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Model parametrization and validation

TN-6

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Summary

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1 Introduction

This technical note describes how the parameters in the model have been derived based on:

- NCS data presented in TN-2
- UKCS data presented in TN-3. The UKCS historical data extracted from the HCR database has not used directly when setting the leak frequency model parameter, but constitute an important data basis when evaluating certain aspects of the model parameters
- The leak scenarios presented in TN-4
- The mathematical formulation presented in TN-5

It is important to note that the derivation of the parameterization described in the initial version of PLOFAM (TN-6 in Ref. /1/) is an important reference document. In this updated version of the PLOFAM parameters, the analysis performed in the initial version forms the starting point for the PLOFAM parameterization process. The methodology is the same, but the parameterization is in the updated version is mostly based on data from installations at NCS. Data from UKCS installations is used for support on some aspects of the model including the overall validation of the model (for instance in the assessment of the average relative leak frequency distribution with respect to leak rate and the average total leak frequency).

2 Parameterization methodology

It was demonstrated in Ref. /1/ that the mathematical frame work described in TN-5 is able to estimate fundamental characteristics of the hole size frequency distribution for the typical equipment in a process system at an oil and gas installation, and including the dependency on equipment dimension. Given this mathematical framework, the parameters for the various equipment can be derived through an iterative process applying the historical data gathered for installations located at NCS. A tool facilitating the iteration has been developed in MS Excel where the mathematical frame work, population data and historical leaks is compiled.

The number of historical leaks and their distribution with respect to initial leak rate per equipment make up a set of targets for the model to satisfy. For each equipment, the various parameters are changed iteratively to obtain the best possible fit to these targets based on the following constraints:

- The relative distribution with respect to initial leak rate obtained for NCS installations for the period 2001-2017 constitute the main overall target for the parameters being decisive for the slope of the hole size distribution. The leaks at installations operating at NCS in the period 1992-2000 is used as reference to determine the dependency on hole size in the region of the distributions being decisive for estimation of the frequency for leaks having an initial leak rate larger than 30 kg/s. The UKCS data is utilized to set the relative distribution with respect to leak rate for the large process equipment (pumps, compressors, pig traps etc.).
- The relative distribution on the various equipment (*e.g.* valve and standard flange) is mainly based on the NCS data for the period 2001-2017. The data from UKCS is used as reference for equipment types where the number of leaks at NCS installations is few (*e.g.* pumps, compressors, pig traps, producing well, gas lift well etc.).
- The parameters determining the frequency for the various equipment are based on the NCS data for the period 2006-2017. In lack of population data, the model parameters for three equipment types are solely based on data from UKCS installations.

In addition to the statistical data, knowledge on failure modes causing leaks for the various equipment is applied where relevant.

The parameterization process for each equipment type applicable in PLOFAM is presented systematically in separate chapters.

The various model alternatives are systematically validated by use of the software routine in Excel. The routine calculates the following for each of the installations being in operation at NCS (see TN-2):

- The frequency distribution versus initial leak rate per equipment type (the method for calculation of the leak rate can be found in TN-5)
- The estimated number of leaks in the relevant period (base case is 01.01.2006-31.12.2017) versus initial leak rate per equipment type

The results are compiled and presented along with the corresponding observed leaks.

Plots used to assess the model performance are presented in the chapters presenting the derivation of the PLOFAM parameters per equipment type.

The contribution from significant and marginal leaks is calculated separately. The validation model does however focus on validating the performance with respect to significant leaks.

The contribution from steel piping is in the validation model estimated by adding a contribution as a fraction of the total frequency estimate for all other equipment types. This is because equipment counts of steel pipe length are only available for 24 installations in the NCS population dataset (see Chapter 9.3 in TN-2). The equipment counts for those 24 installations are utilized to estimate F_{hist} for steel pipe based on the NCS data.

3 General assessment of model validity

The historical data is gathered from offshore installations being operative at NCS and UKCS in the period 1992-2017. The following summarize important notes with respect to the application outside the domain of which data are collated from:

- The PLOFAM parameters derived based on NCS data generate a good fit to the UKCS data (see Chapter 22). The observed deviations are very likely to be explained by the uncertainties in the quality of the UKCS data. This means that the underlying leak frequency at installations located on the UKCS appear to be the same as the underlying frequency at installations on the NCS
- The failure modes are related to the technical properties of the systems and the way offshore oil and gas installations are operated in the North Sea. Hence, the validity of the model for other domains depends on the similarity to the general North Sea industry practice. For instance, the causes for leaks are expected to be correlated with the complexity of the system. A fraction of the failure modes associated with a standard ASME flange installed in process system at an offshore installation may be irrelevant for a small-scale storage tank on land. On the other hand, this very tank may be prone to different failure modes not relevant for the offshore application. Hence, it is suggested that a separate project is run to qualify or modify PLOFAM for the application in other domains
- The statistical data cover leaks having an initial leak rate larger than 0.1 kg/s, which broadly is aligned with a minimum hole size diameter of 1 - 9 mm (see TN-5). In some cases, leaks with a much lower leak rate than 0.1 kg/s has to be considered in a QRA. It is judged that the hole size frequency distribution can be extrapolated to estimate the frequency for leaks originating from smaller hole sizes than 1 mm, but the uncertainty is somewhat more prominent as the model has not been validated for this region. Extrapolation of the PLOFAM model represent to our knowledge the best available methodology for estimation of the risk related to small holes

The equipment categories in PLOFAM cover a broad range of equipment types. The hole size frequency distribution generated by PLOFAM represent the average for the population used to set the parameters. This is in particular important to note for standard flanges and valves. The model for standard flanges applies for all types of couplings (*e.g.* ring joint flanges, raised face and grey lock), which may be quite different in terms of design and operation. The category valve lumps all type of valves in one group, but the actual failure modes may be very specific to each type of valve (ball valve, gate valve, check valve etc.). It is recommended to spin off a separate project aiming at refining the model for valves and flanges into subcategories acknowledging the individual characteristics of the equipment.

4 Model parameters

The parameters defined in the mathematical formulation of the model are described in TN-5. The model parameters and additional parameters used in the estimation and validation process are given in the table below.

Table 4.1 - Summary of all parameters used in the model (see TN-5)

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)

Parameter	Description
F_1	Additional full bore hole frequency [year^{-1} equipment^{-1}]
$\varphi(D)$	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

5 Model targets

5.1 Overall qualitative targets

The fundamental assumptions for the model and the requirements to the model are described in TN-5.

The following overall targets have been established for the derivation of the parameters:

- The model shall reproduce the number of observed significant leaks in the period 2006-2017 at the installations in the NCS population dataset (see Chapter 6 in TN-2). The total number of observed significant leaks in the period is 104
- The model shall reproduce the relative complementary cumulative leak frequency distribution of observed significant leaks in the period 2001-2017 at the installations in the NCS population dataset (see Chapter 6 in TN-2)
- A best possible prediction of the observed number of leaks originating from the various types of equipment at NCS installations is targeted. UKCS data is used as reference for definition of targets for equipment with few objects. This applies in particular to leaks from pumps
- The hole size distribution shall aim at reflecting knowledge on the failure modes associated with the various equipment

The specific targets per equipment category are presented in the following section.

5.2 Target per equipment category

5.2.1 Valve, standard flange, instrument and steel pipe

The target for the overall relative leak rate distribution for valve, standard flange and instrument are shown in Figure 5.1, which is based on the observed significant leaks at NCS installations in the period 2001-2017 (see TN-2). The historical data show that the fraction of large leaks is much higher given a leak from a flange or a steel pipe compared to both valves and instruments. Furthermore, leaks from instruments are considerably smaller than leaks stemming from the other types of equipment, which is strongly correlated to the equipment dimension. It is important to note that the uncertainty related to the target increase with increasing leak rate. There have very few leaks above 10 kg/s. Therefore, NCS data for the period 1992-2000 and UKCS data is used as support when assessing the parameters being decisive for the slope of the hole size distributions.

The targets for the frequency parameters are the number of leaks observed in the period 2006-2017 as shown in Figure 5.2. The relative distribution per equipment using the entire data period (2001-2017) is considered to give a better estimate of the underlying distribution the effect of randomness is averaged out when a bigger dataset is used. In order to investigate any drift in the relative distribution, the result based on the period 2001-2017 is also shown. In this case, the number of leaks in each group is normalized with the total number of significant leaks in the two periods (104 and 191). The results demonstrate that drift in relative distribution is insignificant.

These equipment's constitutes about 90% of the total number of leaks (90 out of 104 significant leaks). The targets are not treated absolute for each equipment category when setting the parameters. An overall assessment is performed as part of the parameterization process. This means that the target can rather be formulated as aiming at the best possible prediction of the number of leaks per equipment category. In addition, the final figures are rounded off to balance accuracy and user friendliness. The model should not give the impression that it is more accurate than it is.

