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Leak frequency model and Guideline for use of PLOFAM in QRAs

TN-5

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Summary

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1 Introduction

In the initial section of this technical note (TN), Chapter 2, the concluded mathematical formulation is given, together with the equipment types included in the model and a description of how to use the model, including an example. The chapter also includes the lower hole size applicable for the model. Chapter 2, together with the model parameters given in the main report, and the guidelines for use of PLOFAM in QRAs given in Appendix B, are regarded as the necessary information to understand how to use the model. The remaining part of this TN explains the model objective and philosophy, the rationale for choosing the number of equipment as the only explanatory variable to build the model on, and the rationale for the mathematical formulation. Finally a set of requirements and assumptions for the model is described. These are essential when parametrizing, validating and evaluating the model performance, which are described in TN-6.

Abbreviations and expressions used in this technical note are described in TN-1: “Abbreviations and expressions”.

2 Model summary and application of the model

This chapter summarizes the mathematical formulation of the model. Furthermore, it gives guidelines for application of the model and for equipment counting used as basis for leak frequency estimation in QRAs. The rationale and detailed description of the model is given later in this technical note.

2.1 Mathematical formulation

2.1.1 General 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:

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

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

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

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

The parameters in the equations above are described in Table 2.1. 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 TN-6 and in the main report. F_{hist} is the historical leak frequency (given in leaks per year per 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 $(F_\mathrm{D}(D) - \alpha \cdot F_\mathrm{D}(D))$ 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 $\alpha = 0$.

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 Appendix A. The appendix also compares the model with the previous leak frequency model used in the industry, denoted SHLFM, ref /1/, and explains the difference.

Table 2.1 - 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 technical note

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. $F_D = F(d=D,D)$.
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)

2.1.2 Additional mathematical definitions

In addition to the equations described in Chapter 2.1, the parameter F_1 is introduced and expressed as a function of F_D as follows, and can be substituted in the equations Chapter 2.1 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 Appendix A).

Furthermore it can be useful to establish the parameters $\varphi(D)$ and $\theta(D)$, as they represents important physical properties in the mathematical formulation that are possible to make qualified assessment of and also find support for in historical data. This becomes crucial in the parametrization of the model described in TN-6. The parameters $\varphi(D)$ and $\theta(D)$are described in Table 2.2 and are expressed as follows:

$$\varphi(D) = A_0 \cdot D^{M_0} \tag{8}$$

$$\theta(D) = A_D \cdot D^{M_D} + B_D \tag{9}$$

Hence $\varphi(D)$ and $\theta(D)$ can be used in the expression for $F_0(D)$ and $F_D(D)$ as follows:

$$F_0(D) = F(d = 1, D) = F_{hist} \cdot \varphi(D) = F_{hist} \cdot (A_0 \cdot D^{M_0}) \tag{10}$$

$$F_D(D) = F(d = D, D) = F_0(D) \cdot \theta(D) = F_0(D) \cdot (A_D \cdot D^{M_D} + B_D) \tag{11}$$

Table 2.2 – Additional mathematical parameters defined

Parameter	Description
F_1	Additional full bore hole frequency [year^{-1} equipment^{-1}]
α	The parameter is repeated here as it can be described through the newly introduced F_1 parameter, as the ratio between the added full bore hole frequency F_1 and the total full bore hole frequency $F_D(D)$. See also Appendix A. $$\alpha = \frac{F_1}{F_D}$$
$\varphi(D)$	The ratio between the total leak frequency $\mathrm{F}_0(D)$ and the total leak frequency including all equipment dimensions for the relevant equipment type (i.e. the average leak frequency (independent of equipment diameter)). This can also be seen as an adjustment factor of the total leak frequency relative to the weighted average leak frequency F_{hist}
$\theta(D)$	Full bore hole fraction, $$\theta(D) = \frac{F_D(D)}{F_0(D)}$$

2.1.3 Simplified mathematical formulation

The formulation given in Chapter 2.1 is the general formulation for all equipment types. For several equipment types, many of the parameters are set to 0 or 1, resulting in a simpler formulation for that particular equipment type. For example, for many equipment types F_0 and $F_D$are modelled as independent on the equipment diameter and with a regular power law, i.e. the parameters are set to: $A_0 = 1, M_0 = 0,\ A_D = 0,\ M_\mathrm{D} = 0,\ \alpha = 0$. In this case the mathematical expression can be reduced to the much simpler formula:

$$F(d; D, P) = \begin{cases} F_{\mathrm{hist}} \cdot d^{\log(B_\mathrm{D})/\log(D)} & ,\ 1 \le d \le D \\ 0 & ,\ d > D. \end{cases} \tag{12}$$

2.2 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 2.3.

Table 2.3 - 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	
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

2.3 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). 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 2.1.1.
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 where the frequency is multiplied with the number of steel 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 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.

2.4 Example of application of the model

This example is given to illustrate the recipe given in Chapter 2.3. The frequencies for a "Significant leak" (Significant leak is a leak where the total released quantity is ≥10 kg/s, see TN-4) from a 4" standard flange, containing gas with density 132 kg/m³ at pressure 156 bara is calculated.

The model parameters for Standard flange are given in Table 2.4. Following step 1- 4 in Chapter 2.3, gives $F_0(D)$, $F_D(D)$, $F_1(D)$ and $m(D)$ as given in Table 2.5.

By using the relation between hole size and leak rate the given in 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 2.3. The results are given in Table 2.6 together with the corresponding cumulative leak frequency calculated following step 6 in Chapter 2.3.

Next the leak frequency for the leak rate intervals and corresponding hole size intervals can be calculated following step 7 in Chapter 2.3. The results are given in Table 2.7.

Table 2.4 – Model parameters for Standard flange

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

Table 2.5 – 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.

Parameter	F_0	F_D	F_1	m
Value	2.50E-05	6.79E-07	3.39E-07	-0.93

Table 2.6 – Leak rates, corresponding hole sizes and cumulative leak frequency

	Leak rate [kg/s]					
Parameter	0.1	0.5	1	5	10	30
Hole diameter [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 2.7 - 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

2.5 Lower hole size applicable for the model

The lower hole size that the model is valid for is set to 1 mm. This chapter presents a discussion that justifies the lower hole size applicable for the model.

TN-6 presents the model validation, and shows that the model reproduces the number of observed leaks > 0.1 kg/s. This is based on the NCS population dataset and on equations for leak rate estimation for gas and liquid leaks (see Appendix B). Figure 2.1 gives the hole size that gives 0.1 kg/s leak rate as function of gauge pressure for Methane, Ethane, Propane and oil with density 800 kg/m³. The leak rate equations used in the validation model (see Appendix B) are applied. The NCS population database shows that the majority of equipment is associated with a pressure in the range 10 – 150 barg. For gas leaks, the hole size generating a leak rate of 0.1 kg/s, which is the minimum leak rate used in the validation process, is in the range 2-9 mm (see Figure 2.1). For liquid leaks the corresponding range is 1-2 mm. Thus the model can be said to be validated for hole sizes down to 2 mm for gas leaks and 1 mm for liquid leaks. This puts confidence behind the lower hole size that the model is valid for, which is set to 1 mm.

Note that the model may also be applicable also for lower hole sizes, but this has not been validated.

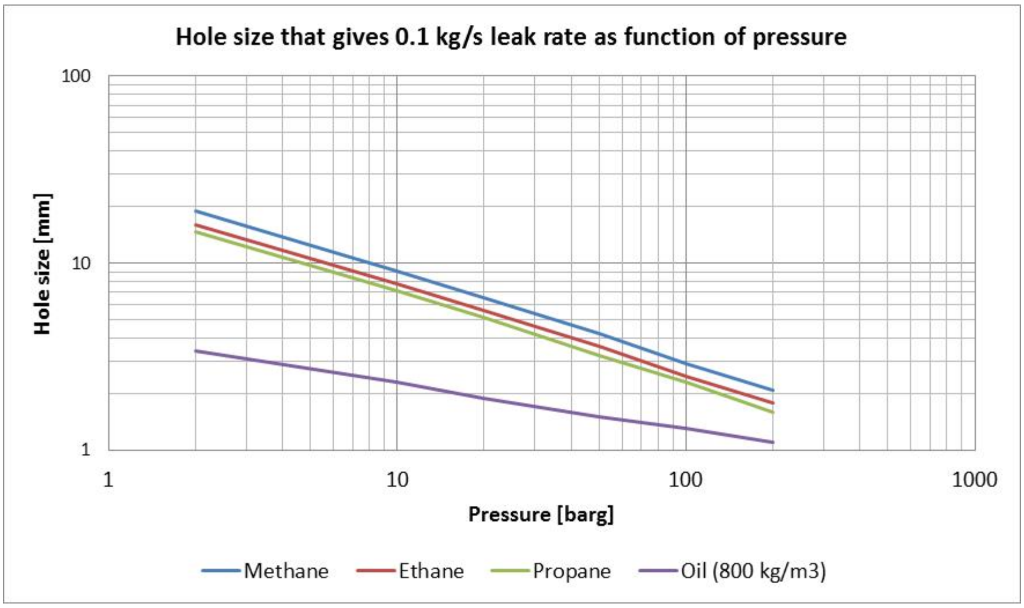

Figure 2.1 - Hole size that gives 0.1 kg/s leak rate as function of gauge pressure for Methane, Ethane, Propane and oil with density 800 kg/m³

3 Model objective and model philosophy

3.1 Model 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.

3.2 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. Some factors that may have implications on the leak frequency at an installation are:

- The components that the process system consists of, i.e. type of equipment, material, design and technology
- The equipment size distribution
- The process conditions
- Environment around the process system
- The maintenance scheme
- Training of personnel
- Work culture
- Time and cost requirements

Many of these factors will be different from installation to installation and some will strongly influence on 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. A model to be used in QRAs should be kept reasonable simple as it will be used by a large number of persons without a detailed overview of factors influencing on the phenomenon and the background for the model. Furthermore QRAs are often performed in early phases and plays an important role in connection with design of installations. In early phases detailed information is normally not available. Therefore, in order to build a model for use in QRAs, the complexity should be limited to a user friendly and appropriate level. Hence there will be factors influencing the leak frequency that are not captured by the model, and the model will therefore not be able to capture all differences between installations and exactly estimate the leak frequency for all installations on NCS. 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. Therefore the objective is not to be able to predict the exact leak frequency for every single installation at NCS, but rather to predict the leak frequency and leak rate distributions for all installations together, i.e. for an average installation.

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, 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.

One obvious challenge in model design is of course that dominating known failure modes being reflected in a model will be given focus and are often then eliminated through technology development, reducing the model's ability to predict correct leak frequencies and related properties. However, this illustrates how detailed risk modelling can catalyse increased knowledge about failure modes and hence reduce risk by putting focus on risk driving parameters. Furthermore it demonstrates why risk modelling is a continuous work where model development and technology development is an iterative process.

4 Leak frequency explanatory variables

The previous leak frequency model, Ref./1/, was based on the fundamental presumption that the leak frequency is proportional to the number of equipment of each type.

Based on Norwegian Continental Shelf (NCS) population data established in the project (see TN-2) the recorded number of leaks at installations at NCS can be plotted against the number of equipment years per installation. The results are presented in Figure 4.1 and Figure 4.5, where leaks with initial release rate >0.1 kg/s and 10 kg/s are shown, respectively. In these figures all equipment types are included.

The correlation analysis presented in this chapter has not been updated since the first revision of PLOFAM, Ref. /2/. Hence the results are generated using data from 62 installations for the period 2001 – 2014. This is done because the correlation analysis using work orders, presented in this chapter was performed using data from 2001 – 2014, and has not been updated. Furthermore, this was the analysis put as basis for the decision of building the model one explanatory variable (equipment counts), which has not been re-assessed in this revision of PLOFAM. The results and conclusions are not expected to change if including a larger population set and three more years.

The coefficient of determination, i.e. the R^2-value of the linear regression displayed in Figure 4.1 is 0.61 for leaks with initial leak rate >0.1 kg/s, while the sample correlation coefficient given by the general formula

$$\text{Sample correlation coefficient} = \frac{\sum(x-\bar{x})\,(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{13}$$

is 0.79, which indicates a strong correlation. In Figure 4.2 - Figure 4.4, only valves, standard flanges and instruments are included, respectively. The coefficient of determination, i.e. the R^2-value of the linear regression, is 0.35, 0.29 and 0.06, while the sample correlation coefficient is 0.59, 0.54 and 0.26, respectively. The correlation is stronger if all equipment types are considered together, than if each is studied separately. Based on the figures below, the number of equipment is concluded as one explanatory variable.

It should be noted that for leaks with initial release rate >10 kg/s, the correlation is not that strong, indicating that there are other explanatory variables for the large leaks. This has also been pointed out at an early stage in the project by Lundin based on experience with large leaks. However, other explanatory variables for large leaks have not been investigated in the project. Thus they are treated similar to smaller leaks in the model.

