipment counts have not been available, the population data (*i.e.* equipment counts) has been estimated by defining an equivalent installation in the NCS population dataset. The equivalent installation has been based on an overall evaluation of the installation characteristics. Only 11 out of the 25 installations have been in operation in the period 01.01.2001 – 31.12.2017, while 14 installations have either been decommissioned before 2001 (13 installations) or not been set in operation yet (1 installation). In total the population data set consist of 109 installations where 90 of them have been in operation in the period 2001 – 2017, and is denoted “NCS population dataset”.

The data basis of recorded leaks at the NCS has 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

Recorded leaks at NCS have all an initial hydrocarbon leak rate of 0.1 kg/s or larger.

The total number of leaks reported in RNNP in the period 01.01.2001 – 31.12.2017 is 260. After review of the incidents, it has been concluded that 43 of those incidents are not relevant for the leak scenarios to be modelled by PLOFAM, i.e. they are not process leaks or topside well leaks during normal operation (see Chapter 2). Typical properties of 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 covered by the model, such as a pipeline or a riser
- The leak is occurring in the well system during a drilling operation or intervention

Out of the remaining 217 leaks (260 - 43), 210 leaks have occurred on the 85 installations in the "NCS population dataset" where equipment counts have been performed. The remaining 7 leaks have occurred on the 11 installations where equipment counts are established based on equivalent installations. Detailed information about all 217 relevant leaks is given in TN-2 Appendix A.

5.2 UKCS data

Information about offshore releases of hydrocarbons at United Kingdom Continental Shelf (UKCS), are collected in Hydrocarbon Release Database (HCRD). The database is operated by Health and Safety Executive (HSE).

In total 4863 events occurring in the period Q3 1992 - Q1 2015 are recorded in HCRD. Not all of the incidents are relevant for the defined leak scenarios (see TN-4). A thorough analysis has been necessary to extract the relevant incidents for the model. The resulting databasis consist of 2855 recorded incidents from the period Q3 1992 - Q1 2015, and 1597 recorded incidents from the period Q1 2001 - Q1 2015 that are fed through process systems. By also taking process leaks fed through utility systems and topside leaks from well systems during normal operation into account, the total number of leaks considered is 3208 for the period (Q3 1992 - Q1 2015. The number of relevant leaks at UKCS installations in the period Q2 2015- Q4 2017 is 210. The total number of leaks at UKCS installations thus becomes 3318.

The UKCS historical data extracted from the HCR database has not been used directly when setting the leak frequency model parameters. The UKCS data, with its uncertainties, does (however) nevertheless, constitute an important data basis when evaluating certain aspects on a higher level, such as:

- the relative distribution of leaks on the various types of equipment
- the relative distribution of leaks in terms of the initial leak rate, *e.g.* the fraction large vs. small leaks
- the relative distribution of leaks equivalent with the leak scenario modelled in QRA's (leak from a fully pressurized isolatable process segment during normal operation) and leaks from initially isolated and/or depressurized segments (in PLOFAM denoted 'Significant' and 'Marginal' leaks respectively)
- the time trend of observed leaks at UKCS demonstrating a downward trend from the initial years levelling out around year 2010 to around 10 leaks per year

The UKCS data is also important for our confidence in the performance of the PLOFAM model based on NCS data. The PLOFAM parameters derived based on NCS data generate a good fit to the UKCS data when accounting for the uncertainties in the UKCS data. The observed deviations are very likely to be explained by differences in counting rules and in the general quality of the UKCS data (such as lack of consistency in the way incidents are logged, inconsistency in the logged hole size/leak rate and higher uncertainties related to the population data). Taking this into account, the underlying leak frequency at installations located on the UKCS appears to be the same as the underlying frequency at installations on the NCS (see also TN-3).

6 Model parameterisation and validation

The parametrisation and validation process is interlinked, as the target for the model is defined based model performance when applying PLOFAM to all installations being in operation at NCS in period 2006-2017, and the parametrization is performed as an iterative process where these results are assessed towards the model targets and adjusted to give satisfactory results. However, the overall validation of the model also includes other assessments than defined by the model targets. Both the parametrization process and the overall model validation is described in this chapter.

6.1 Parametrization methodology

The starting point for the parametrization of the model is the model parameters established in the first version of PLOFAM, Ref. /1/. Next the parametrization of the model is performed as an iterative process consisting of the following step:

- Knowledge on failure modes driving the occurrence of leaks for the various equipment types are applied and reflected in the parameters. This consist of reflecting known failure modes for specific equipment types in the total leak frequency $F_0(D)$, the full bore hole frequency $F_D(D)$ and the associated full bore hole fraction (rupture fraction) $\theta(D) = \frac{F_D(D)}{F_0(D)}$ and α (see also TN-5). An example is given below for valves, where $F_0(D)$, $F_D(D)$ and $\theta(D)$ are plotted for different values of the equipment diameter. The failure modes for the most important equipment types (valve, standard flange and instrument) were discussed together with subject matter experts in Equinor. Some equipment types defined in the model consist of several equipment types with different failure modes. This is for example the case for the equipment type standard flange which includes clamp connectors (*e.g.* Grayloc) and flanges with different sealing designs (ASME ring joint and raised face). Due to variability within the equipment category known failure modes may be more difficult to reflect in the joint model parameters for all types within the category. For more homogenous equipment categories, such as compact flanges, parameterisation based on failure modes is more straight forward.
- The model is applied to all installations being in operation on NCS in the period 2006 – 2017 (86 installations), and model performance is compared with the defined targets for the model. The model is also applied to all installations being in operation on NCS in the period 2001 – 2017 (90 installations). The defined targets for the model are described in TN-5 and TN-6. The most important targets are:
    1. The historical leak frequency on NCS in 2006 – 2017 is regarded as a reasonable estimate for future leak frequencies (see TN-2). Hence, the model should be able to reproduce the total number of leaks observed for all installations at NCS being in operation in the period 2006-2017
    2. The model should be able to reproduce the total cumulative leak rate frequency distribution seen in historical data from NCS in the period 2001 - 2017 when applied to all installations on NCS (see TN-2)
    3. The model should be able to reproduce the relative leak rate frequency distribution per equipment type seen in the experienced data from NCS (and UKCS). Stochastic effects are expected to be prominent in this regard as the number of incidents will be few for some equipment types

Some types of equipment have been subjected to special evaluations where the methodology for parameterization deviates slightly from the general methodology described above. This is either due to lack of data in either of the datasets or uncertainties/shortcomings in the available data. The types of equipment subjected to special evaluations and the reason for the alternative approach is summarized in Table 6.1.

The concluded model parameters are given in Chapter 7.