The overall fraction marginal leaks are 12% for these equipment's (21 out of 180 leaks). The fraction is highest for valves. No marginal leaks from instruments have been recorded. Based on this, marginal leaks from instruments are disregarded. Using a fraction of 15% for valves, standard flange and steel pipe reproduce the observed number of incidents (21). One could argue that the fraction should be set higher for valves than the other types. However, using 15% for equipment generate reasonably high probability for observing the number of marginal leaks for each of the three equipment types (see Figure 5.4). In addition, the estimate of marginal leaks is in most cases not important for the risk assessment of major accidents. The resulting model is however allowed to deviate somewhat from the targeted 15% in order to comply with the overall target for all leaks in addition to the effect of rounding off the frequency parameters.

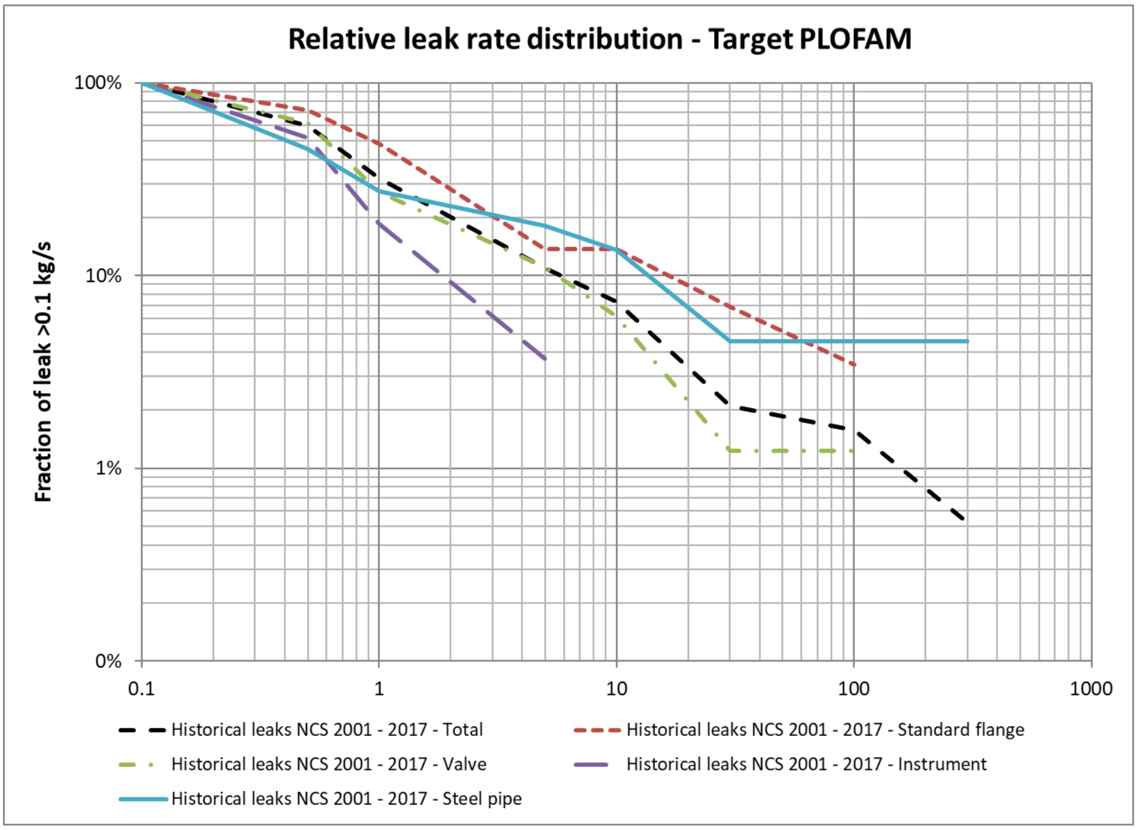


Figure 5.1 – Targeted relative leak rate distributions for valve, standard flange, instrument and steel pipe

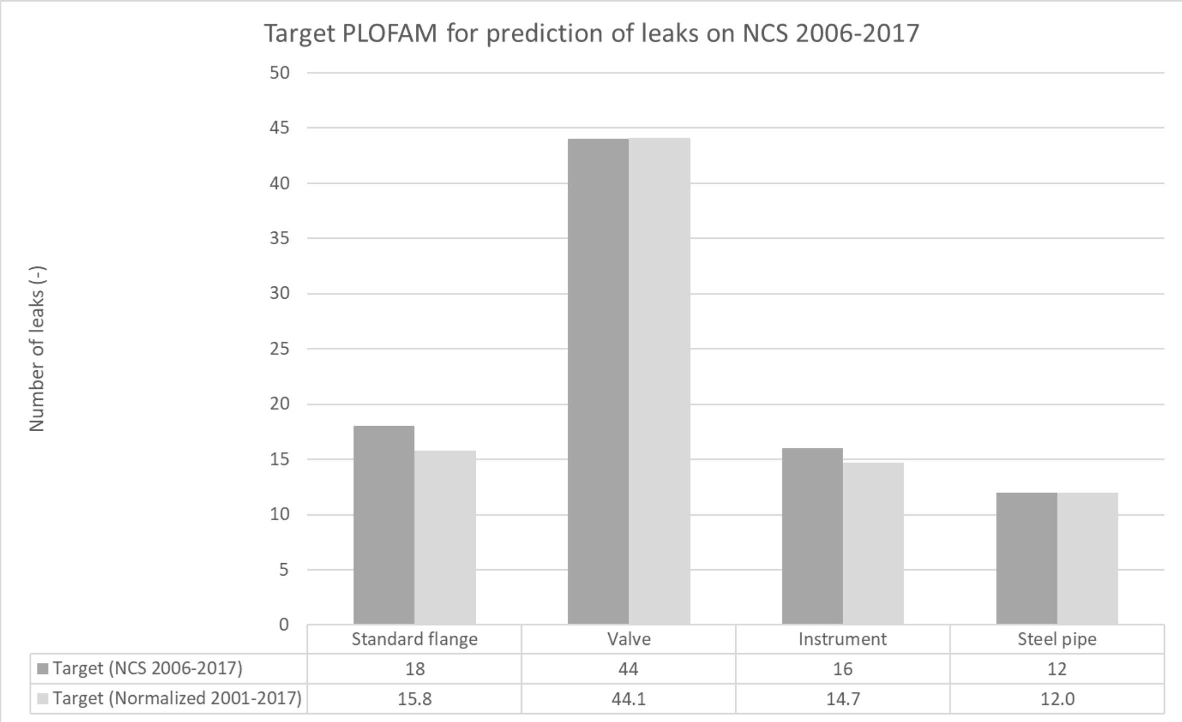


Figure 5.2 – Targeted expected number of significant leaks ≥ 0.1 kg/s for valve, standard flange, instrument and steel pipe. 'Target (NCS 2006-2017)' display the target based on the actual leaks at NCS in the period 2006-2017. 'Target (Normalized 2001-2017)' presents the results based on the period NCS 2001-2017 normalized with 104/191 (ratio of number of significant leaks in the two periods respectively)

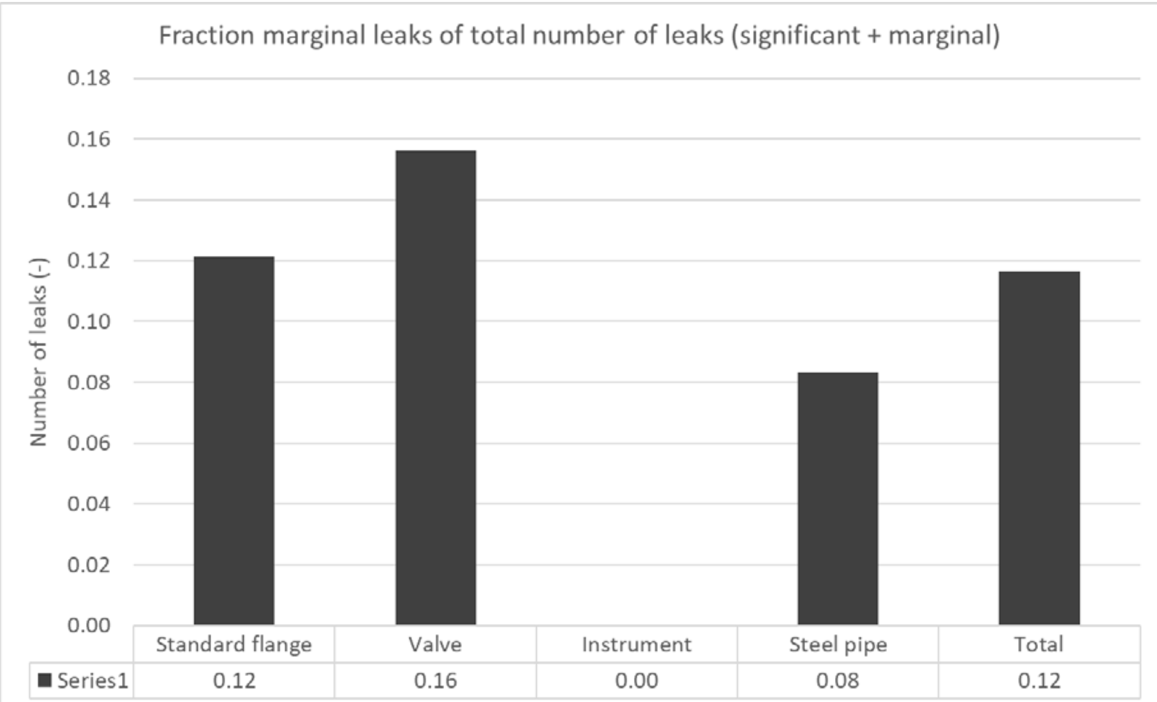


Figure 5.3 – Fraction marginal leaks (of total number of leaks)