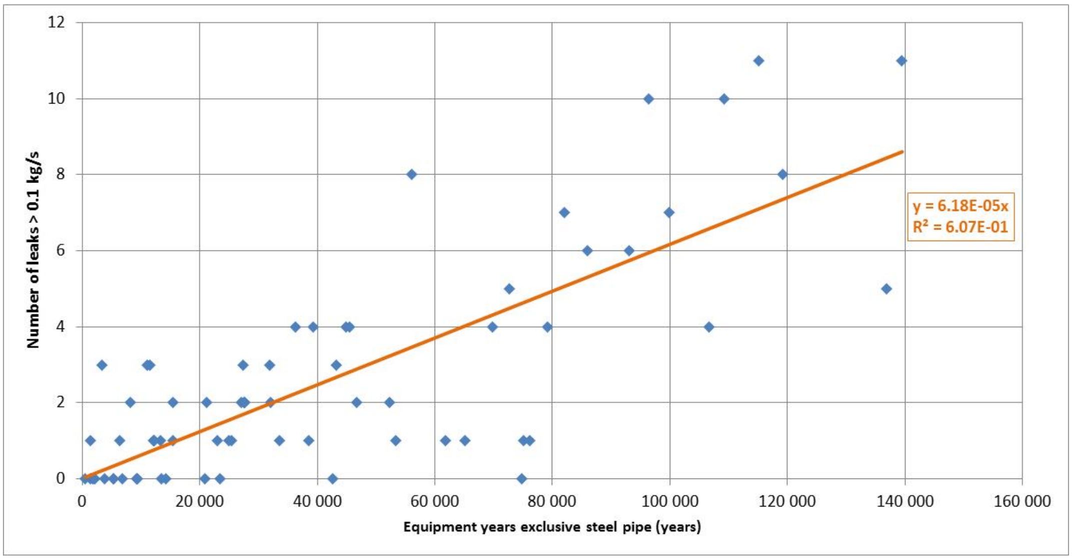

Figure 4.1 - Number of recorded leaks with initial leak rate >0.1 kg/s vs. recorded equipment years at installations at NCS. Note that steel pipes are not included. Each dot represents one installation

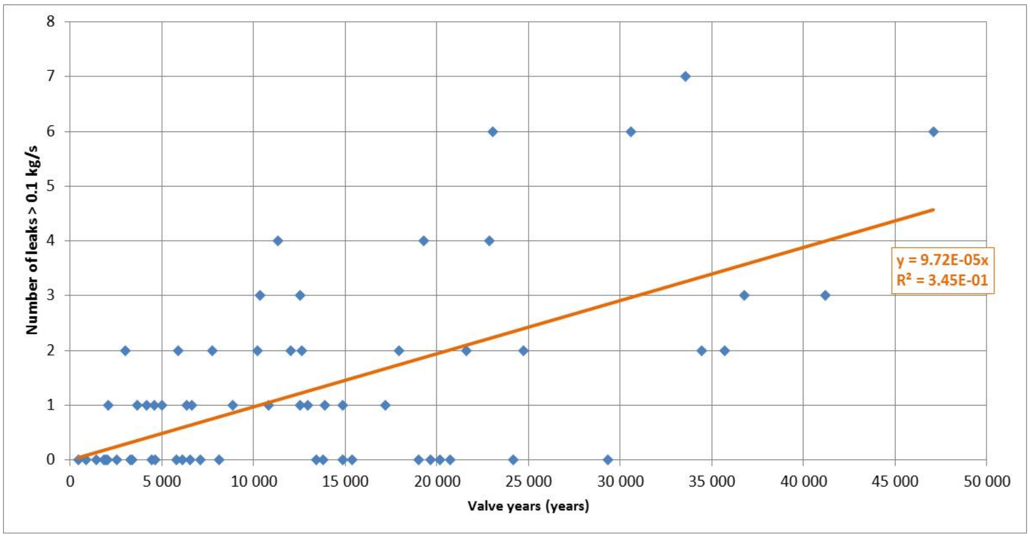

Figure 4.2 - Number of recorded leaks from Valves with initial leak rate >0.1 kg/s vs. recorded valve years at installations at NCS

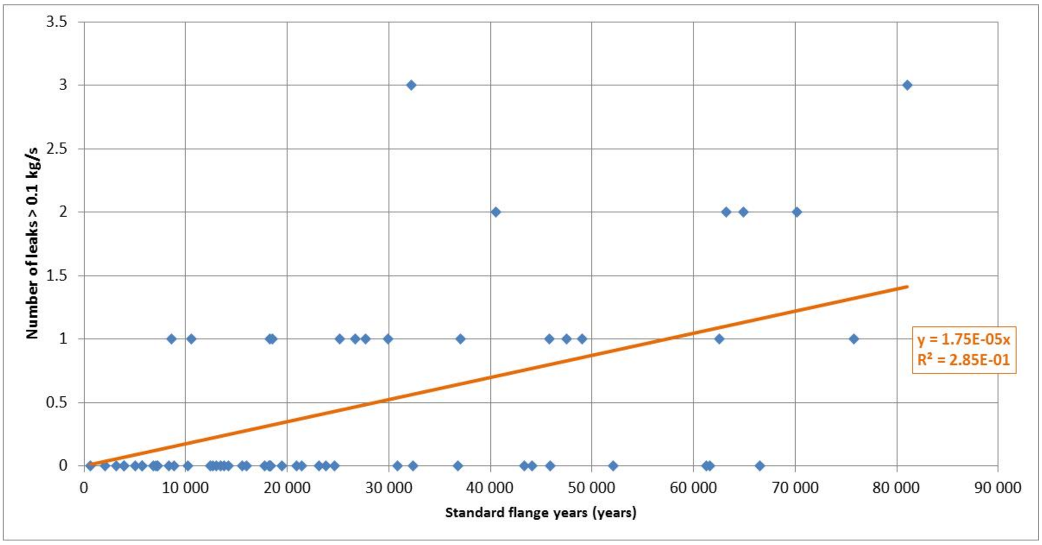

Figure 4.3 - Number of recorded leaks from Standard flange with initial leak rate >0.1 kg/s vs. recorded Standard flange years at installations at NCS

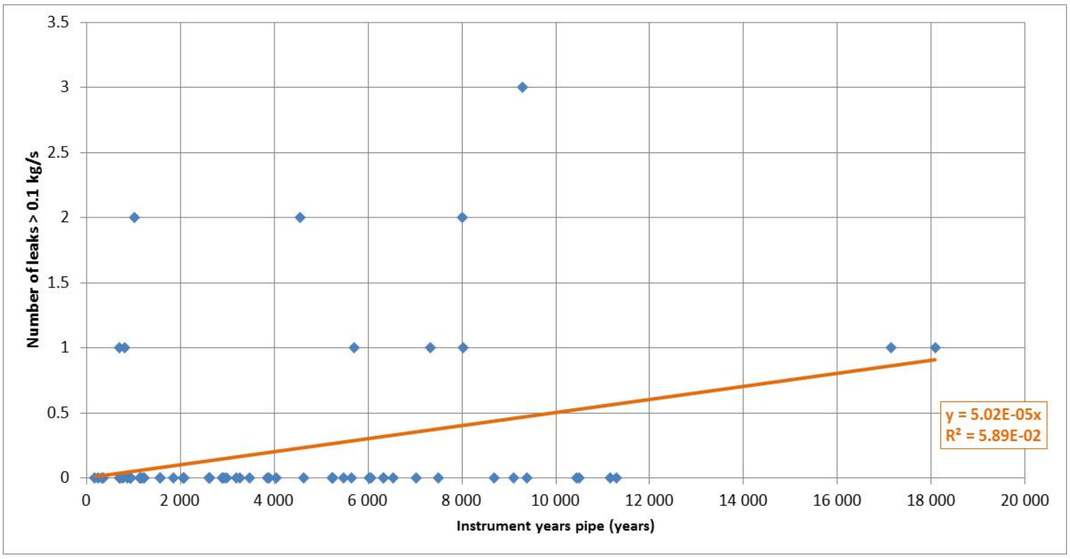

Figure 4.4 - Number of recorded leaks from Instruments with initial leak rate >0.1 kg/s vs. recorded instrument years at installations at NCS

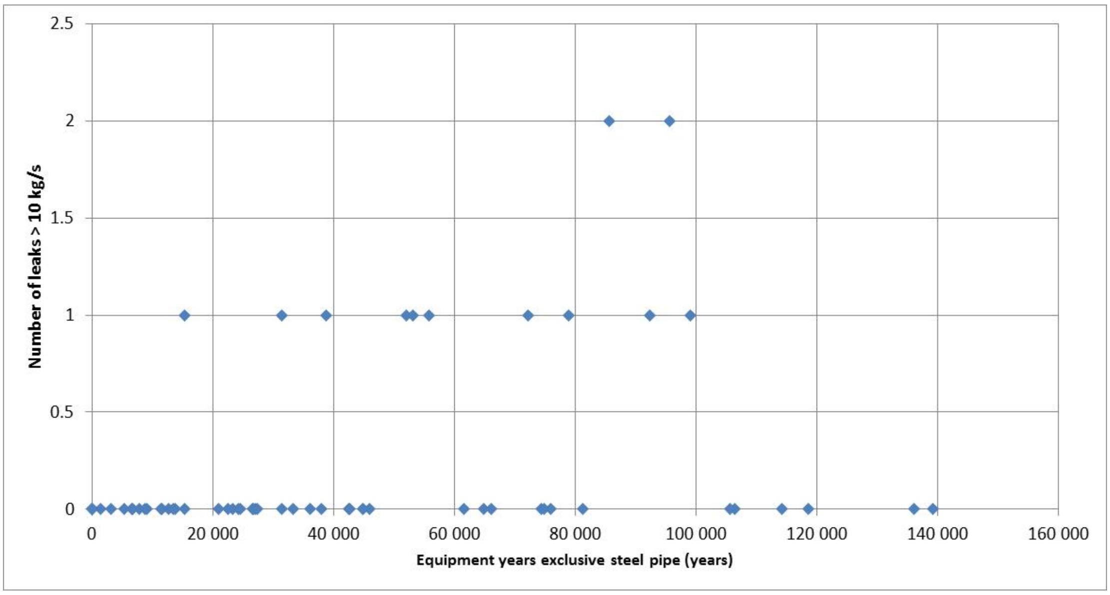

Figure 4.5 - Number of recorded leaks with initial leak rate >10 kg/s vs. recorded equipment years at installations at NCS. Note that steel pipes are not included. Each dot represents one installation

To investigate if also work orders (WO) on HC-equipment could be used as an explanatory variable, Safetec has performed dependence test using Pearson correlation test, and a distance correlation test. Compared to the correlation test, the distance correlation test will not be similarly sensitive to the fact that both the number of leaks and equipment years are positive defined variables. The tests are performed by the use of leak frequency data from RNNP from the period 2001 –2014 for 34 installations with the same operator, and WOs collected for the year 2013.

Based on the following BORA (Barrier and operational risk analysis) classifications:

- Operational failure: BORA classification B and C
- Non-operational failure: BORA classification A, D, E and F

the tests are performed for three types of leak frequency:

- Total leak frequency
- Operational failure leak frequency (BORA cat. B and C)
- Non-operational failure leak frequency.

In this way it can be investigated if the operational and non-operational leak frequencies have different types of relations with the explanatory variables. The test used a confidence interval of 1 % (p-value 0.01). The results are given in Table 4.1 below. It is seen that equipment is seemingly a stronger explanatory variable than work orders, but both could be used as explanatory variables. These results cannot be conclusive as the activity data is less detailed than the equipment count. The equipment count, represented by the estimated leak frequency using SHLFM, is based on 18 different equipment categories benchmarked with historical leak frequency, while the activity data explanatory variable in the correlation analysis is based solely on WO (on HC equipment). In order to have a valid comparison, leak frequencies should be calculated using the activity based model and these calculated frequencies should be used as explanatory variables representing activity level (Activity based model split activity in three groups; Extensive WO, Limited WO and normal operations). It is considered likely that such an approach would increase the correlation between activity level and operational caused HC leaks.

Table 4.1 - Results from dependence test using Pearson correlation, and a correlation test for both operational related leaks, non-operational leaks and all leaks. Light blue indicates that the p-value is >1 %, while dark blue indicates that the p-value is <1 %, and thus concluded to be strong explanatory variable

All leaks (2001 - 2014) - normalized					
	Dependence test		Correlation test		
Explanatory variable	Significantly dependent?	p-value	Significantly correlated?	p-value	Correlation
Workorders (HC)	NO	0.015	NO	0.0181	0.51
Equipment (estimated leak freq)	YES	0.005	YES	0.0073	0.57

Operational related leaks (2001 - 2014) - normalized					
	Dependence test		Correlation test		
Explanatory variable	Significantly dependent?	p-value	Significantly correlated?	p-value	Correlation
Workorders (HC)	YES	0.005	YES	0.00445	0.59
Equipment (estimated leak freq)	YES	0.005	YES	0.00012	0.74

Non - operational related leaks (2001 - 2014) - normalized					
	Dependence test		Correlation test		
Explanatory variable	Significantly dependent?	p-value	Significantly correlated?	p-value	Correlation
Workorders (HC)	NO	0.02	NO	0.0398	0.45
Equipment (estimated leak freq)	YES	0.005	YES	0.0002	0.7252

Work orders could be used to include activity in the leak frequency model. There are several reasons why a leak frequency model where activity is taken into account would be beneficial:

- Enhances understanding of risk drivers
- Focus both on consequence of leaks and reducing probability of leak
- Reflects segment specific issues (sand, corrosive fluid/gas etc.)
- Takes into account that different operations has different leak potential
- Is in accordance with management regulations §4
- The model could easily be used to analyse high activity periods

Despite the fact that approximately 50 % of all leaks at NCS are related to activity, and the above indicates that WO can be used as an explanatory variable, the project concluded not to implement WO as an explanatory variable for the model. This is partly based on the following:

- The number of WOs is correlated with the number of equipment
- Data is not publicly available
- And use and duration of work orders may differ severely between operators
- It is considered too challenging to include a model reflecting activity in this project.

Thus the number of equipment (for each equipment type) is the only explanatory variable assumed in 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 on the leak frequency that are not captured by the model. Including more explanatory variables in the model is challenging and left for potential future work in order to keep the model reasonably simple (Ref. Chapter 3).