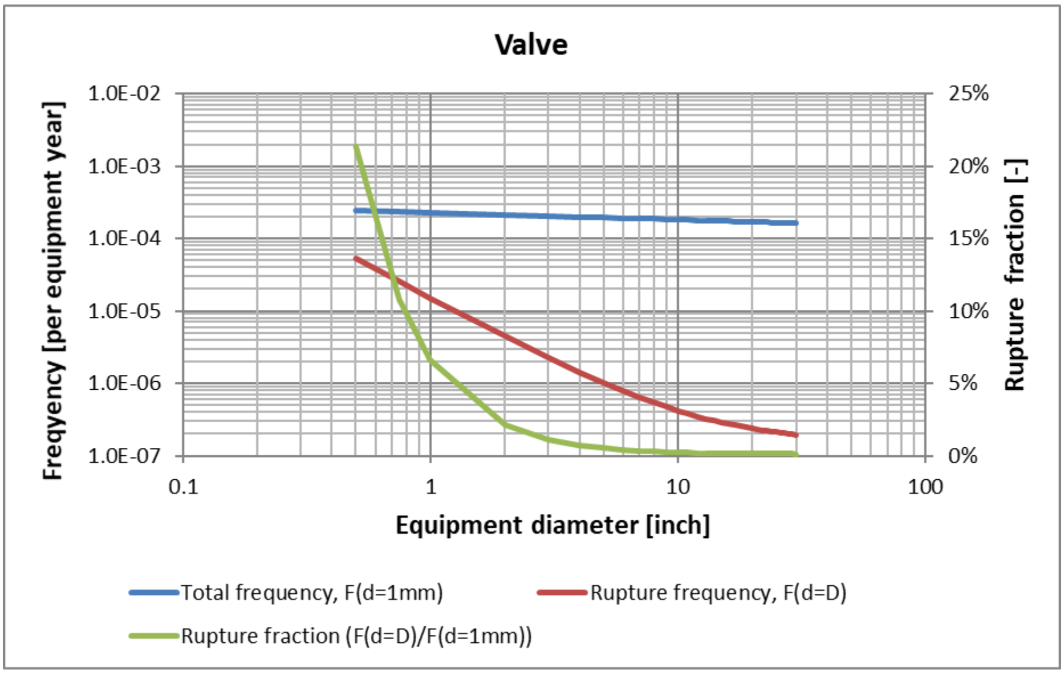


Figure 6.1 – Total frequency, rupture fraction (full bore hole fraction) and rupture frequency for valve

Table 6.1 - Equipment types subjected to separate parameterisation process

Equipment type	Description
Hoses	No data available in HCRD on leaks occurring under temporary operations involving use of hoses. The defined model parameters are therefore solely based on data gathered from installations on the NCS
Steel pipe	The quality of the population data in HCRD for steel pipes is judged to be poor. Hence, the model is parameterized based on a subset of the NCS population dataset where equipment counts of length steel pipe are available. However, available data in HCRD have been used to model the effect of equipment size on the hole size distribution for steel piping
Compact flanges	No data is available from UKCS and only limited data available from installations on NCS. A separate assessment is performed to set the model parameters
Air-cooled heat exchanger	No units registered at NCS. UKCS data applied to set parameters.
Flexible piping	No population data available at NCS. UKCS data applied to set parameters.
Atmospheric vessel	No data available at NCS nor UKCS. Recommended to use process vessel model presuming that the vessel is slightly over-pressurized.

6.2 Overall validation

The validation model has demonstrated that PLOFAM is able to:

- Reproduce the total number of significant leaks (104) observed at NCS in the period 2006 – 2017 when applied to all installations on NCS being in operation in this period. Details are presented in TN-6
- Reproduce the total cumulative leak rate frequency distribution seen in historical data from NCS in the period 2001 - 2017 when applied to all installations on NCS. See Figure 6.2 , which shows good agreement between the resulting relative leak rate distribution from applying PLOFAM to all installations in operation in the period 2006 – 2017 and historical leak rate distributions recorded both at UKCS in the period 1992 – 2017 and NCS in the period 2001 – 2017
- Reproduce the total cumulative leak rate frequency distribution for every equipment type seen in historical data from NCS in the period 2001 - 2017 when applied to all installations on NCS. TN-6 shows the resulting cumulative leak rate frequency distribution for every component when applying the model to all installations being in operation in the period 2006 – 2017, and compares it with the historical data both from both NCS and UKCS. The results shows good fit with historical data
- Generate the split on the number of leaks being significant and marginal, when applied to all installations on NCS being in operation in the period 2006 - 2017. These results are presented in TN-6
- Reproduce the relative distribution between equipment types seen based on experienced data from NCS and/or UKCS. See further details below

The average number of leaks per installation is given in Figure 6.3. The average number of leaks >0.1 kg/s predicted by the model is 0.1 leaks per installation per year. The figure shows the average cumulative number of leaks per installation (i.e. the average number of leaks larger than the value on the x-axis) for the main equipment types. Other equipment types are grouped together. The historical distribution is also given both for the period 2001 – 2017 and for the period 2006 – 2017. As the average number of leaks in the period 2001 – 2017 is higher than for the period 2006 – 2017, the historical number of leak in 2001 – 2017 has been adjusted to give the same total number of leaks as predicted in the period 2006 – 2017. It is however included to demonstrate that the model is able to reproduce the model target defined by the relative leak rate distribution for the full period.

To assess how the model performs for each installation in operation in the period 2006 – 2017, Figure 6.4 shows the number of estimated leak versus the number of historical leaks for each installation (each data point represents one specific installation). The number of data points above (overestimated) and below (underestimated) the grey line is about the same, indicating that the overall prediction of the model is good, even though the model is obviously not able to predict the correct number of leaks for every installation. As discussed in TN-5 and TN-6, this is not expected as there are many factors influencing on the leak frequency that are not implemented in the model. However, there is a clear correlation in the data points indicating that the model is able to capture important factors influencing the leak frequency.

It must be noted that this plot is prone to stochastic effects. The model will predict leaks on installations where no leak has occurred yet. Since the model is targeting the total number of observed leaks for all installations, the model will lead to an average underprediction of the number of leaks on all installations with 1 or more leaks. This stochastic effect will diminish with time as the number of installations with zero leaks becomes fewer and fewer. At some point in time it is expected that the scatter plot for all installations will follow an average linear trend with slope 1:1.

The model is mainly validated towards available data of leaks that has occurred at installations on the Norwegian Continental Shelf (NCS), but the data from the United Kingdom Continental Shelf (UKCS) indicate that the underlying hole size frequency distribution for equipment at installations located on the NCS is similar to the distribution for equipment located on UK installations. The differences may be explained by uncertainty related to the datasets (both the leaks and the population data, and the way equipment are counted and leaks are tagged to equipment types).

Figure 6.5 display the number of leaks (significant + marginal leaks) per equipment year (all types of pipes excluded) per year for NCS and UKCS. The plot show that the leak frequency per equipment year and time trend in the leak frequency at UKCS is similar to the time trend seen on NCS. The average frequency appears to be slightly less at UKCS (about 20%), but that may for instance be due to uncertainty in the UKCS population data. The result presented in Figure 6.2 demonstrates that the relative distribution with regards to initial leak rate is the equivalent for the two data sets.

No causal arguments have been found that supports a difference in the underlying leak frequency between NCS and UKCS installations. This does not mean that such a difference does not exist, only that the PLOFAM project has not identified any justification for such a difference. The same conclusion is established in the MISOF project in terms of probabilistic modelling of ignition sources. A hypothesis claiming that the underlying leak frequency and ignition probability is the same for the two domains cannot be rejected based on the available data. Both the PLOFAM model and MISOF model is therefore concluded to be valid for both sectors.

Figure 6.6 display the resulting overall distribution of significant leaks per equipment for all installations operating at NCS and UKCS compared with the PLOFAM prediction. The results show that PLOFAM reproduce the distribution observed at NCS. A significant difference with regards to the data from UKCS installations appear. This may be due to randomness, in particular for equipment with a low number of equipment years, but is also clearly due to differences in the way leaks are logged in HCRD relative to the NCS dataset. In some situations, it is not straight forward to allocate a leak to a specific equipment, leading to uncertainty related to the tagged equipment. However, for NCS leaks extra quality assurance has been performed together with Equinor, Safetec and ConocoPhillips to make sure that the leaks are tagged to the right equipment. A few leaks are tagged to a different equipment than in the previous version of PLOFAM. Typically this was related to small leaks from instrument tubing that previously was tagged to steel pipe that are now tagged to instruments.