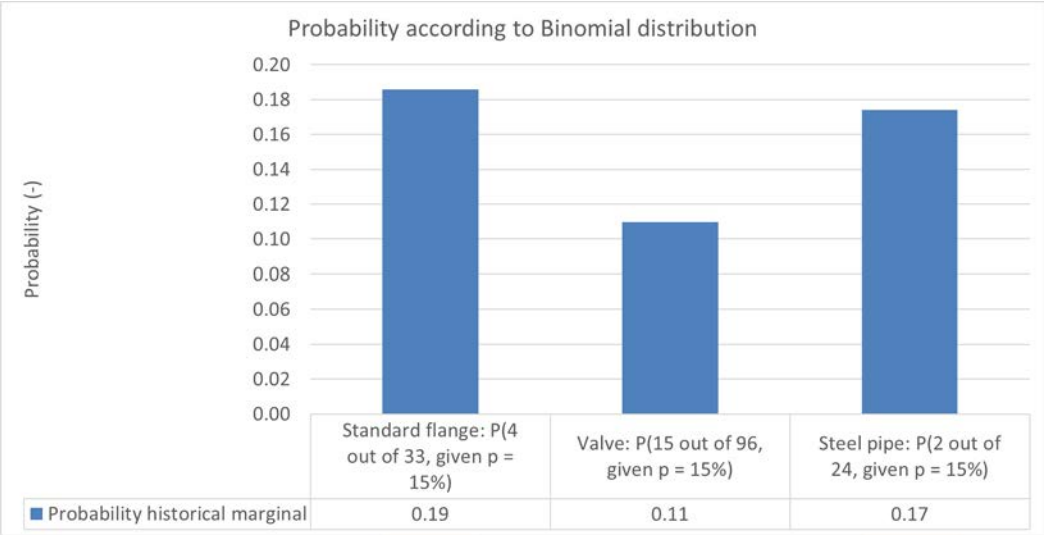


Figure 5.4 – Probability for observing the number of marginal leaks given $p = 0.15$ in binomial distribution

5.2.2 Large process equipment

The target for the other equipment categories, denoted large process equipment, is mainly based on the observed leaks at NCS in the period 2001-2017, but also the total number of leaks at NCS and UKCS for the entire period (1992-2017) is applied as the number of observed leaks are scarce.

Marginal leak is disregarded for the process equipment. Hence, no target is established for marginal leaks. No marginal leaks have been observed stemming from special equipment. This is can be explained by a low underlying frequency for marginal leaks in combination with the small population of special process equipment. It is judged that it is a better approach to reproduce the number of observed marginal leaks by established a marginal fraction from the dominant equipment types in terms of number of leaks observed.

The first step is to set the target per equipment category for the frequency for leaks > 0.1 kg/s. The starting point is the observed leaks associated with the large process equipment in the period 2001-2017. In order to account for randomness per category, it is put down as a premise that the underlying total leak frequency (frequency for leaks > 0.1 kg/s) corresponds to a probability for the observed number of leaks or fewer of 50%. Assuming that the occurrence leaks for each equipment category is a Poisson process; the expected number of leaks for the period can be calculated. For instance, for an equipment category with 0 observed leaks, the expected number of leaks in the period becomes 0.69. The resulting target per category is thereafter normalized with the total for all equipment categories obtaining a target based on the period 2001-2017. The final step is to adjust the target with the ratio between observed significant leaks in the period 2001-2017 and 2006-2017.

The resulting target for the total frequency per equipment category for leaks > 0.1 kg/s is shown in Table 5.1. Requiring that the total should not exceed 13.67 results in that the target for equipment categories with more than 3 observations becomes slightly less than the observed number of leaks (2.72 vs. 3 observations). However, the targets are not used strictly and it's the target for the period 2006-2017 that applies. The number of historical leaks related to all process equipment types is 7, which is consistent with 7.44 as overall target for all process equipment types.

Table 5.1 – Target for per equipment category for significant leaks ⩾0.1 kg/s (see TN-5)

Equipment	Observed number of leaks NCS 2001-2017	Target using Gamma distribution and a p-value of 50%	Normalising target 2001-2017 with respect to 13.67*)	Target 2006-2017 normalized with 104/191
Centrifugal compressor	3	3.67	2.72	1.48
Reciprocating compressor	0	0.69	0.51	0.28
Pump	3	3.67	2.72	1.48
Plate heat exchanger	0	0.69	0.51	0.28
Shell and tube heat exchanger	1	1.68	1.24	0.68
Process vessel	2	2.67	1.98	1.08
Filter	3	3.67	2.72	1.48
Pig trap	1	1.68	1.24	0.68
Total	13	18.43	13.67	7.44

*) The Gamma distribution (p-value set to 50%) used to set the target for the total number of leaks (13.67 = expected value requiring 50% probability for observing 13 leaks or fewer)

A target for leaks > 10 kg/s is developed to set the slope of the hole size distribution for these equipment categories. The target is derived based on the observed distribution for significant leaks at both UKCS and NCS in the period starting 1992 (see Table 5.3).

Note the considerable difference between the NCS and UKCS data. The historical leak frequency related to the large process equipment appears to be much higher at UKCS installations compared to NCS installations. It is judged that this is related to the way leaks are tagged to equipment in the UKCS data. One explanation may be that a leak from a valve, instrument or flange where the root cause is related to the large equipment is tagged to the large equipment. For instance, a leak from an instrument due to vibration induced by a pump is classified as a pump leak instead of an instrument leak. The quality of the categorisation of leaks to equipment at NCS is considered to be much better as it is based on review of specific accident investigation reports. The relative distribution of leaks with respect to leak rate at UKCS is judged to be more reliable, and is utilized to set the target for large leaks.

The fraction of historical leaks > 10 kg/s per equipment type for NCS and UKCS installations (1992-2017) is presented in Table 5.2. The resulting target is the product of the target for leaks > 0.1 kg/s (Table 5.1) multiplied with the fraction > 10 kg/s presented in Table 5.2. No leaks larger than 10 kg/s have been observed for filters. The target is therefore set using the Gamma distribution and p-value of 50% (equivalent with using the expected value requiring 50% probability for observing zero leaks).

Table 5.2 – Target for per equipment category for significant leaks ⩾10 kg/s (see TN-5)

Equipment	Observed number of leaks > 10 kg/s NCS 2001-2017	Number of leaks > 10 kg/s on NCS and UKCS 1992-2017	Fraction > 10 kg/s based on leaks on NCS and UKCS 1992-2017	Target 2001-2017 number of leaks > 10 kg/s	Target 2006-2017 number of leaks > 10 kg/s
Centrifugal compressor	0	1	0.091	0.33	0.18
Reciprocating compressor	1	2	0.100	0.07	0.04
Pump[1)]	0	1	0.016	0.06	0.03
Plate heat exchanger	0	1	0.040	0.03	0.02
Shell and tube heat exchanger	0	1	0.100	0.17	0.09
Process vessel	0	1	0.043	0.12	0.06
Filter	0	0.69[2)]	0.037	0.14	0.07
Pig trap	0	1	0.176	0.30	0.16
Total	1	8.69	0.091	1.21	0.66

1. Amalgamated model for pumps developed for centrifugal and reciprocal pumps. Historical data indicate that the historical frequency is similar for both types
2. No leaks > 10 kg/s stemming from filters observed in the period. The Gamma distribution (p-value set to 50%) used to set the target (using the expected value requiring 50% probability for observing zero leaks)