5 Rationale for the mathematical formulation of the model

The mathematical formulation should be able to describe how the leak frequency is distributed across different hole sizes taking into account that this may vary with equipment size, i.e. equipment diameter. Through the development of the mathematical formulation, different options were discussed:

1. An equipment size independent model, i.e. a model where the hole size probability is independent of the equipment size
2. An equipment size dependent model based on a strict power law
3. A refined equipment size dependent model based on a modified power law with reduced probability of hole sizes slightly smaller than the equipment diameter, which is the concluded model

The rationale for the mathematical formulation of the three options above is described in Appendix A. Furthermore, guidelines for use of PLOFAM in QRAs including guidelines for counting of equipment are given in Appendix B. The final mathematical formulation is described in Chapter 2.

6 Requirement to the model and basic assumptions

Based on the model objective and philosophy presented in Chapter 3, a set of technical requirements to the model is established in this chapter. Furthermore, basic assumptions that the model is built on is presented.

6.1 Requirement to the model

The following technical requirements are established for the model:

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
4. The model should be able to reproduce the relative distribution between equipment types seen based on experienced data from NCS and/or United Kingdom Continental Shelf (UKCS)
5. The model should be able to reproduce the relative distribution between oil and gas leaks seen in the experienced data from NCS and UKCS
6. The model must account for uncertainty in the underlying data basis as well as the stochastic effects related to the observed phenomena
7. The model should be equipment size dependent and as far as possible valid for single components
8. The model should be as simple as possible. i.e. the simplest possible model taking account for trends, and effects that are justified through available data or argumentation, should be chosen
9. The model should be robust towards changes in the dataset

6.2 Basic assumptions

The following basic assumptions are made:

1. Data from NCS are the most relevant data for validation of the model. Where data from NCS is not sufficient, data from UKCS is regarded as the best available alternative. Data from UKCS may be used to validate the cumulative hole size probability distribution for the different types of components
2. A model that fulfils the requirements described in Chapter 6.1 is assumed to produce the best estimate for future leak frequencies
3. Each equipment can be associated with a leak frequency with a continuous holes size distribution. Both the frequency and the hole size distribution is dependent on the type of process equipment
4. The underlying hole size distribution is the same for gas and oil leaks. The validity of this assumption will be investigated as part of the validation process

7 References

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

/2/ Lloyd's Register Consulting, "Process leak for offshore installations frequency assessment model – PLOFAM", TN-5 "Leak frequency model", report no: 105586/TN-5, Rev: Final B, Date: 18.03.2016

Appendix A

Rationale for the mathematical function for hole size distributions

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Page

1 Introduction

This appendix describes the rationale for the mathematical formulation of the model. This is done through three steps:

1. Chapter 2 presents the rationale for describing the hole size frequency distribution as a power law and how an equipment size independent model can be built using a modified power law with a hole size dependent slope parameter
2. In Chapter 3 an explanation why the modified power law with a hole size dependent slope parameter gives a good fit to the data is presented. It is further described how this understanding can be used to describe an equipment size dependent model. The model presented in Chapter 3 is a special case of the mathematical formulation presented in Chapter 4
3. In Chapter 4 the mathematical formulation of the equipment size dependent model presented in Chapter 3, is further developed to have the possibility to take expected properties of the hole size distribution into account, i.e. a parameter $F_1 = \alpha \cdot F_D$ was introduced to account for a reduced probability of hole sizes slightly smaller than the equipment diameter. Failure modes where this model is useful are described in TN-6. Note that in case $\alpha = 0$, the mathematical formulation is identical to the one presented in Chapter 3. This formulation is the concluded mathematical formulation of PLOFAM.

2 Equipment size independent hole size distributions

One of the model requirements is that the model should give a continuous hole size distribution for each equipment type. HCRD incident data gives hole sizes for recorded leaks (NCS data gives leak rate) and indicates that the hole size frequency distributions can be modelled by a power law relation (see Figure 2.1):

$$F(d) = F_0 \cdot d^m \tag{1}$$

Where $F_0 = F(d = 1\ \mathrm{mm})$ is the total leak frequency for holes >1 mm from the relevant equipment type, d is the hole size and m is the slope parameter (further described below). This is supported by the NCS data which indicates that the complementary cumulative leak rate distribution follows a power law.

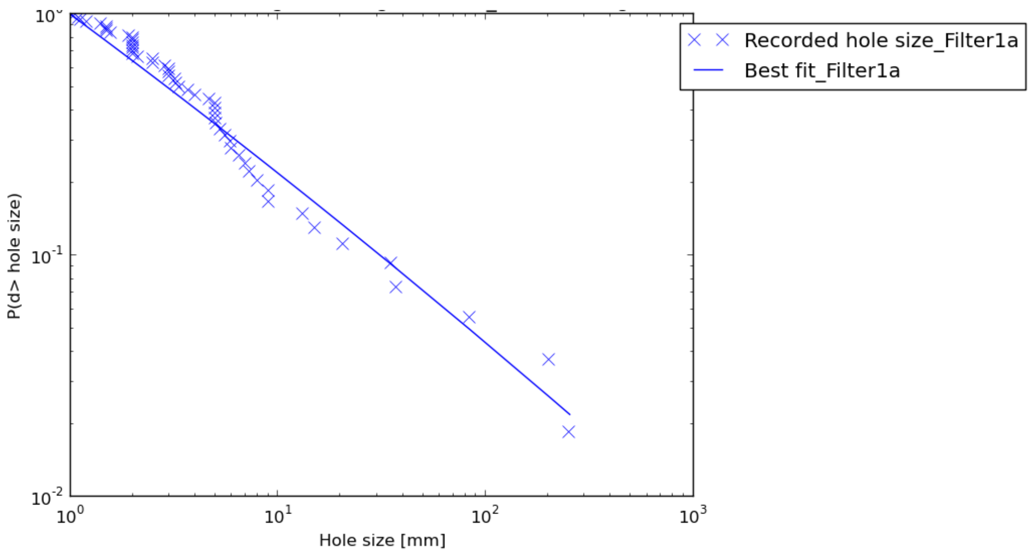


Figure 2.1 - Curve fitting to recorded HCRD hole size distribution for Standard flange (Medium size: 3-11"). The data shows a power law behaviour

Three basic strategies for building a model exist:

a) Build the model solely based of available data material. This will of course require good quality of the data, but it will also require the format of the data to be on the desired format and the necessary level of detail

b) Build the model based on rational arguments of expected properties of the model

c) A combination of a) and b)

As one of the requirements defined in TN-5 (main document) states that the model should be equipment size dependent and as good as possible valid for single components, strategy a) will not give a satisfactory model. The reason is that the HCR data does not contain information about the equipment size as part of the incident data (equipment dimensions are made available to the project for valves, flanges and pipes, but not other equipment types. However, as the number of different equipment sizes is high, the number of incidents for each equipment size would most likely not be sufficient to build hole size distributions on). Thus, curve fitting to hole size distributions would represent hole size distributions for a range of equipment sizes, where the equipment size distribution is unknown. This implies that the correct usage of such a model would be to let this hole size distribution be valid for all equipment sizes included in the underlying data material. Thus, such a model would not be able to distinguish on equipment size, as all equipment would give frequency contribution for hole sizes up to the upper validity range of the model, i.e. most equipment would give frequency contribution at hole sizes, d, larger than the equipment size, D. Implicitly, the underlying assumption for such a model, when applied on a specific installation, would be that the equipment size distribution at the installation is comparable to the equipment size distribution in the underlying data material (HCRD).

As part of the model development the project did curve fit the above power law equation to the recorded hole size distributions for every type of equipment. It turned out that a better fit was achieved if the slope parameter was expressed as a function of the hole size d as follows:

$$m = a \cdot \log(d) + b \tag{2}$$

Where a and b are constants (normally negative). This function has the ability to reduce the slope parameter for large hole sizes as often seen in the recorded hole size distributions in HCRD. Figure 2.2 illustrates this for centrifugal compressor. Note that a constant slope parameter, is achieved by setting a=0. Thus, curve fitting the power law with $m = a \cdot \log(d) + b$, will give better fit to the data than if m is assumed constant, if a $\neq$ 0.

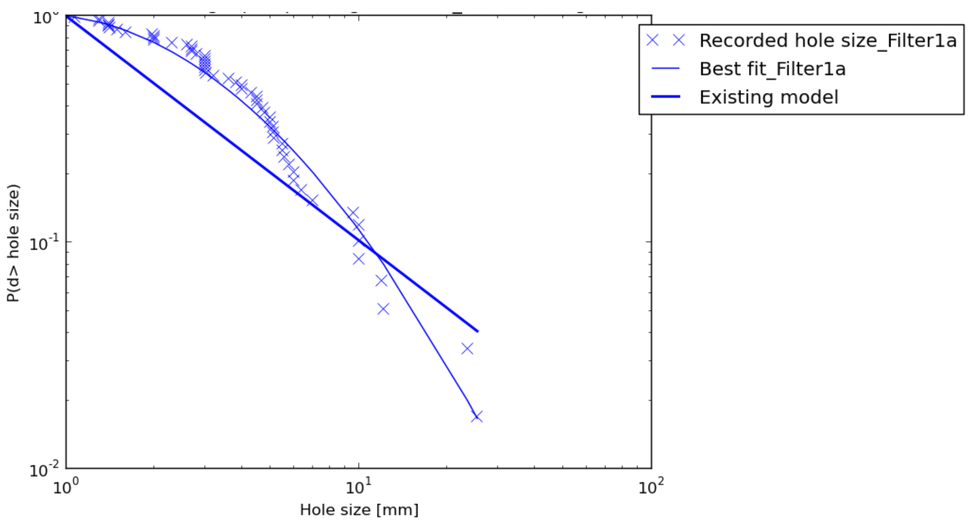


Figure 2.2 - Curve fitting to recorded HCRD hole size distribution for centrifugal compressor. A better fit is achieved using equation (2) for the slope parameter, m (thin blue curve), than by assuming a constant slope parameter (thick blue curve), m. Existing model refers to the SHLFM, Ref. /2/

3 Equipment size dependent hole size distributions

In this chapter an equipment size dependent model is described where the frequency for hole sizes d larger than the equipment dimension D is zero, both the total leak frequency $F_0(D)$ and the rupture frequency $F_D(D)$ are modelled as function of the equipment diameter D, while the slope parameter $m\ (D)$ follows from the assumption that the accumulated frequency hole size distribution follows a power law for $1 < d \leq D$, and is also a function of D. The mathematical formulation is given in the following equations (parameters are described in Table 3.1), while a further description and the rationale for the model is described in Chapter 3.1.

$$F(d,D) = \begin{cases} F_0(D) \cdot d^{m(D)} & ,1 < d \leq D \\ 0 & , d > D \end{cases} \tag{3}$$

$$F_0(D) = F(d=1,D) = F_{hist} \cdot \varphi(D) = F_{hist} \cdot (A_0 \cdot D^{M_0}) \tag{4}$$

$$F_D(D) = F(d=D,D) = F_0(D) \cdot \theta(D) = F_0(D) \cdot (A_D \cdot D^{M_D} + B_D) \tag{5}$$

$$m\ (D) = \frac{\log(\frac{F_D}{F_0})}{log(D)} = \frac{\log(A_D \cdot D^{M_D} + B_D)}{\log(D)} \tag{6}$$

Both the total frequency F_0, and the full bore hole frequency, F_D, is in general assumed to be dependent on the equipment diameter D, and are described in equation (2) and (3) above. The parameter F_{hist} gives the average leak frequency (independent of equipment diameter) for the relevant equipment type and can be estimated based on historical leak data. Thus it is required that

$$F_{hist} = \sum_D F_0(D) \cdot x_D = \quad F_{hist} \cdot \sum_D \varphi(D) \cdot x_D \tag{7}$$

where the parameter x_D is the fraction of the relevant equipment type with size D, and could be estimated based on available population data. This gives the following constraint for the parameters A_0 and M_0:

$$1 = \sum_D \varphi(D) \cdot x_D = \sum_D x_D \cdot (A_0 \cdot D^{M_0}) \tag{8}$$

The parameter $\varphi(D)$ gives the adjustment factor of the leak frequency for the relevant equipment diameter relative to the weighted average leak frequency F_{hist}.

$\theta(D) = \frac{F_D(D)}{F_0(D)}$, gives the fraction of the full bore hole frequency for the relevant equipment diameter to the total leak frequency for the relevant equipment diameter. By defining the equipment size dependencies as described above gives the flexibility to estimate $F_0(D)$ and $F_D\ (D)$ as a constant (A = 0), a linear relationship (M =1) and a power law relationship (B = 0) and is therefore a general formulation that is able to reproduce trends seen in the data material.