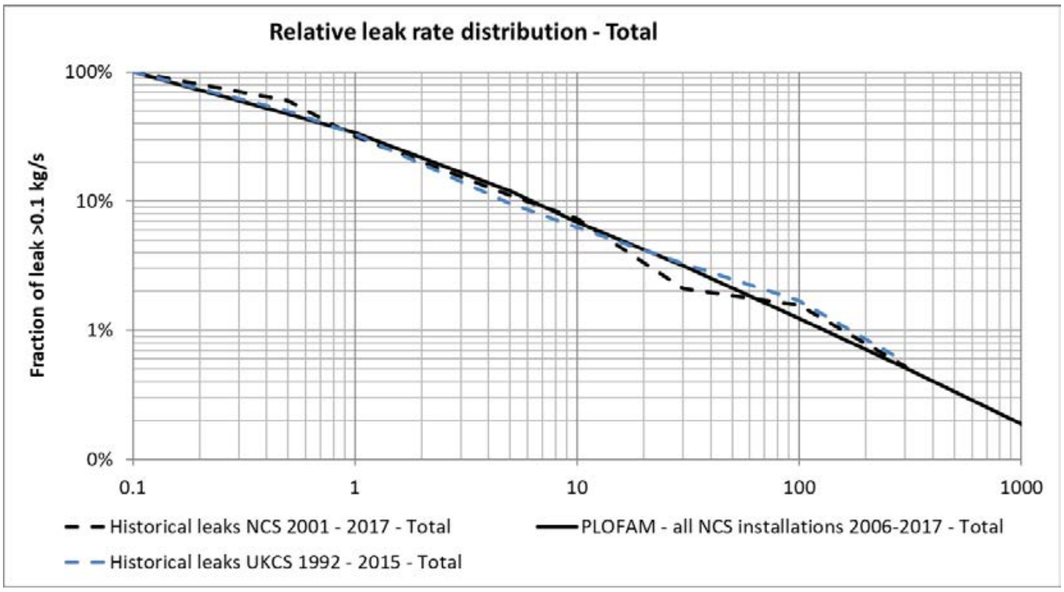


Figure 6.2 – Overall significant leaks: complementary cumulative relative leak rate distribution for all installations operating at NCS in the period 2006-2017

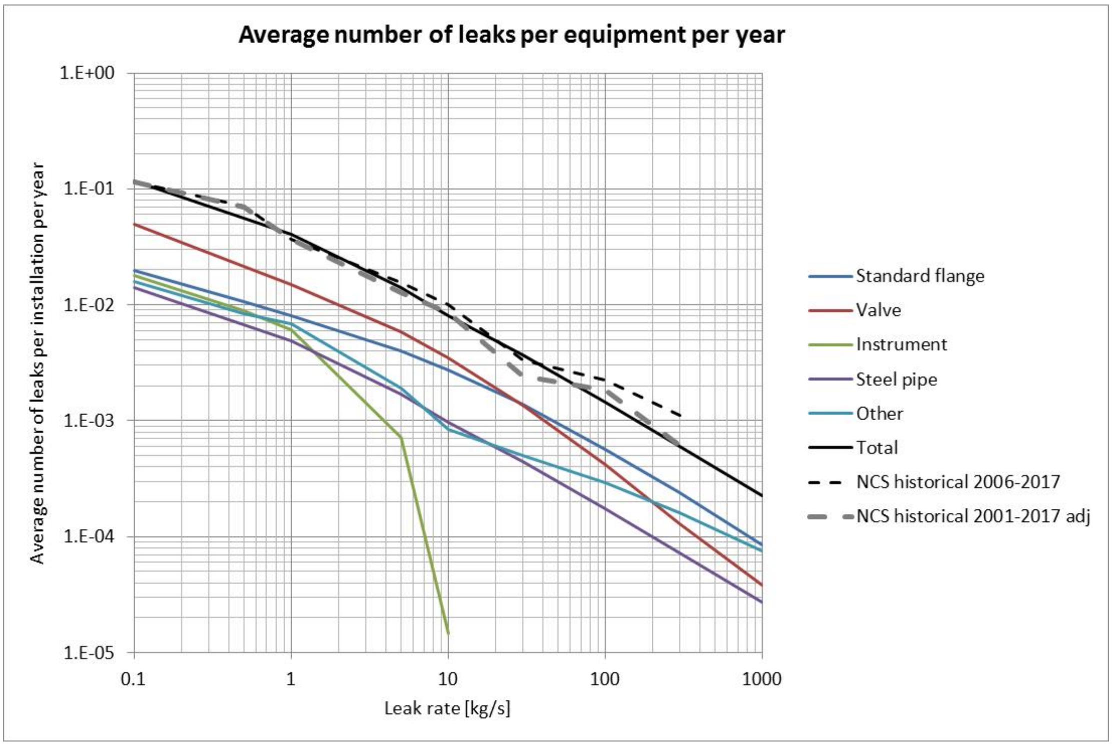


Figure 6.3 – The average number of leaks per installation for the main equipment types predicted by the model for the period 2006 – 2017. Other equipment types than standard flange, valve, instrument and steel pipe are grouped into "Other". The historical number of leak in 2001 – 2017 has been adjusted to give the same total number of leaks as predicted in the period 2006 – 2017. It is however included to demonstrate that the model is able to reproduce the model target defined by the relative leak rate distribution for the full period. The total number of installation years (for installations in operation) for the NCS population dataset is 899 for the period 2006-2017 and 1237 for the period 2001 – 2017