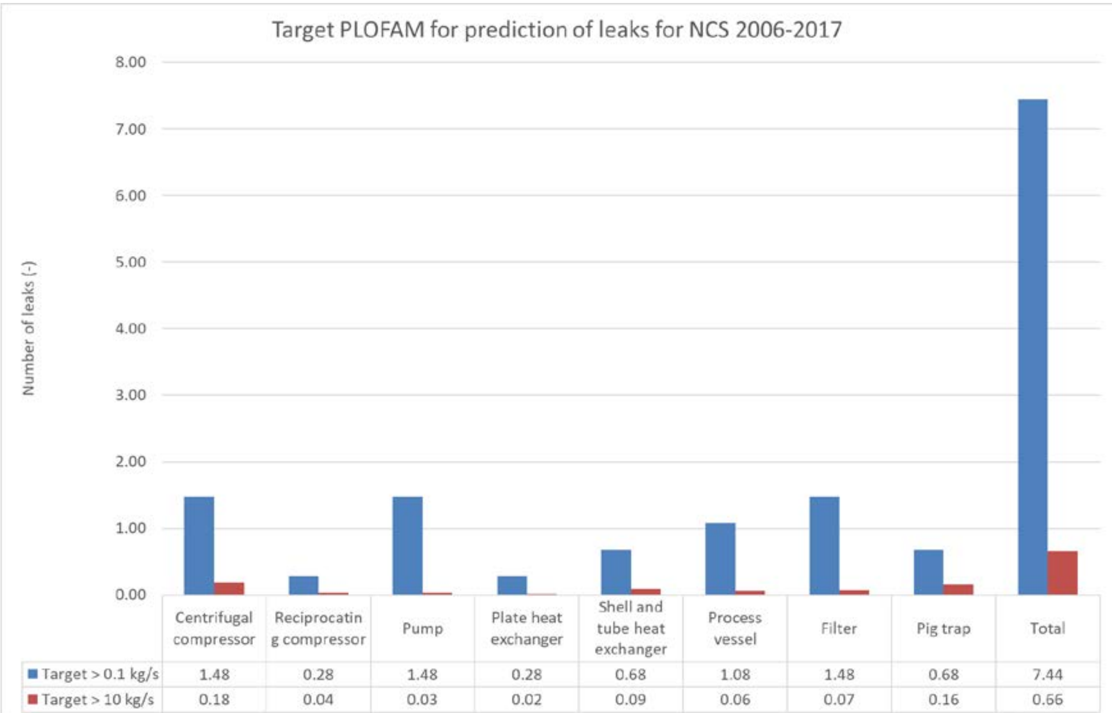


Figure 5.5 – Targeted expected number of significant leaks originating from special types of equipment

Table 5.3 – Historical data NCS and UKCS 1992-2017 for large process equipment

Equipment	Dataset and period	Marginal	Significant			Maximum rate (kg/s)	Equipment years	Leak frequency (per year)		
			Small	Medium	Large					
		(< 10 kg and/or < 0.1 kg/s)	0.1-1 kg/s	1-10 kg/s	> 10 kg/s			Marginal	Significant	Sum
Centrifugal compressor	UKCS <2001	12	3	-	1	24.0	2,247	5.3E-03	1.8E-03	7.1E-03
	UKCS >2001	33	4	-	-	0.8	5,197	6.3E-03	7.7E-04	7.1E-03
	NCS >2001	-	3	-	-	0.7	3,237	0.0E+00	9.3E-04	9.3E-04
	Total	**45**	**10**	**-**	**1**		**10,681**	**4.2E-03**	**1.0E-03**	**5.2E-03**
Reciprocating compressor	UKCS <2001	16	4	-	-	0.3	316	5.06E-02	1.26E-02	6.32E-02
	UKCS >2001	34	5	-	1	0.6	1,287	2.64E-02	4.66E-03	3.11E-02
	NCS >2001	-	-	-	-	20.0	236	0.00E+00	0.00E+00	0.00E+00
	Total	**50**	**9**	**-**	**1**		**1,839**	**2.7E-02**	**5.4E-03**	**3.3E-02**
Centrifugal pump	UKCS <2001	25	17	6	-	5.9	7,649	3.27E-03	3.01E-03	6.28E-03
	UKCS >2001	59	22	4	-	1.9	16,485	3.58E-03	1.58E-03	5.16E-03
	NCS >2001	-	3	-	-	0.1	3,448	0.00E+00	8.70E-04	8.70E-04
	Total	**84**	**42**	**10**	**-**		**27,581**	**3.0E-03**	**1.9E-03**	**4.9E-03**
Reciprocating pump	UKCS <2001	1	3	1	1	371.0	1,681	5.95E-04	2.97E-03	3.57E-03
	UKCS >2001	8	2	2	-	7.9	3,619	2.21E-03	1.11E-03	3.32E-03
	NCS >2001	-	-	-	-		128	0.00E+00	0.00E+00	0.00E+00
	Total	**9**	**5**	**3**	**1**		**5,427**	**1.7E-03**	**1.7E-03**	**3.3E-03**
Plate heat exchanger	UKCS <2001	6	8	2	1	40.0	1,981	3.03E-03	5.55E-03	8.58E-03
	UKCS >2001	17	8	6	-	3.7	5,009	3.39E-03	2.79E-03	6.19E-03
	NCS >2001	-	-	-	-		2,357	0.00E+00	0.00E+00	0.00E+00
	Total	**23**	**16**	**8**	**1**		**9,346**	**2.5E-03**	**2.7E-03**	**5.1E-03**
Shell and tube heat exchanger	UKCS <2001	17	5	1	-	1.8	6,846	2.48E-03	8.76E-04	3.36E-03
	UKCS >2001	28	2	-	1	135.0	14,644	1.91E-03	2.05E-04	2.12E-03
	NCS >2001	-	1	-	-	-	5,417	0.00E+00	1.85E-04	1.85E-04
	Total	**45**	**8**	**1**	**1**		**26,907**	**1.7E-03**	**3.7E-04**	**2.0E-03**
Process vessel	UKCS <2001	30	7	3	1	15.3	14,331	2.09E-03	7.68E-04	2.86E-03
	UKCS >2001	24	9	1	-	0.4	31,773	7.55E-04	3.15E-04	1.07E-03
	NCS >2001*	-	2	-	-	0.5	10,538	0.00E+00	1.90E-04	1.90E-04
	Total	**54**	**18**	**4**	**1**		**56,641**	**9.5E-04**	**4.1E-04**	**1.4E-03**
Filter	UKCS <2001	17	6	1	-	15.3	5,875	2.89E-03	1.19E-03	4.09E-03
	UKCS >2001	19	6	2	-	0.4	13,447	1.41E-03	5.95E-04	2.01E-03
	NCS >2001*	-	2	1	-	3.0	2,285	0.00E+00	1.31E-03	1.31E-03
	Total	**36**	**14**	**4**	**-**		**21,608**	**1.7E-03**	**8.3E-04**	**2.5E-03**
Pig trap	UKCS <2001	11	2	3	3	27.8	2,738	4.02E-03	2.92E-03	6.94E-03
	UKCS >2001	20	7	1	-	3.0	5,759	3.47E-03	1.39E-03	4.86E-03
	NCS >2001*	-	1	-	-	0.1	800	0.00E+00	1.25E-03	1.25E-03
	Total	**31**	**10**	**4**	**3**		**9,297**	**3.3E-03**	**1.8E-03**	**5.2E-03**
Overall	UKCS <2001	135	54	17	7	27.8	44,635	3.02E-03	1.75E-03	4.77E-03
	UKCS >2001	251	61	14	3	3.0	98,416	2.55E-03	7.93E-04	3.34E-03
	NCS >2001*	-	12	1	-	0.1	28,445	0.00E+00	4.57E-04	4.57E-04
	Total	**386**	**127**	**32**	**10**		**174,627**	**2.2E-03**	**9.7E-04**	**3.2E-03**

5.2.3 Hose

There have been 14 leaks from hoses in the period 2001-2017, of which 11 was significant. In the period 2006 onwards, there has been 6 leaks related to hoses (1 out of 6 was marginal). Hence, the relative contribution from hose leaks has decreased slightly. Totally the fraction has decreased from 6.5% (14 out of 217) to 5.8% (6 out of 104). Considering significant leaks, the fraction has shifted from 5.8% (11 out of 191) to 4.8% (5 out of 104). More stringent procedures for use of temporary hoses have been implemented in the period, which could (*i.e.* may also be explained due to randomness) explain why the relative contribution from hoses has dropped slightly.

The target for total number of significant leaks from hoses in the period is set to 5. The distribution with respect to initial leak rate and fraction marginal is discussed in Chapter 18.

5.2.4 Producing well and gas lift well

The number of wells in production in the HCR population data is judged to be more uncertain than population data of wells established for installations on the NCS. It is therefore concluded to use the NCS data to set the parameters for producing well and gas lift well.

One marginal leak classified as producing well has been observed at NCS over the entire period (2001-2017). The leak occurred in 2005. No leaks from gas lift wells have been recorded, but a marginal leak occurring in 2016 is similar to the gas lift well leak scenario. The leak was a leak from an annulus not used for gas lift (leak from annuli E in a well where hydrocarbons were not expected to be present). The two marginal leaks observed at NCS confirm that leaks from well systems not covered by the blow out frequency model are relevant and must be covered by PLOFAM. The fact that both of the relevant incidents are marginal implies that it is reasonable to expect that a major fraction of them result in a limited released amount.