Table 3.1 - Summary of all parameters used for each equipment type in the model. Note that not all parameters are included in the above equations. Some are introduced later in the technical note

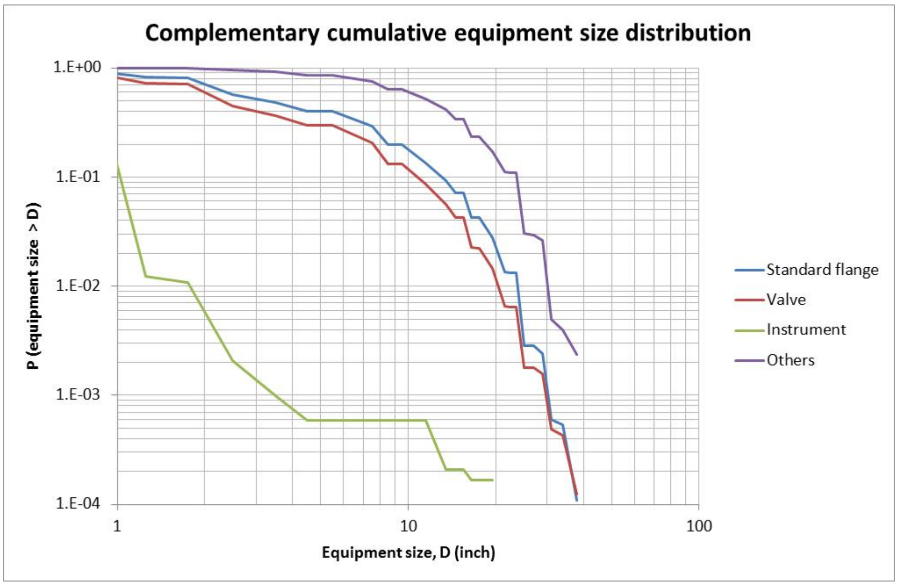
Parameter	Description
$F(d,D)$	Hole size frequency distribution (see TN-1) [year-1 equipment-1].
F_0	Total leak frequency [year-1 equipment-1]. $\mathrm{F_0 = F(d = 1)}$.
F_D	The total full bore hole frequency [year-1 equipment-1] $\mathrm{F_D = F(d = D)}$.
d	Hole size diameter [mm]
D	Equipment diameter [mm]
m	Slope parameter [-]
F_{hist}	The average leak frequency for all leaks from hole sizes > 1mm (independent of equipment diameter) for the relevant equipment type [year^{-1} equipment^{-1}]
A_0	Parameter in equation for total hole frequency
M_0	Parameter in equation for total hole frequency
A_D	Parameter in equation for full bore hole frequency
M_D	Parameter in equation for full bore hole frequency
B_D	Parameter in equation for full bore hole frequency
x_D	The fraction of the relevant equipment type with size D
$\varphi(D)$	Adjustment factor of the total leak frequency relative to the weighted average leak frequency F_{hist}
$\theta(D)$	Full bore hole fraction

3.1 Model description and rationale for the model

In order to develop an equipment size dependent model, one will have to require the following:

1. $F(d = 1) = F_0$
2. $F(d = D) = F_D$
3. $F(d > D) = 0$

Where F_D is the full bore hole frequency. The frequency values for d < D, will be decided by the assumed mathematical function representing the hole size distribution. As described above, the curve fitting to recorded hole size distributions has shown that a better fit is achieved if the slope parameter m, is expressed as a function of the hole size d, as described in equation (2). This can be explained by the fact that the weighted sum of a range of power law hole size distributions will fit to a power law with decreasing slope parameter with increasing hole sizes d (as described in equation (2)), as illustrated in Figure 3.1 . The upper figure gives the complementary cumulative equipment size distribution taken from NCS. Assuming that the hole size probability distribution from equipment of the same dimension follows a power law, given by $F(d)/F_0$, and putting the equipment size distribution for valve as basis for the range of power law functions in the lower figure, results in the sum given by the light green curve in the lower figure (it is also assumed that the rupture fraction follows the equation (3) , with A_D=2.65, M_D=-1,25 and B_D=6.6E-4, which are the parameters for valves, given in the first version of PLOFAM, Ref. /1/). The black dotted line is a power law with a d-dependent slope parameter, m as described in equation (2) (a=-0.5, b=-0.4). This illustrates the point that the sum of power law functions will not be a power law if the equipment size distribution is as given in the upper figure. In that case a power law with d-dependent slope parameter will fit the sum better.



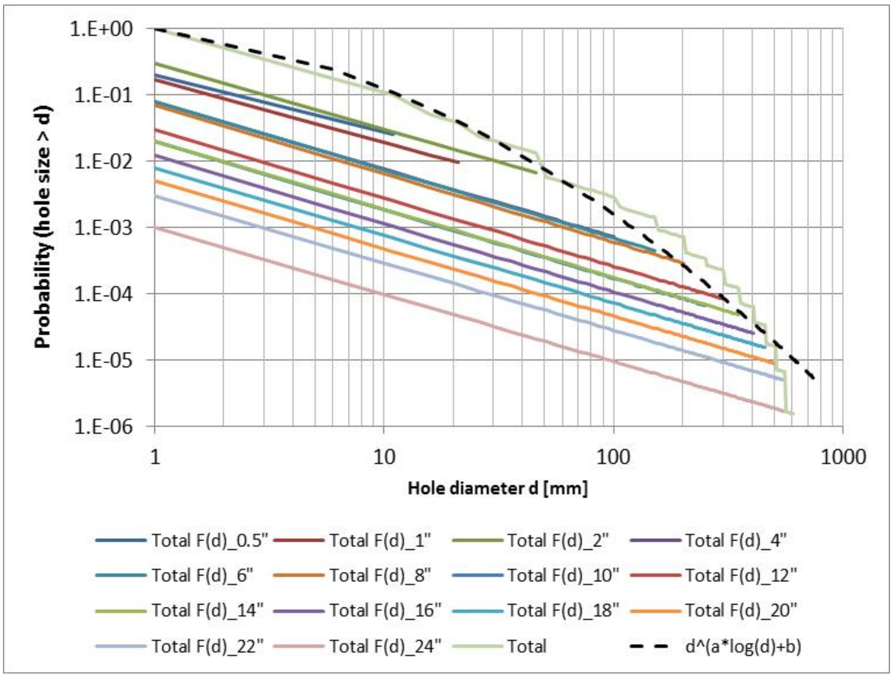


Figure 3.1 - above: The complementary cumulative equipment size distribution at NCS for standard flange, valve and instrument. The distribution for valve is put as basis for the bottom figure. Below: Each power law curve, is the weighted probability hole size distribution for a specific equipment size. The probability hole size distribution is given by $F(d)/F_0$. The light green curve is the sum of all power law curves. The weighted sum of power laws (light green curve) can be fitted using the hole size dependent slope parameter given in equation (7). The black dotted line is achieved by setting a=-0.5 and b=-0.4

There may be explanations why the mathematical function describing the equipment size dependent hole size distribution should also have d-dependent slope parameters. This would for instance be the case if each failure mode is associated with a unique power law, and the total hole size distribution is a weighted sum of contributions from different failure modes. However, documentation of this, requires detailed documentation, and in order to keep the model as simple as possible, it is assumed that the hole size frequency distribution follows a power law in the range d < D.

It follows from initial condition 1 and 2 above that the slope parameter m is given by the following expression:

$$m = \frac{\log(F_D) - \log(F_0)}{log(D)} = \frac{\log(\frac{F_D}{F_0})}{log(D)} \tag{9}$$

This is also illustrated in Figure 3.2. The complementary cumulative probability distributions, given by $F(d)/F_0$, and underlying probability density distributions are illustrated in Figure 3.3 for a range of equipment sizes. The latter distribution is important as it is easier to relate actual physical properties of the holes to the distribution, which in particular is useful for the analysis presented in Appendix B. It gives the probability of holes within a hole size range Δd. In the below figure Δd is 1 mm. This results in a spike with a value corresponding to the full bore hole frequency F_D. Note however that the probability density function value for d=D, $p(d = D)$, depends on the size of Δd. If $\Delta d \rightarrow 0$, $p(d = D) \rightarrow \infty$.

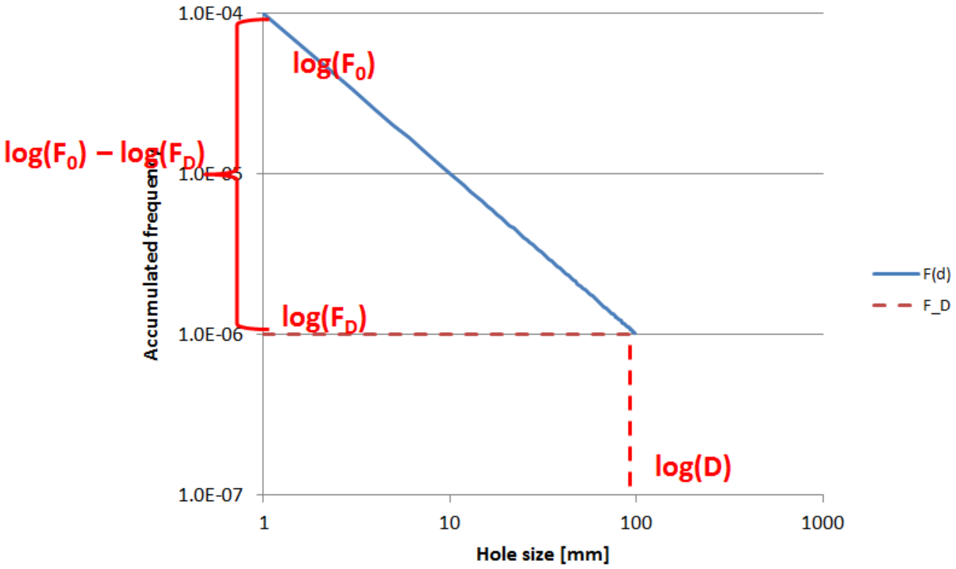
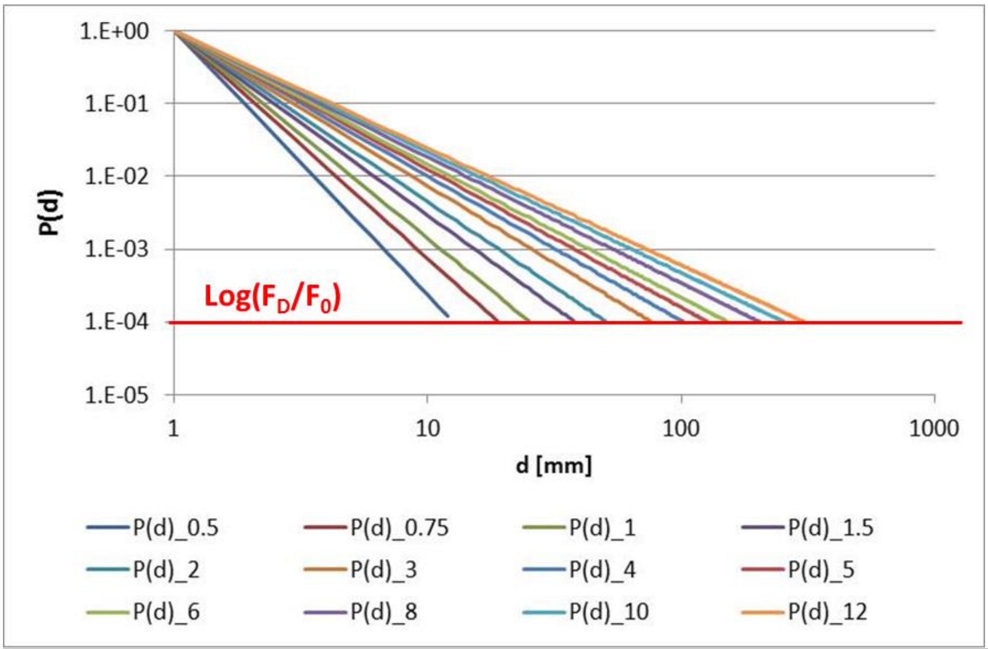


Figure 3.2 - Illustration of the slope parameter, m for a 4 inch equipment



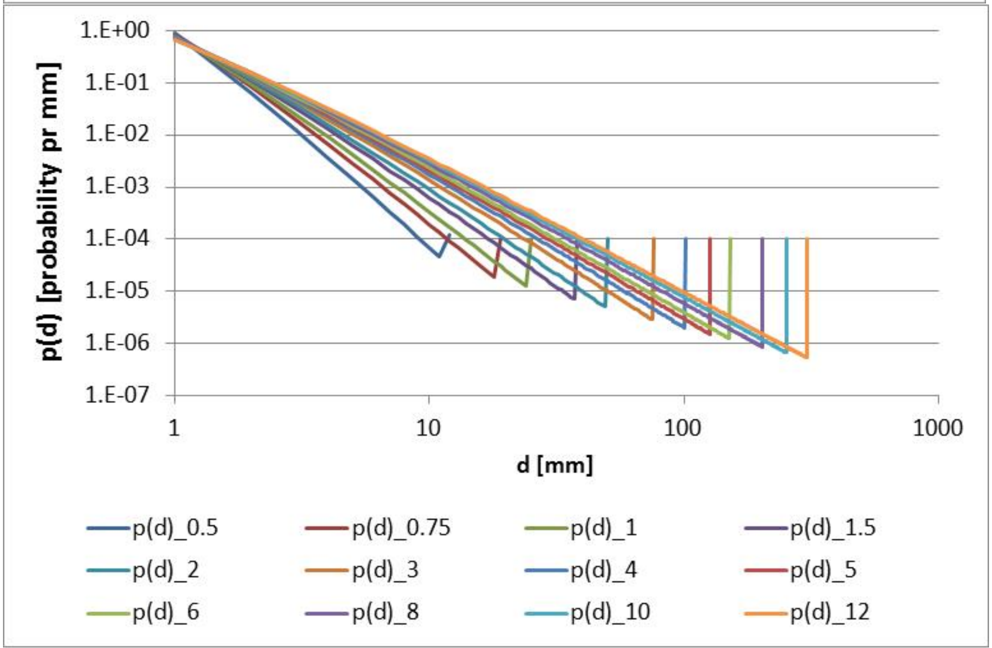


Figure 3.3 - Above: Illustration of the hole size probability distribution, given by $F(d)/F_0$, for a range of equipment diameters (the legend gives the dimension in inches). Below: The underlying hole size probability density distribution

3.2 Model summary and complexity of the model

Ultimately the hole size frequency distribution deduced by the model, is given by the 6 parameters F_{hist}, A_0, M_0, A_D, M_D and B_D. It may seem like this gives a high degree of freedom for the model, and an unnecessary high model complexity. This chapter is prepared to explain the parameters, and why they are necessary to capture the most important effects relevant for the model. Furthermore, this chapter compares the above set of parameters to the set of parameters established in SHLFM, Ref /2/, C, a, n, m and F_{rup}, and relates the parameters to the explicit and implicit model assumptions.