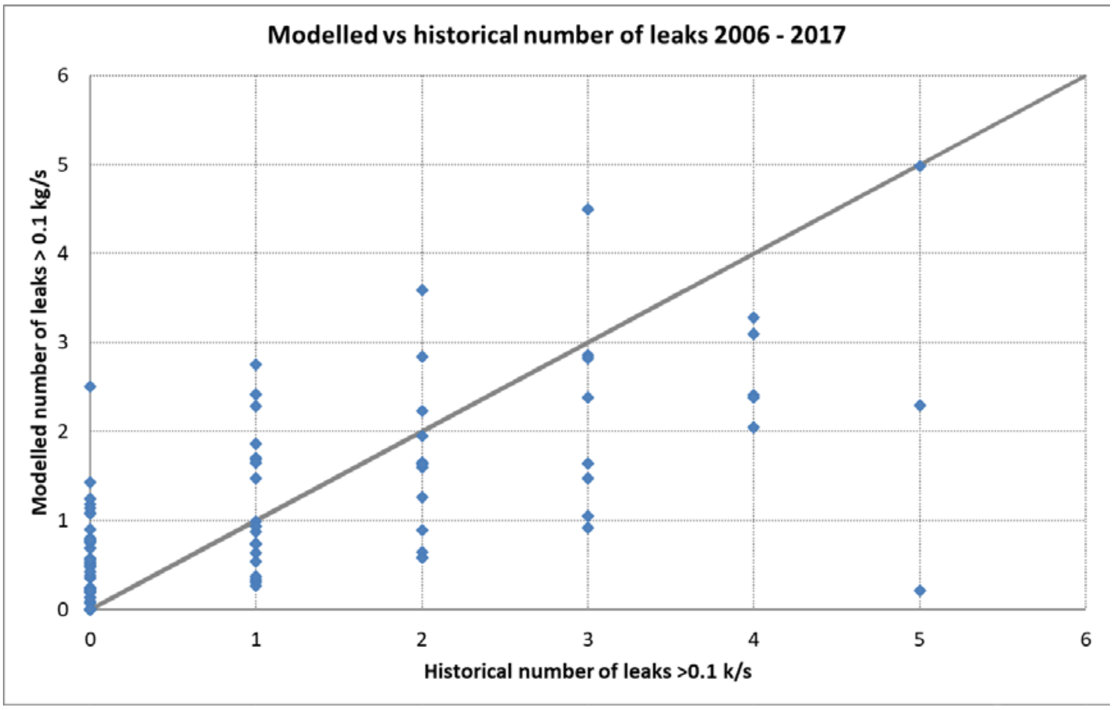
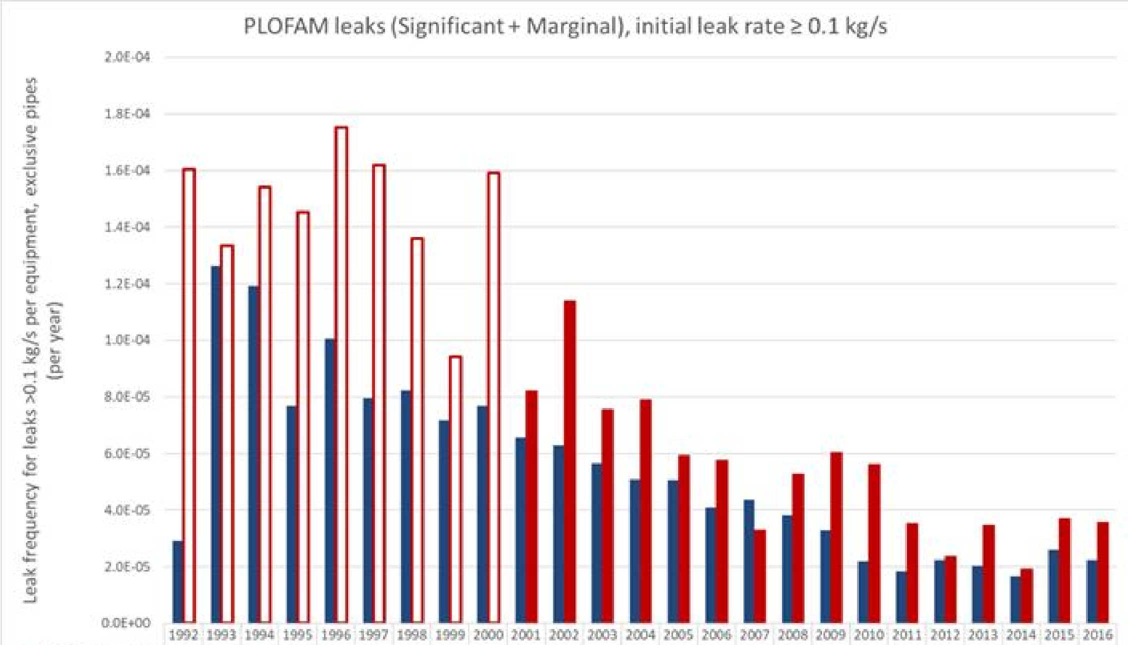
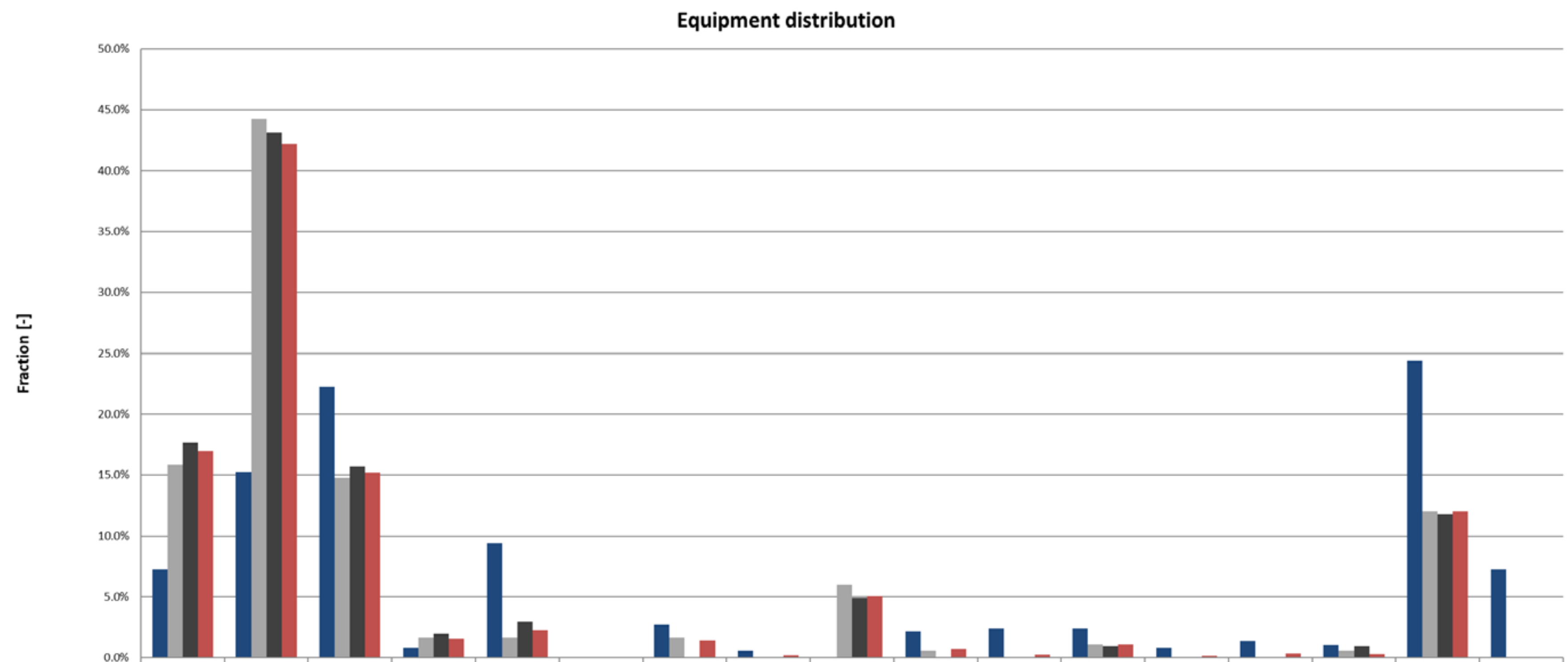


Figure 6.4 – Overall significant leaks: observed number of leaks vs. predicted number of leaks for all installations operating at NCS in the period 2006-2017. Datapoints below the grey line indicate underprediction. Datapoints above the grey line indicate overprediction



	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
PLOFAM leaks UKCS	2.9E-	1.3E-	1.2E-	7.7E-	1.0E-	8.0E-	8.2E-	7.2E-	7.7E-	6.6E-	6.3E-	5.7E-	5.1E-	5.1E-	4.1E-	4.4E-	3.8E-	3.3E-	2.2E-	1.8E-	2.2E-	2.0E-	1.7E-	2.6E-	2.2E-
PLOFAM leaks NCS	1.6E-	1.3E-	1.5E-	1.5E-	1.8E-	1.6E-	1.4E-	9.4E-	1.6E-	8.2E-	1.1E-	7.5E-	7.9E-	5.9E-	5.8E-	3.3E-	5.3E-	6.0E-	5.6E-	3.5E-	2.4E-	3.5E-	1.9E-	3.7E-	3.6E-

Figure 6.5 – Annual frequency for leaks ≥ 0.1 kg/s per equipment (includes all types of equipment except steel pipe) both for UKCS and NCS. For NCS the columns giving the leak frequency after 2001 are filled to indicate that that there is a shift in the uncertainty related to the data. Note however that the uncertainty related to the overall frequency presented in the figure is regarded low also before 2001. No shift in data quality is known for UKCS data. The correct exponent belonging to the figures in the table must be read from the second axis (the font size is maximized to enhance readability of the figures)



	Standard flange	Valve	Instrument	Centrifugal compressor	Pump	Compact flange	Filter	Gas lift well	Hose	Pig trap	Plate heat exchanger	Process vessel	Producing well	Reciprocating compressor	Shell and tube heat exchanger	Steel pipe	Other
UKCS historical	7.2%	15.3%	22.3%	0.8%	9.4%	0.0%	2.7%	0.5%	0.0%	2.1%	2.4%	2.4%	0.8%	1.3%	1.1%	24.4%	7.2%
NCS hist 2001 - 2017	15.8%	44.3%	14.8%	1.6%	1.6%	0.0%	1.6%	0.0%	6.0%	0.5%	0.0%	1.1%	0.0%	0.0%	0.5%	12.0%	0.0%
NCS hist 2006 - 2017	17.6%	43.1%	15.7%	2.0%	2.9%	0.0%	0.0%	0.0%	4.9%	0.0%	0.0%	1.0%	0.0%	0.0%	1.0%	11.8%	0.0%
PLOFAM	17.0%	42.2%	15.2%	1.5%	2.24%	0.0%	1.4%	0.2%	5.0%	0.7%	0.2%	1.1%	0.2%	0.4%	0.3%	12.0%	0.0%