Since no significant leaks has been observed at NCS, a target for the total number of marginal and significant leaks from producing well and gas lift well is set using the Gamma distribution and p-value of 50% (equivalent with using the expected value requiring 50% probability for observing zero leaks). With one observed marginal leak in the period 2006-2017, the target for the expected number of significant and marginal leaks with initial leak rate ≥ 0.1 kg/s for the period 2006-2017 become 1.68.

The relative distribution from UKCS leaks in the period 2001-2017 (see Figure 5.6) is used to distribute the total target (1.68) on marginal and significant for the two leak scenarios. By using the UKCS data to distribute the target; it is implicitly assumed that the number of gas lift wells per producing well is the same at installations on the UKCS and NCS.

The resulting target is presented in Figure 5.7.

The distribution with respect to initial leak rate is discussed in Chapter 17.

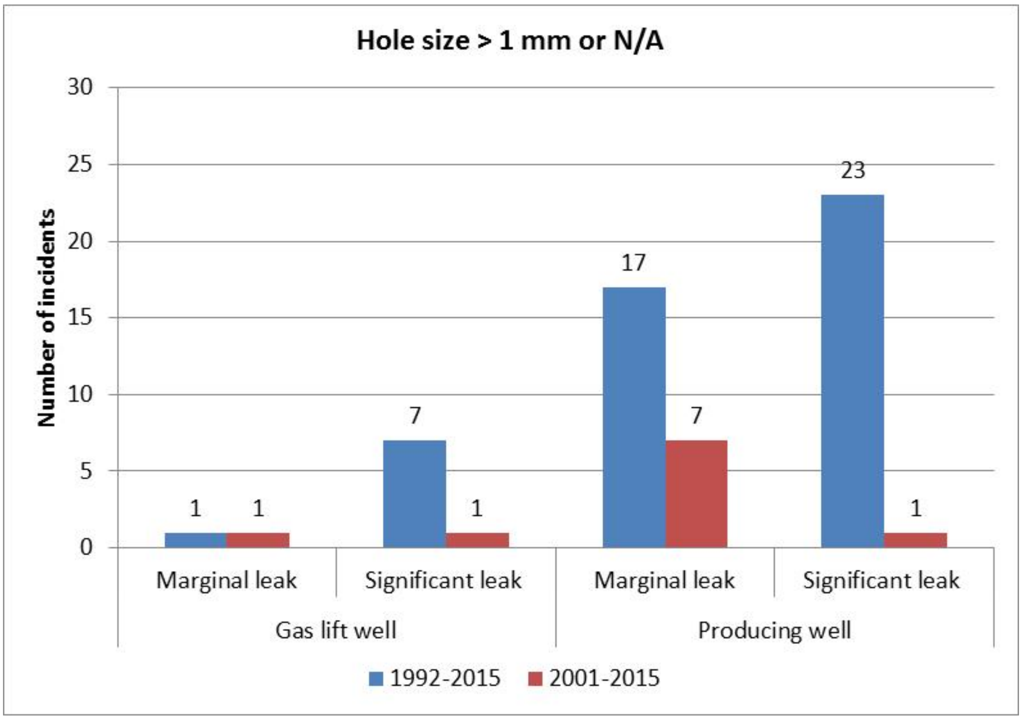


Figure 5.6 – Extracted from HCR (see TN-3): leaks from well system with hole size >1 mm or N/A. No leaks from wells recorded at UKCS in 2016 and 2017

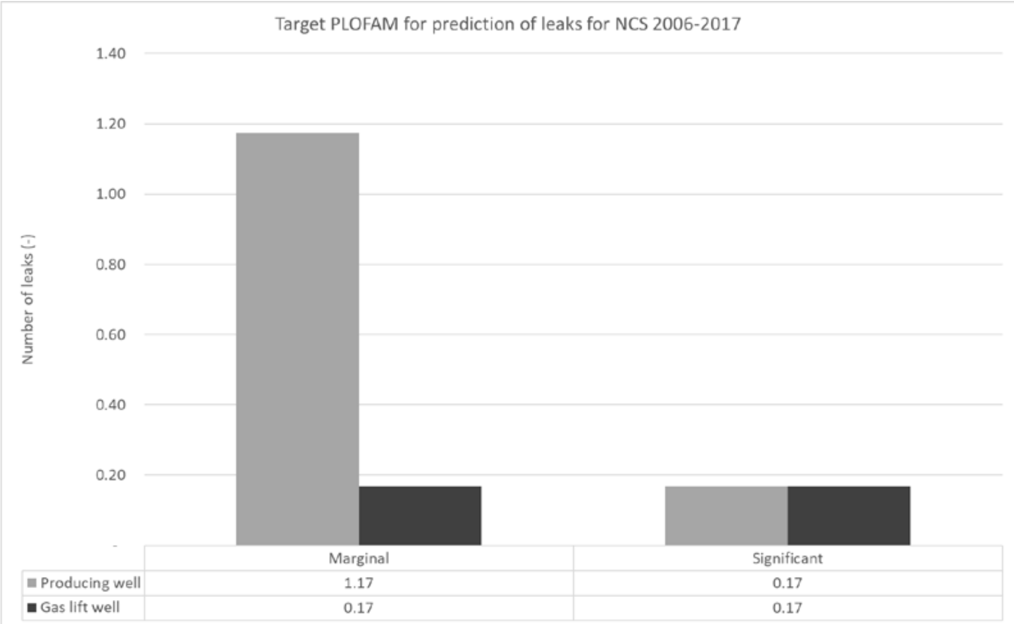


Figure 5.7 – Targeted expected number of leaks ≥ 0.1 kg/s from producing well and gas lift well

5.2.5 Compact flange

The model for compact flanges is derived based on an assessment of the number of equipment years and that no relevant leaks from compact flanges has been recorded (see Chapter 8).

5.2.6 Air-cooled heat exchanger, flexible piping and atmospheric vessel

The population data gathered from installations at NCS does not provide basis for setting targets for the parameters for air-cooled heat exchanger, flexible piping and atmospheric vessel.

The parameters for air-cooled heat exchanger and flexible piping equipment types are therefore set solely based on UKCS data. The model parameters derived for process vessels are recommended for atmospheric vessels (in lack of available data to set specific parameters).

Since the model for these equipment types have not been validated towards a second dataset, the uncertainty associated with these equipment types is therefore more prominent.

6 Valve

6.1 Valve equipment type

The equipment category 'Valve' envelope all types of valves used at an offshore installation. The available data does not allow for derivation of sub categories of valves. The generated hole size frequency distribution for valves therefore must be considered to represent the average for all types of valves.

An adjustment factor for ESD valves has been suggested based on UKCS data.

6.2 Valve PLOFAM parameters

A major fraction of valve leaks is related to latent errors caused by human errors during work on the equipment (*e.g.* maintenance, installation of equipment). The distribution of leaks at installations on the NCS with respect to cause is shown in (Ref. /3/). The typical latent errors related to interventions are:

- Valve left in wrong position after the operation (*e.g.* maintenance), normally small drain and vent valves that may be left in open position before pressurization and hence lead to leak scenarios with full rupture leak rate
- Valve erroneously installed
- Drain plug in valve body left open

Another relevant failure model in this regard is valves erroneously operated during normal operation.

In general, small valves are being operated more frequently than large valves. Combined with that procedures are more stringent for operation of large valves compared to small valves, it is expected that both the full bore hole fraction and the leak frequency decrease with increasing dimension of the valve.

The most common technical failure modes causing leaks in valves are related to the stem seals or drain plugs (Ref. /2/). The hole size resulting from such failures are much smaller than the equipment dimension (available flow area through the valve).

Based on above, the likelihood of failure modes causing intermediate hole sizes is expected to be small for valves. In other words; the dominant failure modes will either cause a small hole (*e.g.* failure of stem seal) or a large hole (valve left in open position).