The model is 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. Note however that the constraint given by Equation (8), reduces the number of degrees of freedom. Note also that in the parametrization of the model (see TN-6) the parameter F_{hist} has to be adjusted to fit historical data if available. Even if there is flexibility with regard to relative contribution from the different components, the degree of freedom is highly restricted by the constraint given by historical data (see TN-6)
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 frequency of hole sizes d in the interval 1 mm < d< D. The model here assumes that the hole size frequency distribution follows a power law, that "starts" at $F(d = 1) = F_0$ and "ends" at $F(d = D) = F_D$.

Modelling of the steps 1-3 is regarded as a minimum to capture the most important effects of the model. Table 4.2 gives a summary of involved model parameters necessary to model the different parts of the model given above, both in PLOFAM and in SHLFM. Constraints reducing the complexity and underlying assumptions are also given. The table shows that modelling of F_0 requires three parameters in PLOFAM where a constraint reduces the number of degrees of freedom to two. In SHLFM the corresponding number of parameters is 4. To model F_D, PLOFAM requires 6 parameters (taking the constraint into account this is reduced to 5), while SHLFM requires 5 parameters. In both cases all model parameters are needed to model F_D. The increased complexity in PLOFAM (compared to SHLFM) is necessary to be able to model the full bore hole frequency properly. Note that in SHLFM only one extra parameter is used to model $F_D$as compared to F_0, while PLOFAM adds 3 parameters, which is necessary to improve the modelling of large hole sizes, which is one of the main reasons for updating the model. The slope parameter given by PLOFAM is apparently complex, but this relation follows from the assumption of a power law relation for leak frequency from hole sizes smaller than the equipment diameter (d< D). No new parameters are introduced. In SHLFM the slope parameter is assumed to be constant, which has implicit implications for modelling of F_D, as described in Table 4.2.

Table 3.2 - The table gives a summary of involved model parameters necessary to model the different parts of the model given above. Constraints reducing the complexity and explicit and implicit assumptions are also given

Part of model	Model parameters in new PLOFAM	Model parameters in SHLFM
F_0	Involved parameters: F_{hist}, A_0 and M_0 Assumption: $F_0 = F_{hist} \cdot (A_0 \cdot D^{M_0})$ Constraint: $1 = \sum_D x_D \cdot (A_0 \cdot D^{M_0})$.	Involved parameters:C, a, n and F_{rup} Assumption: $F_0 = C(1 + aD^n)+F_{rup}$
F_D	Involved parameters: F_{hist}, A_0, M_0, A_D, M_D, B_D. Constraint: Same as for F_0 Assumption: $F_D = F_0(D) \cdot (A_D \cdot D^{M_D} + B_D) = F_{hist} \cdot (A_0 \cdot D^{M_0}) \cdot (A_D \cdot D^{M_D} + B_D)$	Involved parameters: C, a, n, m and F_{rup} Assumption: m= const The assumption that the slope parameter m is constant (independent of equipment size D)leads to the following implicit assumption in SHLFM for F_D: $F_D = C(1 + aD^n)D^m + F_{rup}$
m	Involved parameters: A_D, M_D and B_D. Assumption: $(d = 1) = F_0$, $F(d = D) = F_D$.	Involved parameters: m Assumption: m= const

Part of model	Model parameters in new PLOFAM	Model parameters in SHLFM
	The slope parameter follows from the assumption of power law relation for the hole size frequency distribution: $$m\,(D) = \frac{\log\left(\frac{F_D}{F_0}\right)}{\log(D)} = \frac{\log(A_D \cdot D^{M_D} + B_D)}{\log(D)}$$	
F_1 (denoted F_{rup} in SHLFM) :	Not included in new model (see Appendix B for model alternative including F_1)	Involved parameters: $F_1 = F_{rup}$ Assumption: $F_1 = F_{rup} = const$

The reason for the increased number of parameters in PLOFAM (compared to SHLFM) is the improved modelling of full bore hole releases. This is regarded as necessary to improve modelling of such releases, which is one of the most important features of the model.

4 Equipment size dependent hole size distributions with reduced probability for large hole sizes

During the model development it was argued that there should be a very small probability of occurrence of a hole that is slightly smaller than the equipment diameter. Therefore a model where this effect was taken into account was established. Readers familiar with SHLFM, Ref /2/, will notice that the model documented in this appendix, has similar mathematical form as SHLFM, where a constant (F_{rup}) was included. The main difference is however how the rupture fraction is modelled.

The most general formulation of the mathematical equations for the accumulated frequency hole size distribution model presented in this chapter is

$$F(d,D) = \begin{cases} [F_0(D) - \alpha \cdot F_D(D)] \cdot d^{m(D)} + \alpha \cdot F_D(D) & , \ d \leq D \\ 0 & , \ d > D \end{cases} \tag{10}$$

$$F_0(D) = F(d=1) = F_{hist} \cdot \varphi(D) = F_{hist} \cdot (A_0 \cdot D^{M_0}) \tag{11}$$

$$F_D(D) = F(d=D) = F_0(D) \cdot \theta(D) = F_0(D) \cdot (A_D \cdot D^{M_D} + B_D) \tag{12}$$

$$m\,(D) = \frac{\log(\frac{F_D - F_1}{F_0 - F_1})}{log(D)} \tag{13}$$

where most parameters in the equations are described in Table 3.2, while the added model parameters are presented in and Table 4.1.

Note that the above formulation is the general formulation for all equipment types. For several equipment types, many of the parameters could be set to 0 or 1, resulting in a simpler formulation for that particular equipment type.

Table 4.1 - Summary of all parameters used in the model. Note that not all parameters are included in the above equations, but are them introduced later in the technical note

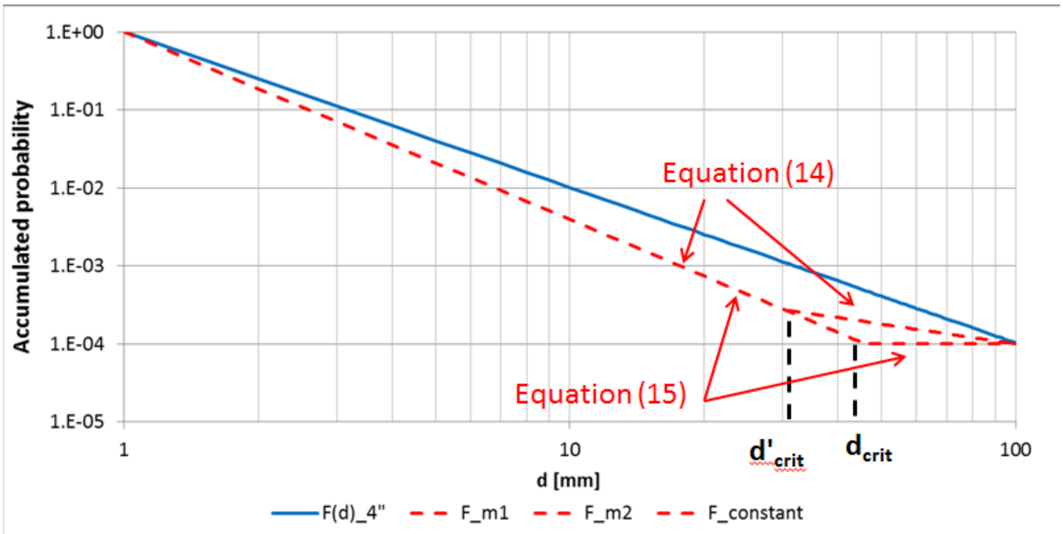
Parameter	Description
F_1	Additional full bore hole frequency [year^{-1} equipment^{-1}]
α	$\alpha = \frac{F_1}{F_D}$

4.1 Model description and rationale for the model

It can be argued that, given a leak, there should be a very small probability of occurrence of a hole that is slightly smaller than the equipment diameter. Thus the power law dependency should be valid only up to some critical hole size d_{crit}. In the region $d_{crit} < d < D$ the probability should be very small. It could potentially be zero and the probability density could both be decreasing and constant with increasing d. For $d = D$ the probability should correspond to the full bore hole probability, resulting in a spike in the probability density distribution for d=D. This is illustrated in Figure 4.1, where the following two functions are plotted to illustrate the concept:

$$F(d, D) = \begin{cases} F_{m_1} = d^{m_1}, & , \ d \leq d'_{crit} \\ F_{m_2} = d^{m_2}, & d'_{crit} < d \leq D \\ 0 & , \ d > D \end{cases} \tag{14}$$

$$F(d, D) = \begin{cases} F_{m_1} = d^{m_1}, & d \leq d_{crit} \\ F_{constant} = Constant & d_{crit} < d \leq D \\ 0 & d > D \end{cases} \tag{15}$$



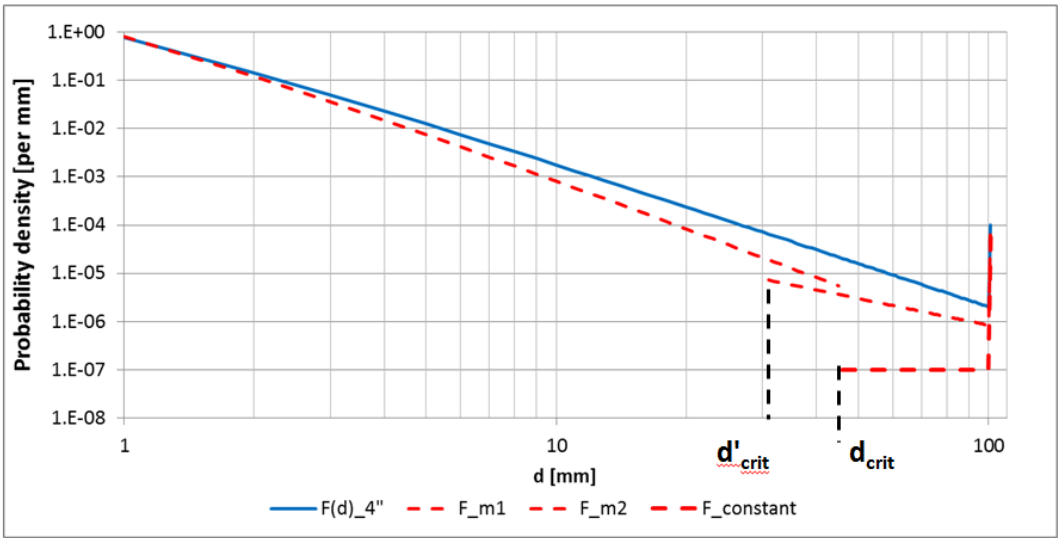


Figure 4.1 - Illustration of how the actual accumulated probability hole size distribution (above) and the probability density hole size distribution (below) might look like. The blue curve is a standard power law for a 4” equipment, while the red curves illustrate the two concepts described in equation (14) and (15) above. F_m1, F_m2 and F_constant have identical line colour as they belong to the same model.

To determine the exact hole size distributions and the parameter d_{crit} would require detailed analysis together with specialists on every single equipment included in the model, and exceeds the possible detail level in this project. However, a pragmatic solution to the challenge, that has the ability to capture the described effects, would be to include an additional full bore hole frequency F_1 in the frequency equation.

$$F(d) = (F_0 - F_1) \cdot d^m + F_1 \tag{16}$$

In order to keep F_0 as the total leak frequency for the relevant equipment type, F_1 must be subtracted from the first factor in the equation. This function is shown in Figure 4.2, together with the other possible model suggestions illustrated in Figure 4.1. The light green curve (F_1) and the dark green curve ($(F_0 - F_1) \cdot d^m$) are also plotted and add up to the total frequency function $F(d)$.

This solution has the advantage that it gives a continuous differentiable frequency function (except at $d = D$, where it is already discontinuous), and that it gives the same mathematical form as applied in the existing model, Ref /2/. Hence, it is familiar to the industry. It should be noted that neither of the suggested models represent the correct hole size distribution, but equation (16), has the capability to capture effects of the hole size distributions that have been argued for in the project. The suggested model is assessed as the simplest possible model that incorporates the effect of reduced probability of large hole sizes (relative to the standard power law).

It follows that the slope parameter m, can be expressed as

$$m\ (D) = \frac{\log(F_D - F_1) - \log(F_0 - F_1)}{\log(D)} = \frac{\log(\frac{F_D - F_1}{F_0 - F_1})}{log(D)} = \frac{\log(\frac{F_D - \alpha \cdot F_D}{F_0 - \alpha \cdot F_D})}{log(D)} \tag{17}$$

The parameter F_1 is expressed as a function of F_D as follows:

$$F_1(D) = \alpha \cdot F_D(D) \qquad , \alpha \in [0,1\rangle \tag{18}$$

where the parameter $\alpha = \frac{F_1}{F_D} = constant$ is thus the ratio between the added full bore hole frequency and the total full bore hole frequency $F_D(D) = F(d = D)$. $\alpha > 0$ will give a curved line, while $\alpha = 0$ will give a normal power law.