Figure 6.6 – Historical (both for NCS and UKCS) and modelled equipment type distribution for Significant leaks. Both the historical equipment type distribution for the period 2001 – 2017 and 2006 – 2017 are given. The modelled result is achieved by applying PLOFAM to all installations at NCS being in operation in the period 2006 – 2017

7 PLOFAM parameters

A list of PLOFAM parameter values for F_{hist}, A_0, M_0, A_D, M_D, B_D and α necessary to estimate leak frequencies for all equipment types are given in Table 7.1. F_{hist} is given both for Significant and Marginal leaks. The parameters are documented in TN-6. Note that for the equipment types marked with a star (*), the data basis is scarce and the model parameters are related with higher uncertainty than for the remaining equipment types (see TN-6).

Table 7.1 – PLOFAM model parameters. F_{hist} is given both for Significant and Marginal leaks.

Equipment type	A_0	M_0	A_D	M_D	B_D	α	$F_{hist,\text{Significant}}$	$F_{hist,\text{Marginal}}$
Air-cooled heat exchanger*	1	0	0	0	3.0E-02	0	5.0E-04	0
Atmospheric vessel*	1	0	0	0	1.0E-01	0	5.0E-04	0
Centrifugal compressor	1	0	0	0	6.0E-03	0	1.3E-03	0
Centrifugal pump	1	0	0	0	3.0E-05	0	3.0E-03	0
Compact flange	1	0	0	0	1.0E-03	0.90	3.0E-06	0
Filter	1	0	0	0	8.0E-04	0	2.3E-03	0
Flexible pipe*	1	0	0	0	4.0E-01	0.75	1.4E-04	0
Gas lift well	1	0	0	0	2.5E-02	0	1.0E-04	1.0E-04
Hose	1	0	0	0	4.0E-01	0.75	6.0E-05	1.5E-05
Instrument	1	0	0	0	1.5E-01	0	1.3E-04	0
Pig trap	1	0	0	0	2.0E-02	0	1.7E-03	0
Plate heat exchanger	1	0	0	0	1.0E-03	0	3.5E-04	0
Process vessel	1	0	0	0	6.0E-04	0	5.0E-04	0
Producing well	1	0	0	0	2.0E-02	0	2.0E-05	1.3E-04
Reciprocating compressor	1	0	0	0	1.0E-02	0	5.0E-03	-
Reciprocating pump	1	0	0	0	3.0E-05	0	3.0E-03	-
Shell and tube heat exchanger	1	0	0	0	7.5E-03	0	3.3E-04	-
Standard flange	1	0	18.0	-1.45	5.0E-03	0.50	2.5E-05	5.0E-06
Steel pipe	4.20	-0.3	17.6	-1.75	1.0E-03	0.90	1.4E-05	2.0E-06
Valve	1.11	-0.1	16.0	-1.70	1.0E-03	0.50	2.15E-04	3.5E-05

8 Comparison of PLOFAM and SHLFM

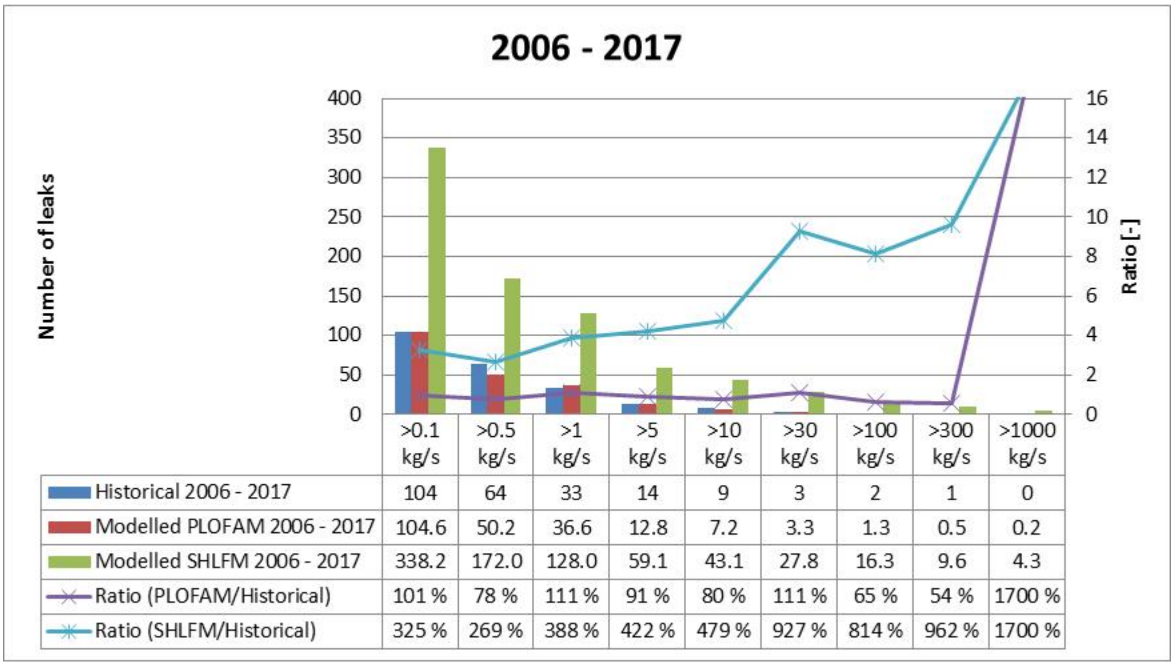
Frequency estimated using PLOFAM, is compared with the current frequency model commonly used in the industry in Norway, denoted SHLFM (Ref. /4/).

The resulting frequency distributions obtained when applying PLOFAM and SHLFM on the NCS population data set for the period 2006 – 2017 are shown in Figure 8.1. Figure 8.2 shows the relative number of leaks estimated using PLOFAM relative to using SHLFM. The results show that the difference between the two models is considerable. The difference is following from:

- PLOFAM is based on historical data of leaks occurring at installations on the NCS in the period 2001-2017. The last version of SHLFM was solely based on data of leaks occurring at installations on the UKCS in the period 1992-2010. There has been a considerable decrease in historical leak frequency at installations on the UKCS over this period. It has been shown that the underlying hole size frequency distribution on the UKCS and NCS after year 2000 is similar, and most likely the same statement is valid for the total leak frequency as well
- Enhanced understanding of the quality of the data in the HCR database, which has provided basis for implementing considerably less conservatism to account for uncertainty related to the data basis. This has been made possible by the fact by that more data related to the leaks in HCRD has been made available by HSE. Two items have been particularly important in this regard. Firstly, the actual hole size for incidents where the hole size was larger than 100 mm has been provided. Previously, it was stated that the hole size was > 100 mm in such cases. The additional information on large hole sizes has provided confidence in estimation of a more accurate frequency for large leaks. Secondly, it has been found that the population data (*i.e.* number of equipment years) in HCRD has not been updated after 2005, which means that the estimated frequency for leaks extracted from HCRD will lead to an excessive estimate of the leak frequency even for installations located on the UKCS
- The mathematical formulation in PLOFAM enables an improved representation of the effect of the equipment size on the hole size frequency distribution for the various equipment types. In SHLFM, the capability in terms of capturing the shift in hole size distribution with varying equipment size for a given equipment was less pronounced. In combination with parameterisation of SHLFM outside the range of HCRD data for large holes led to estimation of excessive frequency for large holes for all equipment sizes for all equipment type. Moreover, as additional data on equipment size per incident in HCRD has been made available to the project, and more insight has been gained related to failure modes and their influence on different equipment sizes, it has been possible to develop and parameterize the equipment size dependent model in PLOFAM
- PLOFAM is unbiased and parametrized to reproduce the number of historical leaks at NCS in the period 2006 - 2017. Bias of frequency towards large hole sizes were included in SHLFM to account for uncertainty