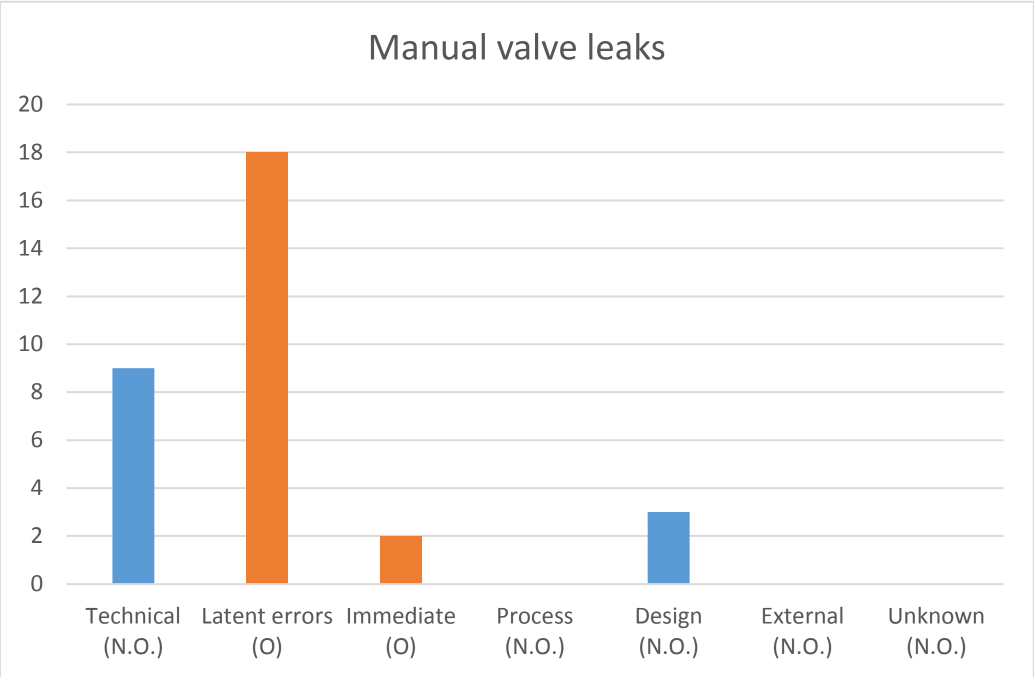


Figure 6.1 - Manual valves: Leaks at installations on the NCS classified according to cause (Ref. /3/). Operational errors (O) marked with orange font

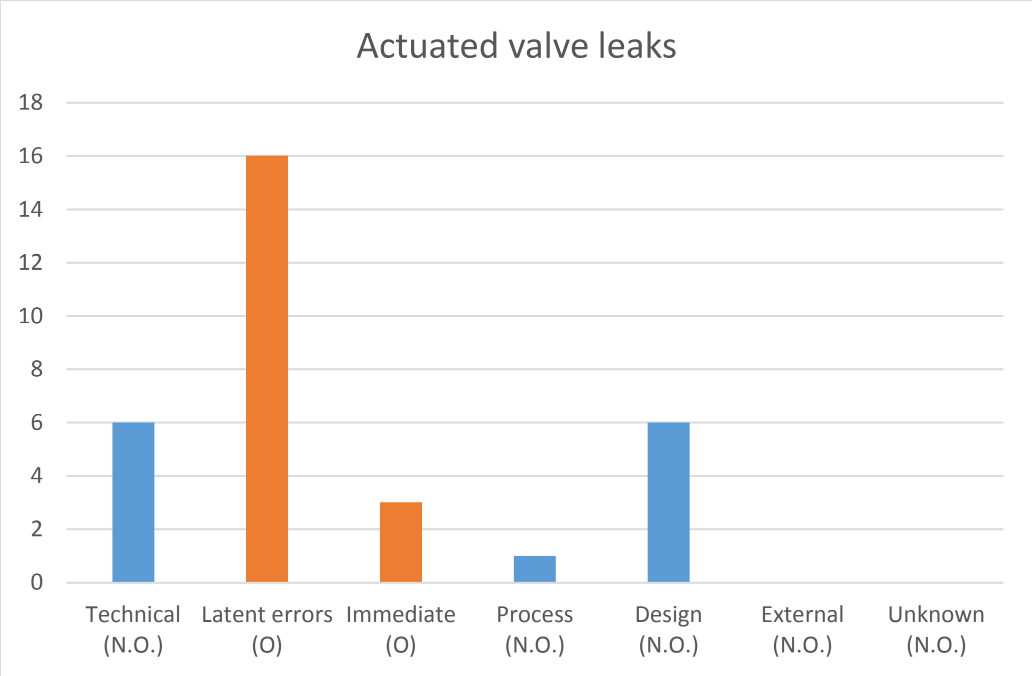


Figure 6.2 – Actuated valves: Leaks at installations on the NCS classified according to cause (Ref. /3/). Operational errors (O) marked with orange font

The resulting model parameters for valves are summarized in Table 6.1. α is set to 0.5 to suppress the frequency for intermediate hole sizes.

The trend with equipment dimension is visualized in Figure 6.3 ($\varphi(D) \cdot F_{hist}$, $\theta(D)$ and $\theta(D) \cdot F_{hist}$). $\theta(D)$ is decreasing steeply with increasing equipment diameter. The decreasing trend is in according with the evaluation of failure modes, but cannot be explicitly derived quantitatively from analysis of the failure modes. The UKCS data (presented in TN-6 in Ref. /1/) support a decreasing trend, but the slope is hard to derive. The gradient of $\theta(D)$ is obtained by seeking the best possible fit with the relative leak rate distribution. Future studies should investigate the relationship between the mathematical model and the failure modes more in detail. A main challenge is that the valve category includes all types of valves. Different types of valves are expected to be prone to different failure modes.

It is also difficult to quantify the leak frequency trend with equipment dimension. The strategy in the parameterisation process has been to obtain a best possible fit with the data. A slight decreasing trend of $\varphi(D)$ with equipment dimension gives the best result compared with the historical data from installations on NCS, which is shown in Figure 6.5. The relative distribution obtained from UKCS installations is also displayed, demonstrating that the data from NCS and UKCS installations for valves are quite similar in terms of the relative distribution.

In Figure 6.4, the resulting hole size frequency distributions for a few valve dimensions are shown. The distributions are quite similar for equipment dimensions above 2". The increasing shift in shape for smaller equipment dimensions is related to the increasing rupture fraction for small equipment dimensions (for $D \leq 2"$, $\theta(D)$ increase steeply with decreasing equipment dimension).

Table 6.1 – Valve parameters

Parameter	Description
F_{hist}	Significant leaks: $2.15 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: $3.5 \cdot 10^{-5}$ [year^{-1} equipment^{-1}]
A_0	1.11
M_0	-0.1
A_D	16.0
M_D	-1.70
B_D	$1.0 \cdot 10^{-3}$
α	0.5

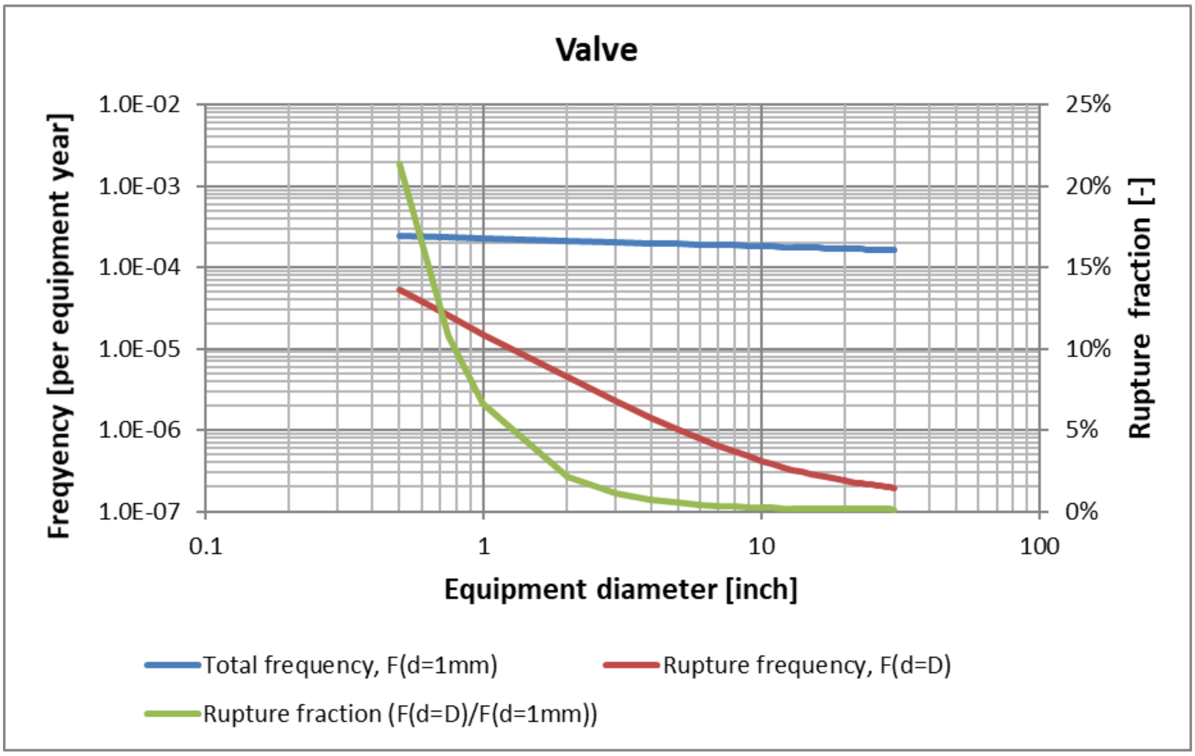


Figure 6.3 – Valve: total frequency, rupture fraction (full bore hole fraction) and rupture frequency