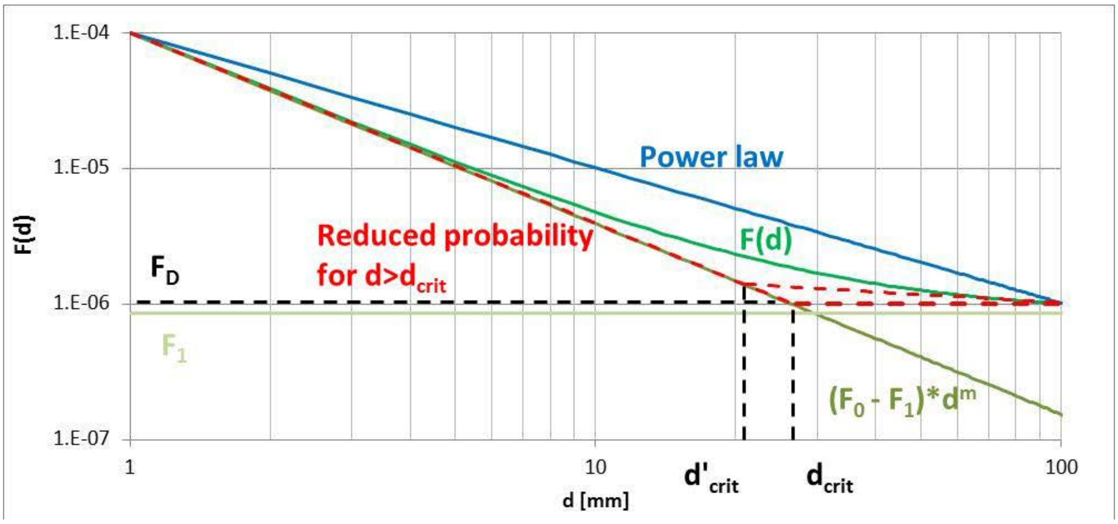


Figure 4.2 - Illustration of the suggested mathematical model F(d) (green curves) together with other suggested models: Standard power law (blue curve) and a model where the probability of hole sizes close to the equipment diameter is lowered compared to the standard power law (red curve). Two different models for high hole sizes are illustrated: One second power law for $d'_{crit} < d < D$ and one solution with constant probability for $d_{crit} < d < D$. In this illustration F_0=1e-4 per year per equipment, and F_D= 1e-6 per year per equipment, while $\alpha = \frac{F_1}{F_D}$ = 0.85

4.2 Implicit assumptions in the model

This chapter describes the implicit assumptions in the model with respect to the parameter d_{crit} defined in Chapter 4.1. This is presented as it is important to have an overview of the underlying assumptions and behaviour of the model. In particular it is important to know how the model relates to physical properties that are possible to make qualified assessment of, such as d_{crit}.

As described in Chapter 4.1, the mathematical model has the capability to capture the effect that hole sizes close to the equipment diameter in the range $d_{crit} < d < D$ is expected to be even lower than estimated by the normal power law (the normal power law is achieved by setting $\alpha = 0$. By increasing α, m is reduced). The parameter d_{crit} can in the concluded model be defined as the hole size where the hole size dependent part of the equation equals the full bore hole frequency F_D(this is in accordance with the definition in Chapter 4.1 if $F_{constant}$=0):

$$(F_0 - F_1) \cdot d_{crit}^m = F(D) = (F_0 - F_1) \cdot D^m + F_1 \qquad (19)$$

It follows that d_{crit} can be expressed as follows:

$$d_{crit} = \left[D^m + \frac{\alpha \cdot F_D}{F_0 - \alpha \cdot F_D}\right]^{\frac{1}{m}} \qquad (20)$$

Figure 4.3 shows how d_{crit} varies with equipment diameter, D for different values of α, and thus the implicit assumption regarding d_{crit} when α is kept constant (independent of D). Furthermore the parameter β may be defined as the fraction $\frac{d_{crit}}{D}$:

$$\beta = \frac{d_{crit}}{D} = \left[1 + \frac{\alpha \cdot F_D}{D^m \cdot (F_0 - \alpha \cdot F_D)}\right]^{\frac{1}{m}} \qquad (21)$$

Figure 4.4 shows how β varies with equipment diameter, D for different values of α, and thus the implicit assumption in the model regarding β when α is kept constant. The figure shows that for low values of α, the fraction $\frac{d_{crit}}{D}$ is close to constant. For higher values of α, the fraction decreases with increasing equipment diameter, D. The exact expected behaviour is difficult to state, but it seems reasonable that β decreases with increasing D. Based on this assessment it is concluded that keeping α constant gives a model that is in line with the projects understanding and assessments of how hole sizes develop in equipment of different dimensions.

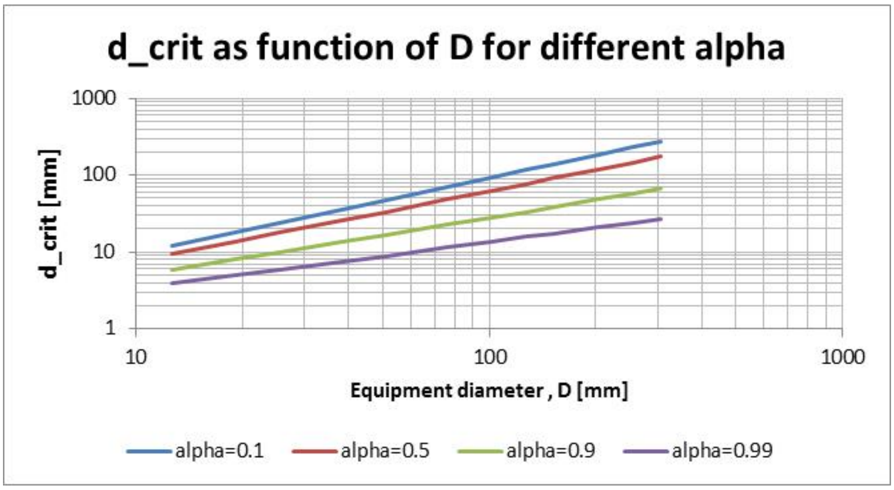


Figure 4.3 - d_{crit} as function of equipment diameter, D for different values of α

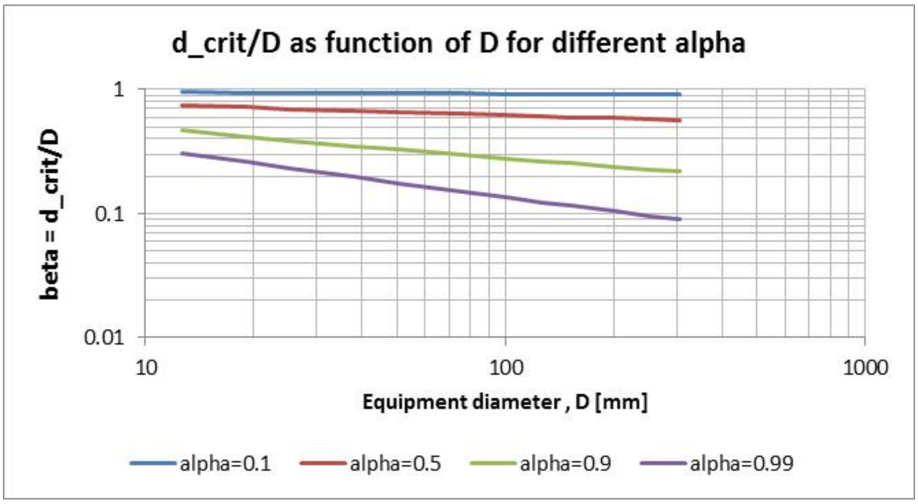


Figure 4.4 - $\beta = \frac{d_{crit}}{D}$ as function of equipment diameter, D, for different values of

4.3 Model summary and complexity of the model

Chapter 3.2 presents a summary of involved model parameters necessary to model the different parts of the model (in the Chapter "*Model summary and complexity of the model*"), both for PLOFAM and for SHLFM. This chapter gives explanations of the added model parameter α (added in the model described in this chapter) and model parameters influenced by α. Including the α parameter, the model is described by the 7 parameters F_{hist}, A_0, M_0, A_D, M_D, B_D and α. The parameters established in SHLFM, Ref. /2 /, are C, a, n, m and F_{rup}.

The model is built up of 4 parts, where parts 1-3 are described in Chapter 3.2. The additional model part introduced in the model described in this chapter is:

4. To capture the effect that hole sizes close to the equipment diameter in the range $d_{crit} < d < D$ is expected to be even lower than estimated by the normal power law, the parameter $F_1$is introduced (see Chapter 4.1), which relates to $F_D$through the parameter α (α assumed constant. The effect of a constant α is analysed in Chapter 4.2).

Modelling of the steps 1-3 (see chapter 3.2) are regarded as a minimum to capture the most important effects of the model, while step 4 adds flexibility to improved modelling of failure modes with small probability of resulting in hole sizes close to the equipment diameter. One example of this is flanges where the gasket is broken (or a fraction of it). The hole size will then be decided by the thickness of the gasket and the fraction of it that is blown away. The ratio d/D is given in Figure 4.5. The curves could be compared with Figure 4.4, giving good reasons for arguing for a high alpha value for flanges with gaskets. Table 4.2 gives a summary of involved model parameters necessary to describe the different parts of the model given above both for PLOFAM and for SHLFM.

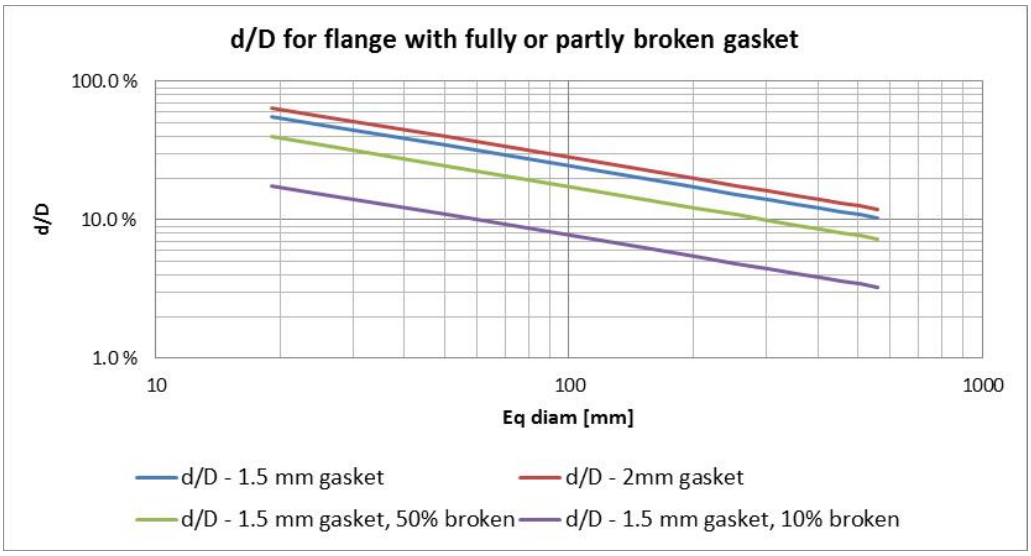


Figure 4.5 – d/D for flanges with fully or partly broken gasket. The curves could be compared with Figure 4.4, giving good reasons for arguing for a high alpha value for flanges with gaskets

The slope parameter in PLOFAM is apparently complex, and introducing the parameter α makes it even more complex, but this relation given for the slope parameter follows from the assumption of a power law relation for leak frequency from hole sizes 1 mm < d< D. No new parameters are introduced. In SHLFM the slope parameter is assumed to be constant (independent of equipment size D), which has implicit implications for modelling of F_D, as described in Table 4.2. Finally, introducing the parameter F_1, requires one extra parameter (α) to be defined in PLOFAM, while SHLFM apparently does not need new parameters to be defined, as F_{rup} is already defined as a part of F_0. This is however related to the way F_0 is defined in the two models. Obviously the parameter F_{rup} in SHLFM has the same effect as the parameter α in PLOFAM. One can argue that F_{rup} is not really necessary to model F_0 and F_D in SHLFM, and that F_{rup}, being part of F_0 and F_D (in the table below) in SHLFM, is related to the definition of F_0 and F_D in PLOFAM. In that case the parameters necessary to model F_0 and F_D in SHLFM should be reduced by one, and the number of parameters necessary to model F_1 would then be one (F_{rup}).

Table 4.2 - The table gives a summary of involved model parameters necessary to model the different parts of the model given above. Constraints reducing the complexity and explicit and implicit assumptions are also given

Part of model	Model parameters in PLOFAM	Model parameters in SHLFM
F_0	See Table 3.2	See Table 3.2
F_D	See Table 3.2	See Table 3.2
m	Involved parameters: A_D, M_D, B_D and α. Assumption: $(d = 1) = F_0$, $F(d = D) = F_D$. The slope parameter follows from the assumption of power law relation for the accumulated leak frequency distribution: $$m\,(D) = \frac{\log\left(\frac{F_D - F_1}{F_0 - F_1}\right)}{\log(D)} =$$	Involved parameters: m Assumption: m= const

Part of model	Model parameters in PLOFAM	Model parameters in SHLFM
	$\dfrac{\log\left(\dfrac{(A_D \cdot D^{M_D} + B_D)(1-\alpha)}{1-\alpha \cdot (A_D \cdot D^{M_D} + B_D)}\right)}{\log(D)}$ Note that setting α =0 simplifies the expression.	
F_1 (denoted F_{rup} in SHLFM) :	Involved parameters: F_{hist}, A_0, M_0, A_D, M_D, B_D and α. Constraint: Same as for F_0 Assumption: $F_1(D) = \alpha \cdot F_D(D) \quad , \alpha \in [0,1\rangle$ $\alpha = const$ The assumption that α is constant (independent of equipment size D) leads to the following implicit assumption in PLOFAM for F_1: $F_1(D) = \alpha \cdot [F_0(D) \cdot (A_D \cdot D^{M_D} + B_D)] =$ $\alpha \cdot [F_{hist} \cdot (A_0 \cdot D^{M_0}) \cdot (A_D \cdot D^{M_D} + B_D)]$	Involved parameters: $F_1 = F_{rup}$ Assumption: $F_1 = F_{rup} = const$ The assumption that F_{rup} is constant (independent of equipment size D) leads to the following implicit assumption in SHLFM for α : $\alpha(D) = \dfrac{F_1}{F_D} = \dfrac{F_{rup}}{C(a + aD^n)D^m + F_{rup}}$

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

Appendix B

Guideline for use of PLOFAM in QRAs

Table of contents

Page

1 Introduction

This Appendix gives guidelines for use of the model in QRAs. This includes first of all guidelines for equipment counting on P&ID's for leak frequency estimation using PLOFAM. Secondly guidance for initial leak rate estimation based on inventory properties and hole size is given.