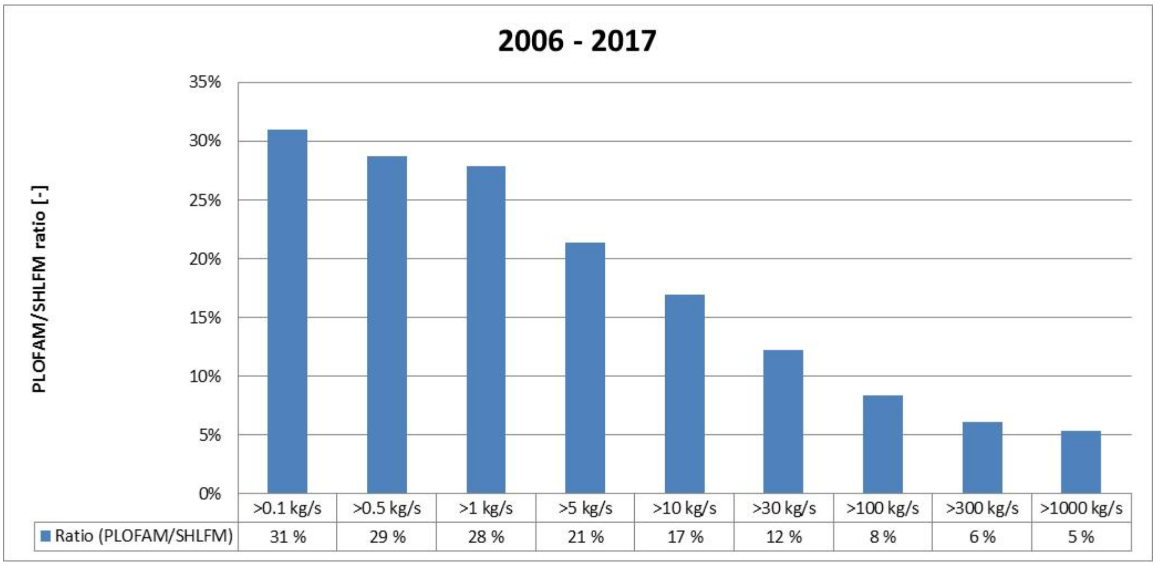
The resulting quantitative fire and explosion risk picture in a QRA for a typical installation on the NCS will be very different based on PLOFAM opposed to SHLFM. The validation model has demonstrated that the model denoted PLOFAM is able to predict the observed number of leaks at installations located on the NCS in the period 2006-2017, whilst SHFLM will overpredict the observed number of leaks in the same period. Hence, SHFLM is not recommended for prediction of the frequency for leaks on oil and gas installations at NCS.

The total quantitative fire and explosion risk picture is determined by combining PLOFAM with the MISOF ignition model. In the MISOF report, a more thorough comparison of PLOFAM and SHLFM including the effect of modelling of ignition probabilities is included (Ref. /2/). The effect on the fire and explosion frequency is prominent.



	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Historical 2006 - 2017	104	64	33	14	9	3	2	1	0
Modelled PLOFAM 2006 - 2017	104.6	50.2	36.6	12.8	7.2	3.3	1.3	0.5	0.2
Modelled SHLFM 2006 - 2017	338.2	172.0	128.0	59.1	43.1	27.8	16.3	9.6	4.3
Ratio (PLOFAM/Historical)	101 %	78 %	111 %	91 %	80 %	111 %	65 %	54 %	1700 %
Ratio (SHLFM/Historical)	325 %	269 %	388 %	422 %	479 %	927 %	814 %	962 %	1700 %

Figure 8.1 – Comparison of SHLFM and PLOFAM. The frequency is the sum of frequency for gas and liquid leaks. For the SHLFM model, only Full pressure leaks and Limited leaks are included. In PLOFAM, only significant leaks are included. Note that the ratio for leaks >1000 kg/s is infinite but plotted as 1700% to illustrate in the figure that the value is high



	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Ratio (PLOFAM/SHLFM)	31 %	29 %	28 %	21 %	17 %	12 %	8 %	6 %	5 %

Figure 8.2 – Comparison of SHLFM and PLOFAM. The bars display the ratio per leak category for the total of gas and liquid leaks. For the SHLFM, only Full pressure leaks, i.e. Full leaks and Limited leaks are included. In PLOFAM, only significant leaks are included

9 Robustness of PLOFAM

The quality and limitations of the data used as basis for the parameterisation of PLOFAM is fundamental for the precision of the model. The quality of the data basis is discussed throughout the report, both in the technical notes presenting the data basis (TN-2 and TN-3), but also in discussion of the results from applying the model to all installations at NCS (see TN-6).

It is judged that the elements affecting the quality and limitations of the data are understood, but some of them may be hard to quantify. On a high level, the frequency distributions based on data extracted from the HCR database and the NCS database is similar. This is considered to be a strong argument for that the PLOFAM model is based on a solid understanding of the data basis. This can for instance be seen from Figure 6.2, where it is shown that the relative complementary cumulative leak frequency distribution for both NCS and UKCS coincide with the PLOFAM estimate.

The quality of the NCS leak database regarded as high because it is established based on review of the accident investigation reports for the incidents.

The overall quality of the NCS population data is discussed in TN-2 and also as part of the guidelines given in TN-5 Appendix B. The data are gathered from QRAs performed by 4 different consultancy companies. In general, the variation between the different consultancy companies is small, which indicates that the industry practice on counting of equipment is quite homogenous. This is interpreted as an argument why the quality of the population data is regarded as good, even though uncertainties do exists. The uncertainties are in general related to how equipment is counted. By introducing guidelines for equipment counting the aim is to achieve an even more unified way of counting equipment (see TN-5). However, as different strategies may have been used as basis for the population database one may introduce a bias toward underpredicting or overpredicting the leak frequencies by applying the guidelines. In such cases the guidelines have in general been formed to rather overpredict than underpredict the leak frequency in future QRAs. Note however that the expected overprediction is expected to be low and well within the uncertainty related to other aspects. It should however be noted that uncertainties related to how pumps are counted relative to how it is recommended counted in the guidelines may introduce a uncertainty related to the fire frequency up to 40% for modules with pumps (see TN-5 Appendix B). Another main uncertainty in the population database is related to the number of wells at the installations. Leaks from wells are however not expected constitute a significant part of leak frequency for most installations.

PLOFAM is designed to be a tool for estimation of future leak frequencies for use in QRAs. Hence an important aspect with respect to robustness is the model target relative to the historical observations. The model target, time trend and stochastic effects are discussed in detail in TN-2 and TN-6. In short PLOFAM is designed to predict the same total leak frequency as seen at NCS in the period 2006 – 2017. Targeting this frequency level would imply that the model will estimate about 30% lower leak frequency than the average leak frequency in the period 2001 – 2017, but also 30% higher leak frequency than seen for any years after 2011, and about 50% higher leak frequency than recorded in 2017. If the observed trend in time for leaks >0.1 kg/s continues, PLOFAM will overestimate the total leak frequency even more, i.e. the chosen target level for the model account for uncertainty in the data material and shifts in underlying causal factors (*e.g.* emerging unknown degradation mechanisms due to age or changing operational conditions) affecting the future trend in leaks occurring on installations on the NCS.