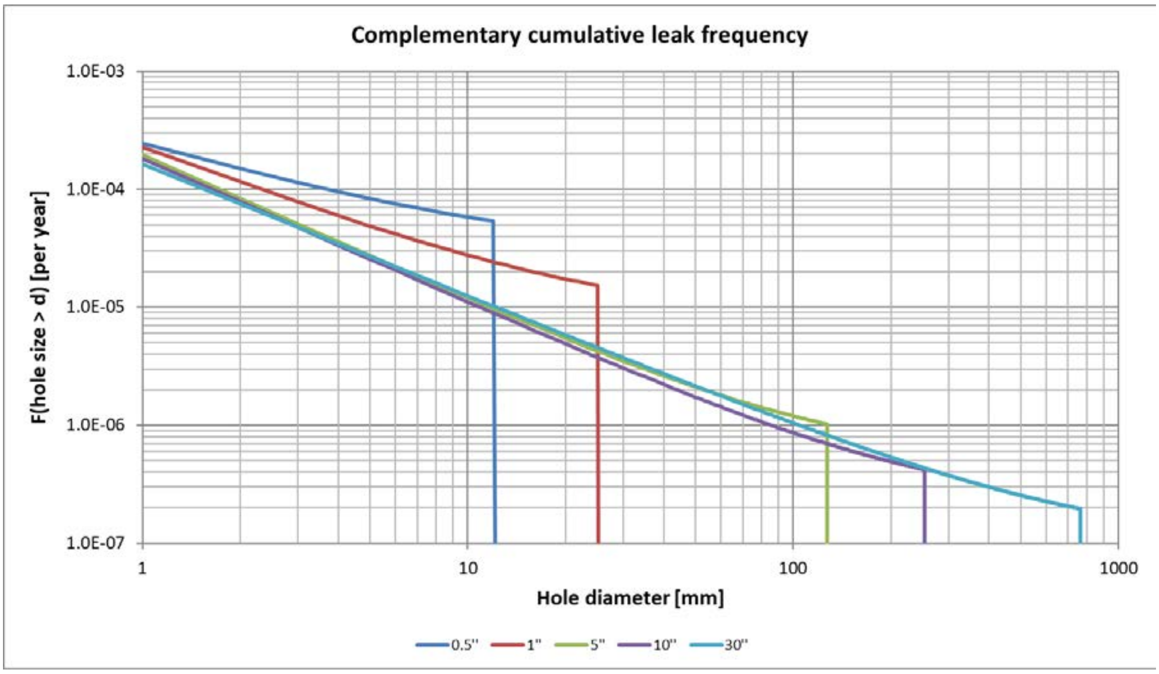


Figure 6.4 – Valve: hole size distribution for various equipment dimensions

The performance of the PLOFAM model for valves with respect to the established targets is shown in Figure 6.5 and Figure 6.6. The results show that the model is able to describe the historical leak rate distribution and the number of leaks observed at installations on NCS.

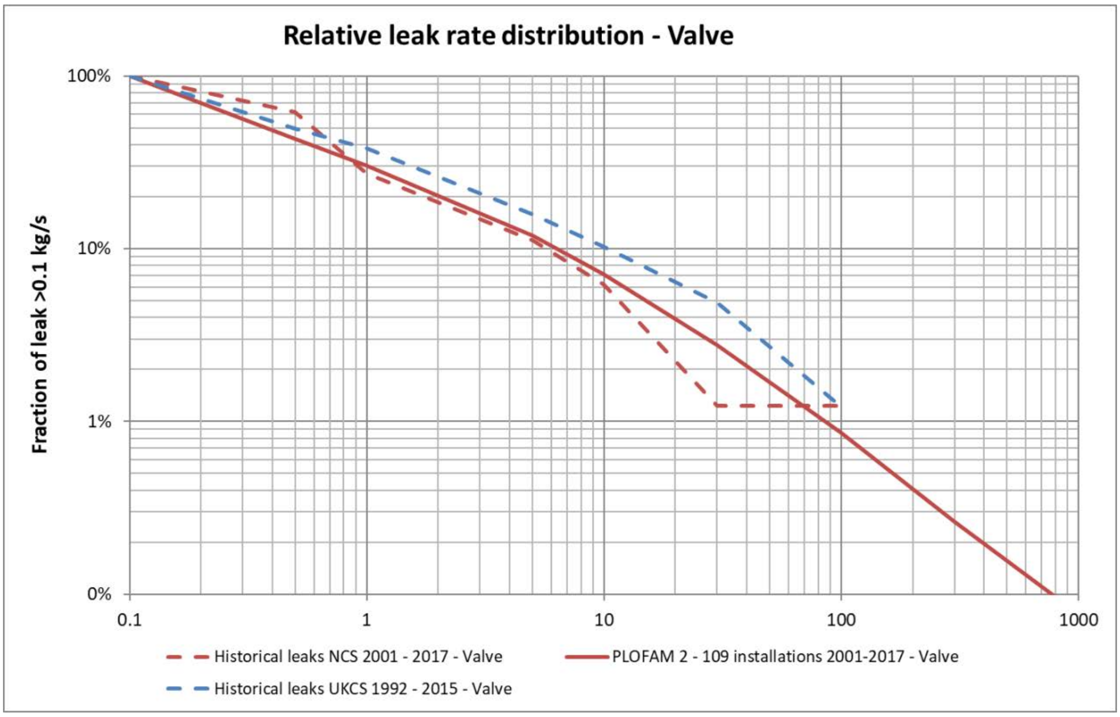


Figure 6.5 – Valve: complementary cumulative relative leak rate distribution

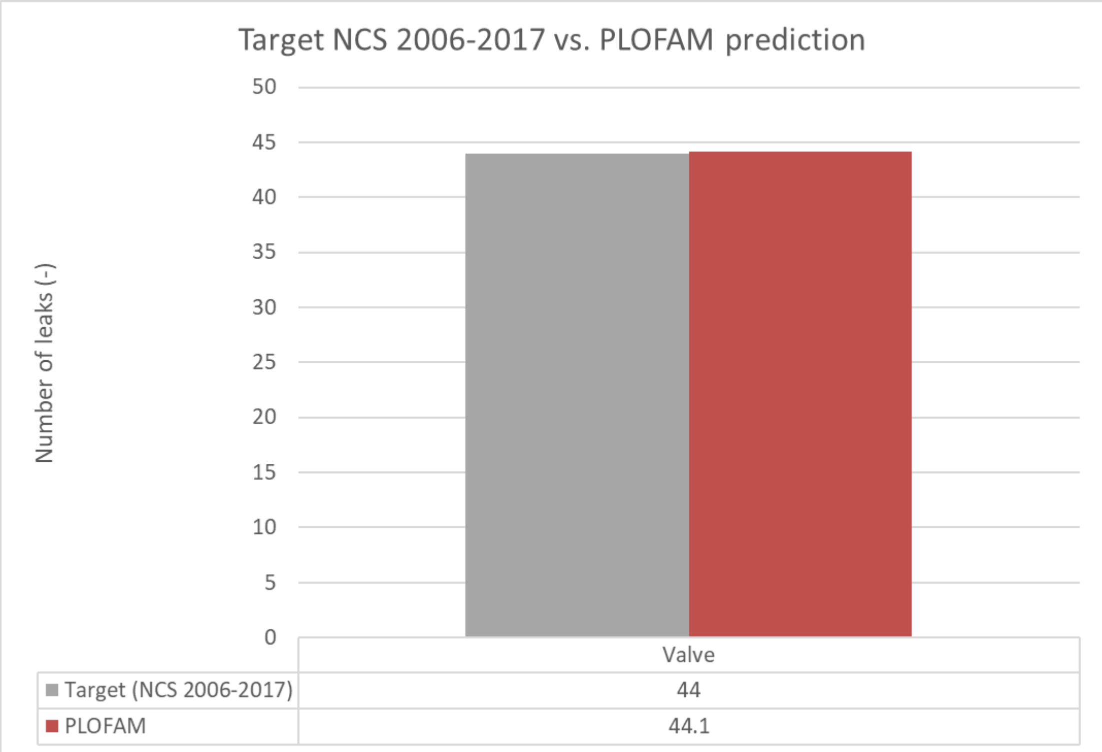


Figure 6.6 – Valve validation: prediction PLOFAM vs. observed leaks at NCS in same period

7 Standard flange

7.1 Standard flange equipment type

The equipment category 'Standard flange' envelope all types of couplings used at an offshore installation (dominated by ASME RTJ, ASME RF/FF and clamp connections (*e.g.* Grayloc) except compact flanges (see Chapter 8). The generated hole size frequency distribution for standard flanges therefore must be considered to represent the average for all types of couplings. The available data does not allow for assessment of specific failure frequencies for the various types of couplings.