2 Equipment counts used as basis for leak frequency estimation

P&IDs (Process and Instrument Drawings) are normally used as basis for the counting of components. Normally, a P&ID Legend is available for correct interpretation of the symbols used on the drawings. P&IDs do in many cases not display all actual leak sources within a system, but is in general accepted as the basis for equipment counts in QRAs. In particular flanges associated with valves, but also elsewhere in the process tend not to be included in P&IDs.

If more detailed information is needed, one can also count from ISO-drawings or even from CAD-models. In some cases, lists of components can be generated from other systems holding information about equipment. Be however aware that ISO-drawings and CAD-models not necessarily indicates whether a valve is normally closed or normally open.

For calculation of leak frequencies for use in risk analysis, all leak sources in the process system that are in connection with process fluid, full time or part time (see also further details below), should be identified and counted, as well as the number of well heads. Note that leak points in the utility system (drain system, chemical injection, produced water, flare system (see also Chapter 3.2.3)) should not be counted, and that fuel gas system is defined as a part of the process system. For system boundaries it is referred to TN-4. The following valves are suggested to define the border between the process system and neighbouring systems:

- Between process system and flare system: Blow down valves (BDV), pressure safety valves (PZV) and any other normally closed valves between the two systems
- Between process system and well system: Process wing valve (PWV) and annulus wing valve (AWV)
- Between process system and risers/storage tank: ESV between the two systems
- Between process system and closed drain system: Any normally closed valves between the two systems
- Between process system and chemical injection: Any normally closed valves (including check valve) and/or PSV/ESV between the two systems
- Between process system and produced water: Any normally closed valves and/or PSV/ESV between the two systems
- Between process system and turbine: ESV between fuel gas system (fuel gas system defined as part of the process system) and turbine

An important factor influencing whether the equipment counts should be adjusted for time in operation (i.e. if an equipment pressurized part of the time should be counted equally as an equipment continuously pressurized) is whether this has been done when establishing the equipment counts in the population data base used for parametrization of the model (see TN-2 and TN-6). The equipment counts in the population data base is a collection of equipment counts established in QRAs performed by four consultancy companies. There has previously not been any common guideline for adjustment due to reduced time in operation, and most likely the population database consists of equipment counts where adjustments are not consistently implemented. At some installations the equipment counts are adjusted, while others are not. All four companies confirm that different practice may have been applied in different projects, and also different practice among the companies has been identified. It is also most likely differences in how adjustments are performed. Hence there is an associated uncertainty in the population data base related to how adjustment for time in operation is implemented. The effect on the total leak frequency for installations is however expected to be small. Approaching this uncertainty from the conservative side would imply that one should not adjust for time in operation, as this would rather overestimate than underestimate the leak frequency. This is also in line with the fact that leaks often occur in connection with maintenance, modification or start up/shut down (e.g. latent failure modes such as a valve normally closed left in open position), and the actual operational time will not be important for the occurrence of such leaks. This implies that parallel systems where only one part is in operation at a time (installed for improved regularity), both should be counted. For instance if two heat exchangers with associated flanges, valves and instruments are installed in parallel, all equipment should be counted on both lines. Note that it may be argued for other guidelines, but most guidelines will have consequences that may be claimed to be inconsistent at some level. Note however that PLOFAM is a tool for process leak frequency estimation for use in QRAs, and for this purpose the above described guideline will ensure that the overall frequency estimations in QRAs are performed from the slightly conservative side, and as any guidelines it will ensure consistency in the industry, which is another important aim for the guideline. One downside of the above guideline is however that systems designed for higher regularity with parallel stand-by systems that are normally not in use, will be associated with higher leak frequency than systems where only one line is installed, requiring shut down of the process for maintenance. Arguments presented above points in the direction that this is reasonable, but arguments pointing in other directions do also exist. PLOFAM is however not designed for assessing design alternatives at this detail level, and such assessments should therefore be based on a detailed insight into the background for the guidelines given in PLOFAM, data basis, failure modes and operational procedures. The guideline is developed for a best estimate of the overall leak frequency taking the overall uncertainty in the model into account. Based on the above the following particular guidelines are given

- All process equipment should be counted, regardless of the equipment is in operation part of the time or full time, i.e. no adjustment for reduced time in operation should be introduced. This includes infrequently operated pig segments.
- All parts of parallel systems where only one part is in operation at a time, should be counted. For instance if two heat exchangers/pumps with associated flanges, valves and instruments are installed in parallel, where only one is in used at a time, all equipment should be counted on both lines, also the equipment that is unpressurized (and isolated).

PLOFAM and MISOF, Ref. /1/ are interlinked to ensure a best estimate of fire and explosion frequencies. The immediate ignition probability for pump leaks is significantly higher than the immediate ignition probability for other leaks. Hence overestimating the number of pump leaks due to uncertainty related to how pumps are counted in the population data base relative to the specifications in this guideline, leads to a high impact on the total immediate ignition frequency. If approach suggested by this guideline gives 50% more pumps (upper estimate) the total immediate ignition frequency will increase by up to 40%.

Typical leak sources (equipment types) in a process plant are:

- Compressor (Reciprocating and centrifugal)
- Flange (Standard flange and compact flange)
- Filter
- Heat exchanger (shell/tube side heat exchangers, plate heat exchangers and air cooled heat exchangers)
- Hose
- Instrument
- Pig trap
- Process vessel and atmospheric vessel
- Pump (Reciprocating and centrifugal)
- Steel pipe and flexible pipe (meter piping)
- Valve
- Well heads (Producing well head with gas lift, producing well head without gas lift, gas injection well)

Guidelines for counting of these equipment types are given in the following sub-chapters. It is also referred to leak incident registration rules given in HCR definitions (see TN-3 Appendix A).

Figure 2.1, gives an example of counting on P&ID's that is used as reference in several sub chapters below.

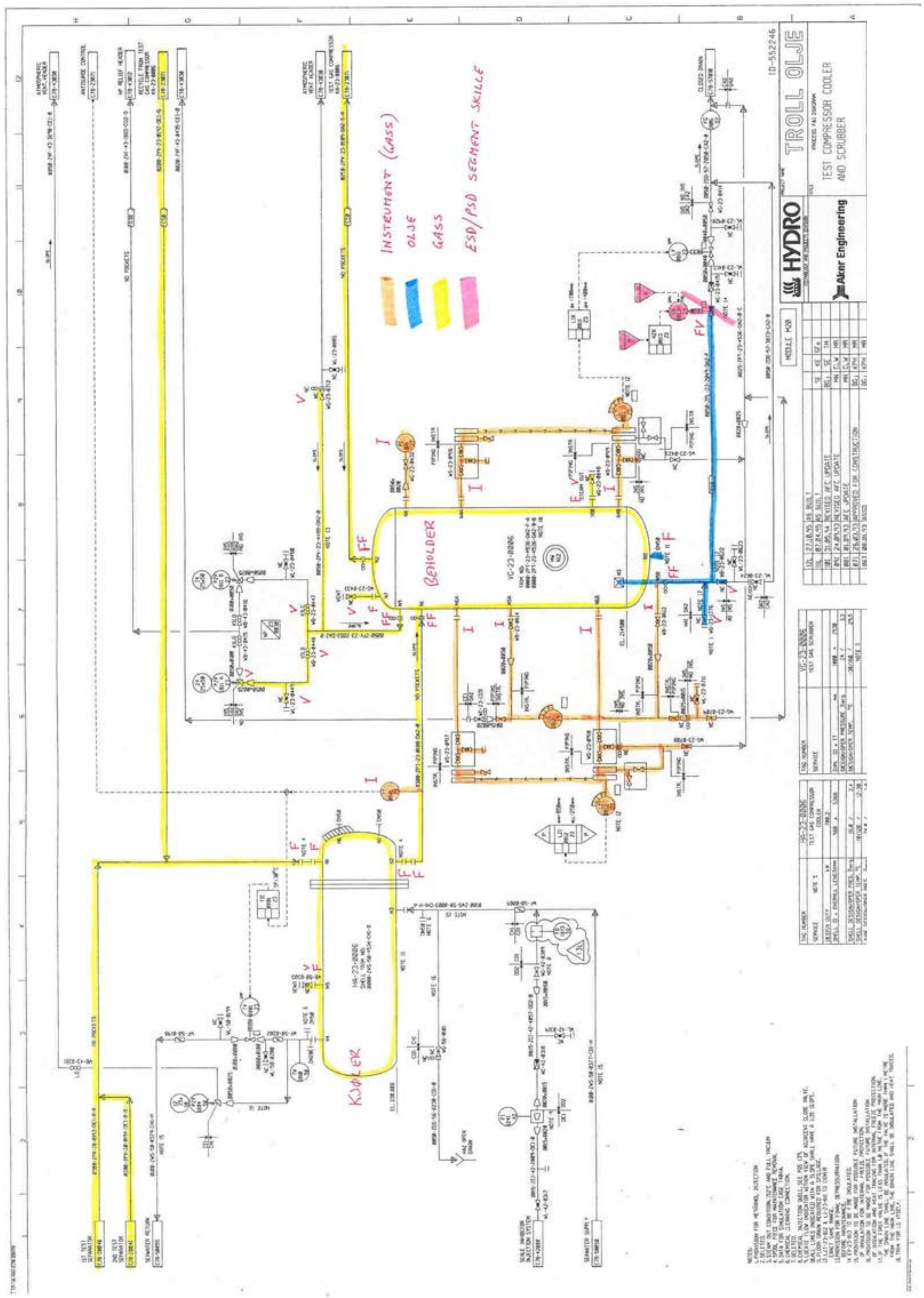


Figure 2.1 - Example of counting on P&ID

2.1 Atmospheric vessel

The same guidelines apply for atmospheric vessels as for process vessels. See Chapter 2.10.

2.2 Compressor

The following counting rules apply:

- It is differentiated between reciprocating and centrifugal compressors in the leak model
- The compressor is defined to have the same dimension as the dimension of the in/outlet piping
- Flanges, valves and instruments connected to a compressor are counted separately as flanges, valves and instruments
- Only the equipment itself should be included in the count, i.e. any valves, piping, flanges, instruments and fittings connected to the vessel should be counted separately
- Each compressor on the P&ID is counted. Also if several compressors are driven by the same shaft, they should all be counted separately (for example if two compressors are driven by the same shaft, they should be counted as two compressors)

Note that the type of compressor is normally not given on the P&ID. This information must then be found from other sources if necessary.

2.3 Flange

The following counting rules apply:

- Two flanges that are connected as one mechanical coupling (flanged joint) are counted as **one** Standard flange or one Compact flange
- One spectacle blind is counted as **two** flanges
- Corrosion coupons are counted as flanges
- An end flange on a pipe is counted as one flange
- Inlets/outlets of a process package (e.g. a metering package, compressor, strainers, etc.) are counted as flanges
- The leak frequencies applied differentiate between a compact flange type (SPO flange) and a standard ANSI or API flange type (standard offshore flange)

Note that flanges are not always marked on P&IDs. This is the case both for flanges associated with valves, but also other flanges. A valve can either be flanged or welded and P&IDs do not always indicate this. Hence, it is important to clarify, whether the valves are flanged or welded. If the valves are flanged, two flanges are normally counted for each valve. If the valve is located on the border between the process system and a neighbouring system, one flange is counted per valve (the flange on the process system side). ISO-drawings could also be used to identify other flanges.

2.4 Filter

Only the equipment itself should be counted. I.e. the equipment should be counted excluding all valves, piping, flanges, instruments and fittings.

2.5 Flexible pipe

To estimate leak frequency from flexible piping, the number of meter of flexible piping in the system in question should be estimated and used as input to the leak frequency model for piping.

2.6 Heat exchanger

The following counting rules apply:

- The model differentiates between four types of heat exchangers:
  - plate exchanger
  - tube side heat exchanger
  - shell side heat exchanger
  - Air cooled heat exchanger
- A heat exchanger is defined to have dimension as the dimension of the inlet/outlets
- Flanges, valves and instruments connected to a heat exchanger are counted separately as flanges, valves and instruments

Note that the type of heat exchanger is normally not given on the P&ID. This information must then be found from other sources if necessary.

2.7 Hose

Hoses are not counted in number of hoses, but in number of operations. Thus they are not counted on P&ID's. Only temporary hoses are counted. Permanently installed hoses are counted as flexible pipe.

Be aware that leaks from hoses constitute around 6% of all leaks at NCS in the period 2001 – 2017 and 5% of the leaks in the period 2006-2017. The number of hose operations varies significantly among installations, due to differences in both design solutions for equipment such as well heads and pig receivers and operational philosophies. This means that for some installations the contribution from hoses will be considerable, while for others it may be negligible. The QRA should therefore base the leak frequency from hoses on quality assured data for the installation in question. This includes number of hose operations, hose dimension and inventory properties (phase, pressure, density).

See also Chapter 3.2.2 for guidance on modelling of releases from hoses in QRAs.