The targeted leak rate distribution is important for estimating the leak frequency for large leaks. As the number of large leaks is few, the stochastic uncertainty of the relative leak rate distribution is significant. Data periods do exist where both higher and lower fractions of large leaks are seen. Considering only data after 2007 will give lower fraction of large leaks if used as basis for the model, whilst considering only data from the period 2006 – 2017 gives a higher fraction of large leaks. It should also be noted that data for the period 1992 – 2000 shows a significant lower fraction of large leaks. The difference is large and cannot be explained solely by stochastic variations. This is first of all a result of the clear time trend seen for leaks >0.1 kg/s, i.e. that the leak frequency is significantly reduced. For leaks > 10 kg/s, it is also likely that there is a time trend, i.e. that the leak frequency is being reduced, but it cannot be ruled out that the observed variations is due to stochastic variations (see TN-2). Hence the increased fraction of large leaks is mainly a consequence of the reduced leak frequency for small leaks (this should be carefully taken into account in future updates of the model).

The robustness of the target value is also discussed in TN-6, where the stochastic uncertainty is shown to increase with increasing leak rate. Due to randomness, one cannot be sure about the targeted leak rate distribution. The parameterisation process in PLOFAM targets the most likely underlying distribution, but both significantly lower or higher target frequency cannot be rule out (illustrated by the fortunate and unfortunate scenarios corresponding to 10% and 90% probability of exceedance, *i.e.* 80% confidence interval). See TN-6 for further explanations of the fortunate and unfortunate scenarios established based on the Poisson process. This aleatory uncertainty should be taken into account in the decision-making process. The ratio between the fortunate and unfortunate scenario relative to the observed/targeted number of leaks are given in Figure 9.1 and summarizes the discussion of the stochastic uncertainty for the defined model target. The increasing spread of relative distributions with respect to initial leak rate for the unfortunate and fortunate scenario displayed in Figure 9.1 is important to consider when evaluating the accuracy of a QRA model based on PLOFAM. For leak rates above about 30 kg/s, the relative difference between the fortunate and unfortunate scenario constitutes a factor in the range 1.5 to 2.5.

In total, the combination of the targeted total leak frequency and the targeted fraction of large leaks will decide the targeted leak frequency for large leaks. The resulting target is regarded reasonable and a best estimate, slightly approached from the conservative side.

Note also that the guidelines for use of PLOFAM in QRAs presented in TN-5 Appendix B are established from the conservative side. First of all it is recommended to model all Significant leaks as leaks occurring during normal operation where the full inventory is released (taking ESD and blowdown into account). Secondly the counting rules takes uncertainty in the population database used for model parametrization into account, by rather overestimate the leak frequency than underestimating it. This adds robustness to the frequency and risk estimates generated in QRAs using PLOFAM.

Although a strict update of the PLOFAM model parameters in case of the occurrence of one future large leak at NCS would lead to a model that would predict a slightly higher frequency for leaks, the current model cannot be disregarded if one (or two) large leak occurs in the near future as the target value used for PLOFAM still would have a relatively high probability of occurrence. Figure 9.2 shows the effect on the targeted relative leak rate distribution if two leaks >100 kg/s where one of them is larger than 300kg/s potentially occurring tomorrow (for comparison there has been three leaks >100 kg/s and one leak >300 kg/s in the period 2001 – 2017). For leaks <10 kg/s the fraction is relatively unchanged, while for leaks >10 kg/s, the fraction is increased by up to a factor of 2. Comparing the updated model target (red curve in Figure 9.2) with Figure 9.1 shows that the updated model target will still be within the limits defined by the fortunate and unfortunate scenarios in Figure 9.1. Likewise, a long period (> 5 years) without observing any large leak in the future does not imply that the current model is conservative in terms of estimation of the frequency for large leaks.

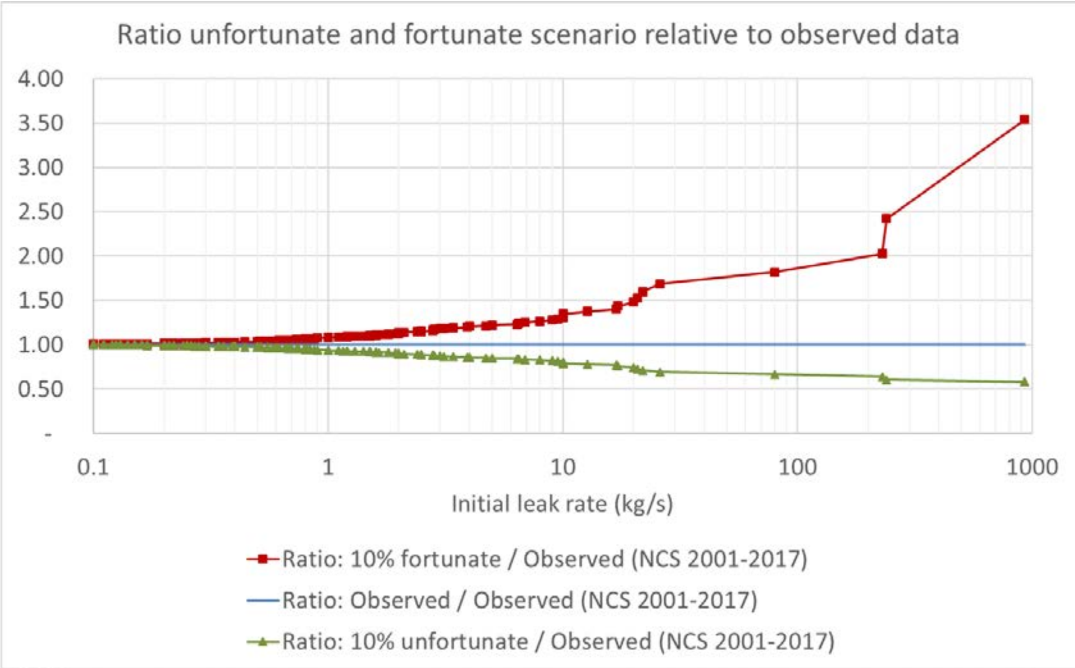


Figure 9.1 – Ratio unfortunate and fortunate scenario (10% percentiles used) with respect to observed data (NCS 20017-2017) versus initial leak rate. These ratios are derived directly from the relative leak rate distributions shown in TN-6