2.8 Instrument

The following counting rules apply:

- All instrument are assumed to have dimension 0.5" (about 12 mm diameter), as most instrument leaks originate from the instrument tubing
- Instruments with two (or more) connection points to the process equipment are counted as two (or more) instruments (e.g. level inductors on vessels). Examples of this are seen in Figure 2.1
- An instrument, including its valves and flanges, is counted as one instrument only. Hence, these valves and flanges should not be counted separately. Examples of this are seen in Figure 2.1
- Flowmeters installed in the flowline and installed with flanges, are not counted as instrument. The flanges in each end of the instrument are counted only

For illustration of instruments couplings see TN-6.

2.9 Pig trap

Each item comprises the item of equipment itself, but excluding all valves, piping, flanges, instruments and fittings beyond the first flange and excluding the first flange itself.

2.10 Process vessel

The following counting rules apply:

- It is not differentiated between types of vessel in the leak statistics
- The vessel should be counted as a vessel with size equal the main inlet/outlet of the vessel
- Flanges, valves and instruments connected to a process vessel are counted separately as flanges, valves and instruments
- Man holes are regarded as part of the vessel and are not counted separately

2.11 Pump

The following counting rules apply:

- It is not differentiated between reciprocating and centrifugal pumps in the leak model
- The pump is defined to have the same dimension as the dimension of the in/outlet of the pump
- Flanges, valves and instruments connected to a pump are counted separately as flanges, valves and instruments
- Only the equipment itself should be included in the count, i.e. any valves, piping, flanges, instruments and fittings connected to the vessel should be counted separately
- Each pump on the P&ID is counted. Also if several pump s are driven by the same shaft, they should all be counted separately (for example if two pump s are driven by the same shaft, they should be counted as two pumps)

2.12 Steel pipe

To estimate leak frequency from process piping, the number of meter of piping in the system in question should be estimated and used as input to the leak frequency model for piping. If the number of meter of piping is not available, the total contribution from piping is recommended set be 12 %. Thus the leak frequency for all other equipment types should be multiplied by a factor $\frac{1}{0.88}$ = 1.14 in order to get the total leak frequency including contribution from piping.

2.13 Valve

The following counting rules apply:

- It is differentiated between ESV's and other valves in the model
- A closed valve and an open valve are both counted as one valve
- For info: P&IDs may label valves as e.g. "LO" (Locked Open), "LC" (Locked Close), "KILO" (key interlock open) or KILC (key interlock closed)
- Any valves between process system and neighbouring systems should be counted as 0.5 valves

2.14 Well

The number of well heads should be counted. Note that other equipment such as flanges, valves and instruments on the well head are <u>not</u> counted separately. The model distinguishes between:

- Producing well head with gas lift
- Producing well head without gas lift
- Gas injection well head

The gas lift is counted separately from the producing well, so that a producing well with gas lift is counted as both a producing well and a gas lift well, whereas a producing well without gas lift is counted as only a producing well. If for example an installation has 15 wells, where 5 have gas lift, this should be counted as 5 gas lift wells and 15 production wells.

Gas injection wells are counted as producing wells.

The dimension of the wells are the flowline diameter from/to the well for producing well and injection wells, while for gas lift it is the dimension of the annulus wing valve.

The barriers between the process system and the well system are described in TN-4.

3 Release modelling

3.1 General formulas for release rate modelling

Equations for calculating initial gas and liquid releases are given in this chapter.

3.1.1 Gas releases

Choked conditions occur as the downstream pressure falls below a critical value P^*. That critical value can be calculated from the dimensionless critical pressure ratio equation:

$$\frac{P^*}{P_0} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

Assuming P^*=1 bara and γ = 1.31 for Methane (see Table 3.2), gives P_0=1.8 bara. Thus gas releases from inventories with over pressure >0.8 barg, which in most cases is the situation for process leaks, should be modelled using the equation for chocked mass flow rate given by the following relationship:

$$Q_g = C_D \cdot A \cdot P_0 \cdot \sqrt{\frac{M \cdot \gamma}{R \cdot T_0} \cdot \left(\frac{2}{(\gamma + 1)}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{2}$$

where the parameters in the equation are given in the table below. Rearranging the above and noting that $\frac{\rho_g}{P_0} = \frac{M}{RT_0}$ gives:

$$Q_g = C_D \cdot \frac{\pi \cdot d'^2}{4} \cdot \sqrt{\gamma \cdot \left(\frac{2}{(\gamma + 1)}\right)^{\frac{\gamma+1}{\gamma-1}}} \cdot P_0 \cdot \sqrt{\frac{\rho_g}{P_0}} \tag{3}$$

The molar mass is not given in the EQCDB. For validation purposes it is assumed that the leaking gas is Methane. Relevant specific heat ratios are given in Table 3.2. Substituting γ = 1.31 for methane, C_D = 0.85, converting the units of pressure to bara and noting that the units of the diameter are in mm we have:

$$Q_g = 0.85 \cdot \frac{\pi}{4} \cdot \sqrt{1.31 \cdot \left(\frac{2}{(1.31 + 1)}\right)^{\frac{1.31+1}{1.31-1}}} \cdot \frac{\sqrt{10^5}}{10^6} \cdot d^2 \cdot \sqrt{\rho_g \cdot (P_g + P_a)} \tag{4}$$

Giving:

$$Q_g = 1.41246 \cdot 10^{-4} \cdot d^2 \cdot \sqrt{\rho_g \cdot (P_g + P_a)} \tag{5}$$

Where d is the hole size [mm], ρ_g is the initial gas density [kg/m³] and P_g is the initial gas pressure [barg] and P_a is the atmospheric pressure.

Note that full pressure gas releases from inventories with over pressure < 0.8 barg should have been modelled using equations for compressible flow. However, in the validation process only the equation for chocked flows is used.

Table 3.1 - Parameters used to calculate gas release rates

Parameter	Description
Q_g	Initial gas release rate [kg/s]
C_D	Discharge coefficient =0.85
A	Hole area [mm²]
d'	Hole diameter [m]
d	Hole diameter [mm]
P_0	Initial gas pressure [Pa]
ρ_g	Initial gas density [kg/m³]
M	Molecular weight of gas [kg/mol]
γ	Specific heat ratio (see Table 3.2)
R	Universal gas constant = 8.314 [J/(K mol)]
T_0	Initial gas temperature [K]
P_g	Initial gas pressure [barg]
P_a	Atmospheric pressure [bara]

Table 3.2 - Specific heat ratio for relevant gases

Gas	Specific heat ratio, γ
Methane	1.307
Propane	1.131
Butane	1.096

3.1.2 Liquid releases

Pure liquid releases are modelled as incompressible fluid flows. Thus the following relationship applies:

$$Q_L = C_D \cdot A \cdot \sqrt{2\rho_L(P_0 - P_a') + 2\rho_L^2 gh} \tag{6}$$

where the parameters in the equation are given in Table 3.3. By neglecting the liquid head, h (see the effect this has in Figure 3.1), substituting C_D = 0.61, converting the units of pressure to bar, noting that the units of the diameter are in mm and replacing the pressure term with the gauge pressure of the liquid, this can be simplified to:

$$Q_L = 0.61 \cdot \frac{\pi}{4} \cdot \sqrt{2} \cdot \frac{\sqrt{10^5}}{10^6} \cdot d^2 \cdot \sqrt{\rho_L \cdot P_L} \tag{7}$$

giving

$$Q_L = 2.14257 \cdot 10^{-4} \cdot d^2 \cdot \sqrt{\rho_L \cdot P_L} \tag{8}$$

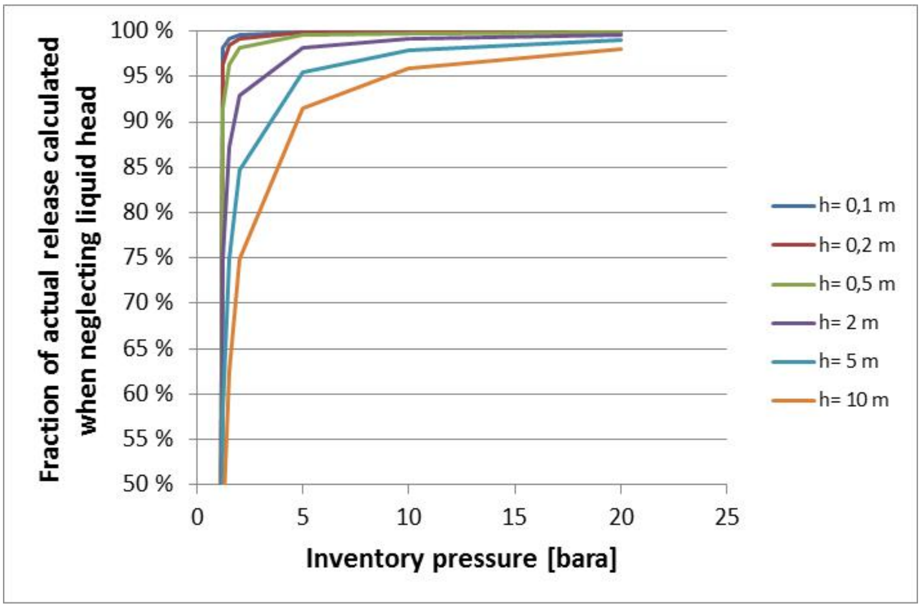


Figure 3.1 - The effect of neglecting liquid head. The figure gives the fraction of the actual leak rate calculated by neglecting the liquid head h, for a range of values for the liquid head

Table 3.3 - Parameters used to calculate gas release rates

Parameter	Description
Q_L	Initial liquid release rate [kg/s]
C_D	Discharge coefficient =0.61
A	Hole area [mm²]
d	Hole diameter [mm]
h	Liquid head [m]
g	Gravitational acceleration [m/s²]

Parameter	Description
P_0	Initial liquid gas cap pressure (inventor pressure) [Pa]
P_a'	Atmospheric pressure [Pa]
ρ_L	Initial liquid density [kg/m³]
P_L	Initial liquid gas cap pressure (inventory pressure) [barg]

3.2 Transient release modelling in QRAs

3.2.1 General

In general it is recommended to model all Significant leaks from process equipment as leaks occurring during normal operation, taking ESD and blow down into account. This means that it should be assumed that fluid is released from the leak source until the process segment has been emptied through the leak source itself and/or through the blow down system. The inventory properties representing normal operation should be used.

For many of the historical leaks (see TN-2) a significant lower quantity has been released than what will be estimated based on this guidance. This constitutes the main conservatism implemented in PLOFAM, as the frequency and hole size distribution is aimed to give an unbiased estimate for the future leak frequency. For hose leaks however a slightly special guidance is given.

The equations for release rate modelling given in Chapter 3.1 are recommended used for gas and liquid releases. For multiphase segments more sophisticated models can be necessary for a more accurate result.

Marginal leaks are modelled the same way as a Significant leaks until the total leaked quantity has reached 10 kg. After this point in time the release rate is set to zero.

3.2.2 Hose leaks

If the relevant information of temporary hose operations at an installation is unknown, the described data basis for the model (see TN-2) can be used as reference. Based on this the following general guidance is given:

- Based on population data presented in TN-2 it is recommended to assume 200 hose operations per year. This is expected to be around the average number of hose operations at installations at NCS, or above
- Hose leaks should be associated with the process segment they will be connected to. If this is not known, use inventory properties given in Table 3.4 are recommended based on the properties associated with historical leaks at NCS
- Use the hose dimensions used for the hose operation at the installation. If this is not known, use ¾" inch. Combined with the suggested inventory properties, this will give a leak with initial leak rate 3.9 kg/s for gas and 8.8 kg/s for oil in case of full rupture
- As explained in TN-2, the majority of leaks from hoses are associated with shorter duration/quantities than if they were connected to an ESD segment under normal operation. It is therefore suggested to limit the **maximum released quantity** for Significant leaks from hoses to **250 kg** to take this into account, i.e. the leak should be modelled as a Significant leak until the total leaked quantity has reached 250 kg. After this point in time the release rate is set to zero. Marginal leaks from hoses should be modelled as normal. 1 of the 13 historical leaks have released quantities larger than 250 kg, and the suggested approach leaves a small residual risk of a hose leak actual giving larger gas clouds than modelled using this approach. This is however small, and in total, taking all equipment types into account, the PLOFAM model is regarded as conservative with respect to the way the leak scenarios are recommended modelled. Note also that the marginal fraction for hose is around 25%, but is set equal to the other equipment types in the model (10-15%)

Table 3.4 – Suggested inventory properties for temporary hose operations

Fluid phase	No of operations	Pressure (bara)	Density (kg/m3)
Gas	160	80	70
Liquid	40	15	800

See also TN-2 and TN-6 regarding uncertainties related to temporary hose operations, and the way uncertainties are taken into account in the model.

3.2.3 Leaks from the flare system

The frequency for leaks from the flare system is included in the leak frequency estimated by counting all process equipment in PLOFAM. Sometimes it may however be necessary to distinguish on flare leaks and leaks from the process system. It is then suggested to base the fraction of leaks from the flare system on the historical fraction of PLOFAM leaks stemming from the flare system. In total 10 of the 191 Significant leaks have occurred in the flare system (see TN-2). Hence the fraction is about 5%. Note that the relative leak rate distribution for flare leaks seem to be somewhat different from the target value used for the PLOFAM model, i.e. for all process leaks. If modelling flare leaks specifically it is therefore recommended to apply the leak rate distribution in Table 3.5.

Table 3.5 – Recommended leak rate distribution for flare leaks if modelled specifically, based on TN-2

Data basis	>0.1 kg/s	>1 kg/s	>10 kg/s	>100 kg/s
NCS Total (2001 - 2017) - only flare	100 %	80 %	50 %	10%

4 References

/1/ Lloyd's Register Consulting, "Modelling of ignition sources on offshore oil and gas facilities - MISOF", Date: November 2018, Report No: 107566/R2, Rev: Final