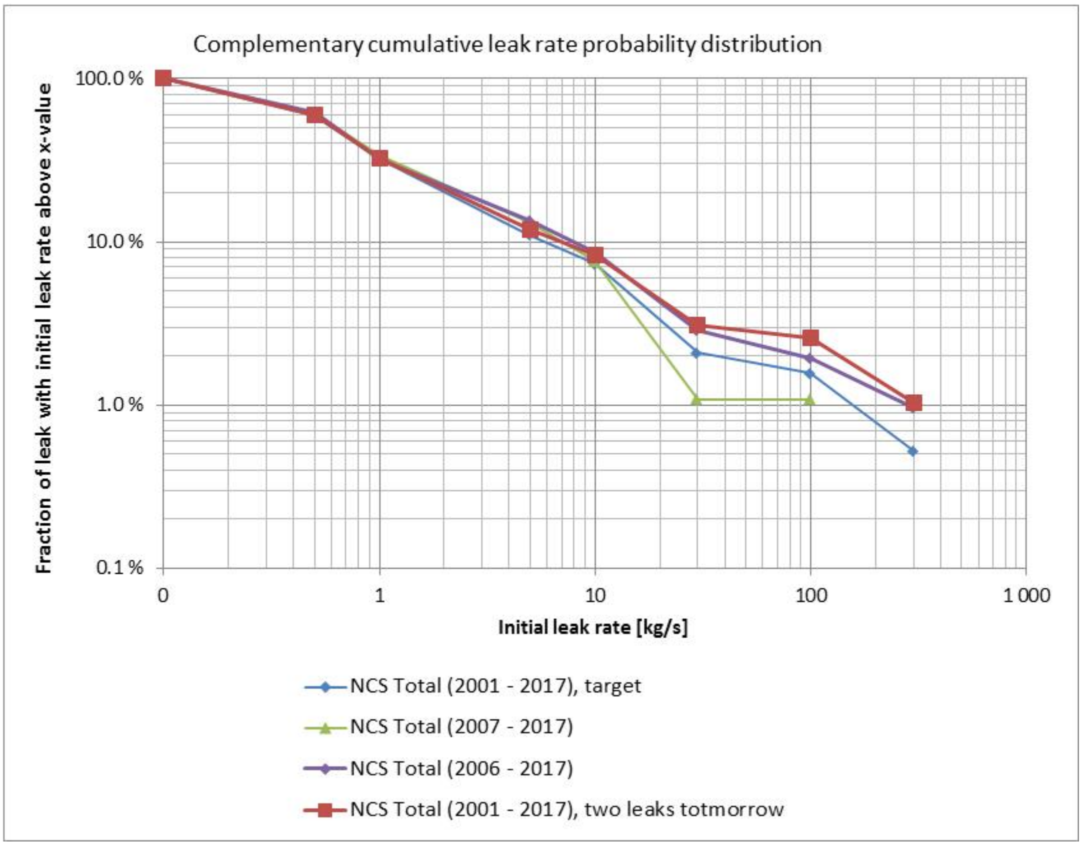


Figure 9.2 – Relative leak rate distributions for the periods 2001 – 2017 (target for model), 2006 – 2017, 2007 – 2017, and 2001 – 2017 including two leaks >100 kg/s where one leak is larger than 300kg/s potentially occurring tomorrow

10 Summary and concluding remarks

The objective has been to build a leak frequency model that will serve as a tool for prediction of the future leak frequency for topside process leaks at installations located on the Norwegian Continental Shelf (NCS) for use in QRAs. The model should be unbiased, i.e. it should aim at a best estimate.

Overall, the model is built on a combination of the explanatory variable that shows the strongest correlations with experienced number of leaks, and rational explanations and causalities reflecting known failure modes. The number of equipment (for each equipment type) is concluded to be the best single predictor to build the model on. However, as only one explanatory variable is chosen for the model, there are many factors influencing on the leak frequency that are not captured by the model, which will give rise to stochastic effects and deviations from the average for single installations.

It should be emphasised that PLOFAM is designed to serve as a tool for prediction of the future leak frequency for topside process leaks at installations located on the Norwegian Continental Shelf (NCS) for use in QRAs. Even if failure modes are aimed to be reflected as well as possible in the model, the model should first and foremost be used for prediction of leak frequencies for complete process systems. The model is to a much less degree valid for single components as a range of different designs (for instance standard flange constitute flanges with different sealing design) have formed the basis for the model. This should be addressed in further work (see TN-6), i.e. improving the capability of PLOFAM to reflect the specific technical characteristics and failure modes of the various types of components (*i.e.* ASME ring joint flange vs. Grayloc clamped connection).

The model is mainly parametrized and validated towards NCS data. The quality of the data is regarded as high. However, data from UKCS seem to show similar hole size frequency distributions, time trends and total leak frequency. The model is therefore regarded as valid for both sectors.

The strategy has been to build a model that gives a best estimate for future leak frequencies, i.e. to create an unbiased model without built in conservatism. It is observed a significant decreasing trend in historical leak frequency with time for installations on the NCS in the period after year 2000 (actually since 1992). The number of historical leaks in the period 2006-2017 is used as target for the total leak frequency while leak data from the period 2001 – 2017 is used as target for the relative leak rate distribution. Targeting this frequency level would imply that the model will estimate about 30% lower leak frequency than the average leak frequency in the period 2001 – 2017, but also 30% higher leak frequency than seen for any years after 2011, i.e. the chosen target level for the model account for uncertainty in the data material and shifts in underlying causal factors (*e.g.* emerging unknown degradation mechanisms due to age or changing operational conditions) affecting the future trend in leaks occurring on installations on the NCS. In total the combination of the targeted total leak frequency and the fraction of large leaks will decide the targeted leak frequency for large leaks, and is regarded reasonable and as a best estimate, slightly approached from the conservative side. Note also that conservatism is embedded in the guideline for use of PLOFAM in QRAs given in TN-5.

Stochastic uncertainty related to the targeted relative leak rate distribution is discussed in TN-2, TN-6 and in the previous chapter. The stochastic uncertainty is larger for large leak rates than for small leak rates. This is important to consider when evaluating the accuracy of a QRA model based on PLOFAM. For leak rates above about 30 kg/s, the relative stochastic uncertainty constitutes a factor in the range 1.5 to 2.5. i.e. based on the historical data it can be argued that the target value used for parametrization of the model can be both a factor 1.5 – 2.5 higher and lower than the target values used in PLOFAM (PLOFAM targets the most likely value). As a consequence it is shown that if two leaks >100 kg/s where one of them is larger than 300kg/s occur tomorrow, the model will still be valid.

The models ability to estimate the target value is discussed in TN-6, and also in Chapter 6.2 above. It is concluded that the model predicts the targeted values well when applied to the all installations in operation on NCS in the period 2006 – 2017, which is in accordance with the requirement to the model. Hence the aimed robustness established when establishing the target values is concluded to be implemented in the model.

The model will show stochastic variations for single installations (see also discussion in Chapter 6.2). As described in Chapter 2 there will be many factors influencing on the leak frequency (where some are installation specific) that are not captured by the model, which will give rise to stochastic effects. The historical leak frequency per installation at the NCS can therefore vary significantly from the NCS average, as illustrated in Chapter 6.2.

PLOFAM has been compared with the commonly used leak frequency model denoted SHLFM ("Standardised Hydrocarbon Leak Frequencies Model", Ref. /4/). The difference between the leak frequencies generated by the two models is considerable. These differences are explained by effects following from properties of the new data material being available for development of PLOFAM as well as new features of the mathematical framework enabling improved representation of the equipment size for the various equipment types. The resulting quantitative fire and explosion risk picture in a QRA for a typical installation on the NCS will be significantly different based on PLOFAM opposed to SHLFM. When applied to all installations being in operations in the period 2006 – 2017, PLOFAM is able to predict the observed number of leaks in this period, whilst SHLFM will overpredict the observed number of leaks for the same period approximately by a factor 3 for small leaks and a factor 10 for large leaks. Hence, SHLFM is not recommended for prediction of the frequency for leaks on oil and gas installations at NCS.

Although 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 in other domains. This should be based on a specific assessment to qualify use of the model in the particular domain. The important element to evaluate is whether the properties of the equipment and operation conditions can be considered equivalent with what are found generally on installations located in the North Sea.

The data basis for PLOFAM and the ignition model MISOF are fully aligned, and should therefore be used together. An important argument is that the historical data put as basis for the models are implemented based on the same assessment and understanding of the leak scenarios. One of the main uncertainties related to PLOFAM is the fraction of large leaks. Note however that if the number of large leaks is misinterpreted in the data material and should have been higher (i.e. that the leak frequency for large leaks should have been higher) then the ignition probability would have been lower in MISOF. This demonstrated why the two models should be used together and not combined with other models.

For further development of the model and future updates, a list of suggested focus areas has been listed in TN-6.

11 References

/1/ Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", report no: 105586/R1, Rev: Final B, Date: 18.03.2016

/2/ Lloyd's Register Consulting, "Modelling of ignition sources on offshore oil and gas facilities - MISOF", Date: November 2018, Report No: 107566/R2, Rev: Final

/3/ Lloyd's Register Consulting, "Blowout and well release frequencies based on SINTEF offshore blowout database 2017", 20 April 2018, Report No: 19101001-8/2018/R3 Rev: Final

/4/ DNV, Offshore QRA – Standardised Hydrocarbon Leak Frequencies, report number 2009-1768, rev. 1, 16.01.2009.