7.2 Standard flange PLOFAM parameters

The distribution of leak at installations on the NCS with respect to cause is shown in Figure 7.1 (Ref. /3/). The typical latent errors related to interventions are:

- Too low/high moment when tensioning
- Wrong (or no) gasket used
- In general, not following procedure when installing the flange

It is judged that such latent errors are more likely for large equipment than small equipment because:

- Larger flanges are more difficult to handle
- Larger flanges require more moment when tensioning the bolts
- A larger flange surface is more challenging to mount correctly

These factors support a moderate positive trend in both $\varphi(D)$ and $\theta(D)$ for increasing equipment dimension, which is consistent with the observed trend in the HCR data (see TN-6 in Ref. /1/). However, it is judged that the implemented measures after the projects run in the industry in Norway after year 2000 to eliminate failure modes has taken effect, and thereby also will affect the trends with equipment dimension. More strict training procedures (*e.g.* certified training certificate required) has been implemented (*e.g.* reducing the occurrence if incidents caused by failure of gaskets) and ring type joint flanges are used more extensively, also eliminating leaks caused by gasket failure (Ref. /2/).

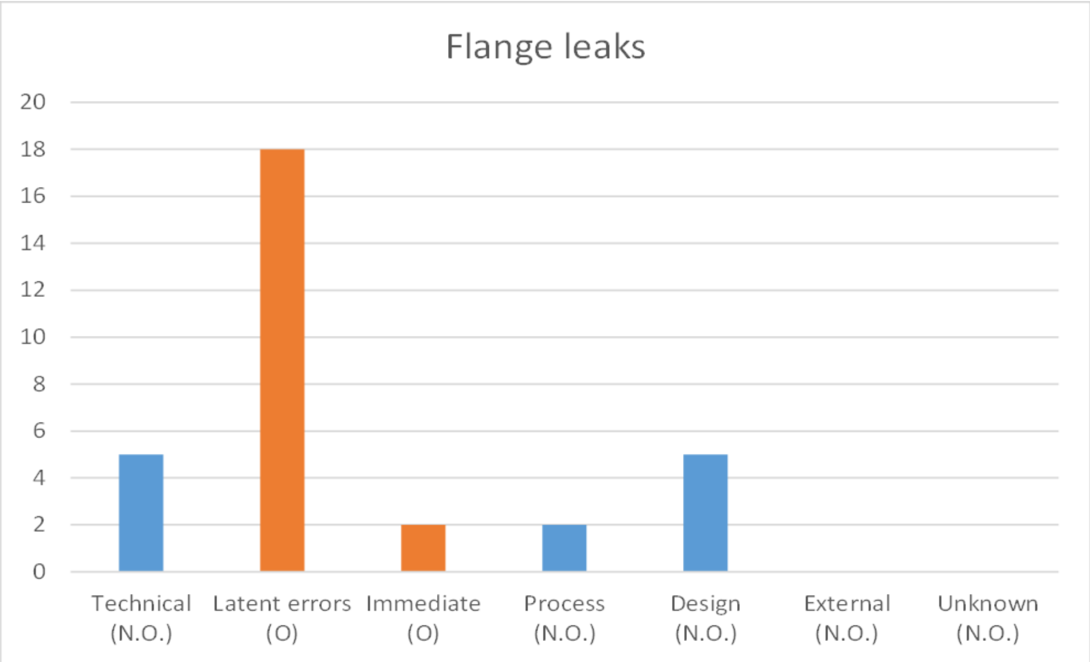


Figure 7.1 - Standard flanges: Leaks at installations on the NCS classified according to cause (Ref. /3/)

The resulting model parameters for standard flanges are summarized in Table 6.1.

A slight decreasing trend of $\varphi(D)$ with equipment dimension gives the best result compared with the historical data from installations on NCS. However, a constant trend is applied in lack of causal arguments supporting a decreasing trend. Based on the failure modes, a rather steep derivative of $\theta(D)$ has been implemented.

Full rupture (hole sizes equal to the equipment diameter) is considered to be a remote event for all types of ASME flanges. The typical leak scenario is failure of the gasket. In most cases only a part of the gasket is blown out. Failure of gasket can however be disregarded for ASME RJ. Metal ring seal is increasingly used at new installations (at NCS), which means that gasket failure is expected to be a more prominent failure mode at older installations. Clamped connections may fail resulting in full ruptures. Also other types of connections (*e.g.* threaded) are used, which means that the parameters must be set reflecting the average for all types of couplings. This also affects the applicability of the α parameter truncating intermediate hole sizes. For ASME RF and FF, it is judged that a rather high α value should be used to reflect that the failure modes are dominated by blow out of the gasket. The hole size in such cases are much smaller than the equipment dimension. This is demonstrated in section 4.2 and 4.3 in TN-5, where it is shown that a high α (> 0.9) is consistent with partly or fully blown out flange gasket. For other types of couplings, we have not identified equivalent failure modes forming basis for setting the parameter value α. Hence, it is recommended that future analysis address potential failure modes for qualitative assessment of the relative difference between the various couplings.

Based on above, α is set to 0.5 to suppress the frequency for intermediate hole sizes.

In Figure 6.5, the complementary cumulative relative leak rate distribution is shown. The relative distribution obtained from UKCS installations is also displayed, demonstrating that the data from NCS and UKCS installations for valves are quite similar. The model demonstrates a good fit with the historical data.

The trend with equipment dimension is visualized in Figure 6.3 ($\varphi(D) \cdot F_{hist}$, $\theta(D)$ and $\theta(D) \cdot F_{hist}$).

In Figure 6.4, resulting hole size frequency distributions for a few flange dimensions are shown.

Table 7.1 – Standard flange parameters

Parameter	Description
F_{hist}	Significant leaks: $2.5 \cdot 10^{-5}$ [year^{-1} equipment^{-1}] Marginal leaks: $5.0 \cdot 10^{-6}$ [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	18.0
M_D	-1.45
B_D	$5.0 \cdot 10^{-3}$
α	0.5

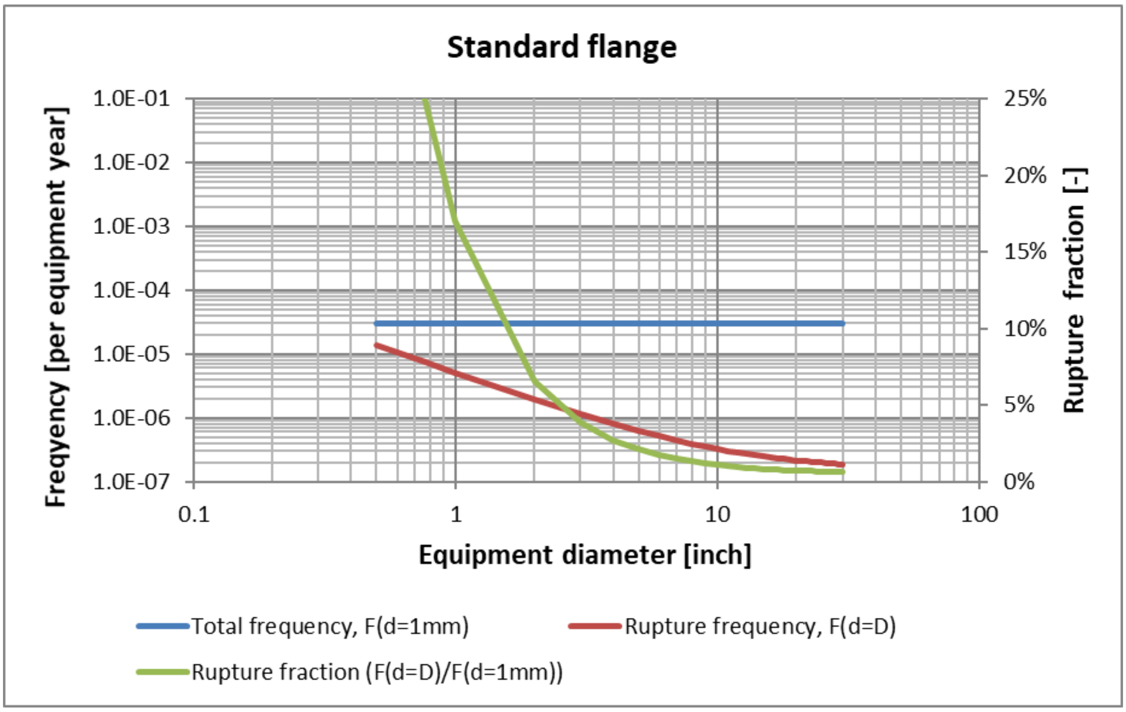


Figure 7.2 – Standard flange: total frequency, rupture fraction (full bore hole fraction) and rupture frequency

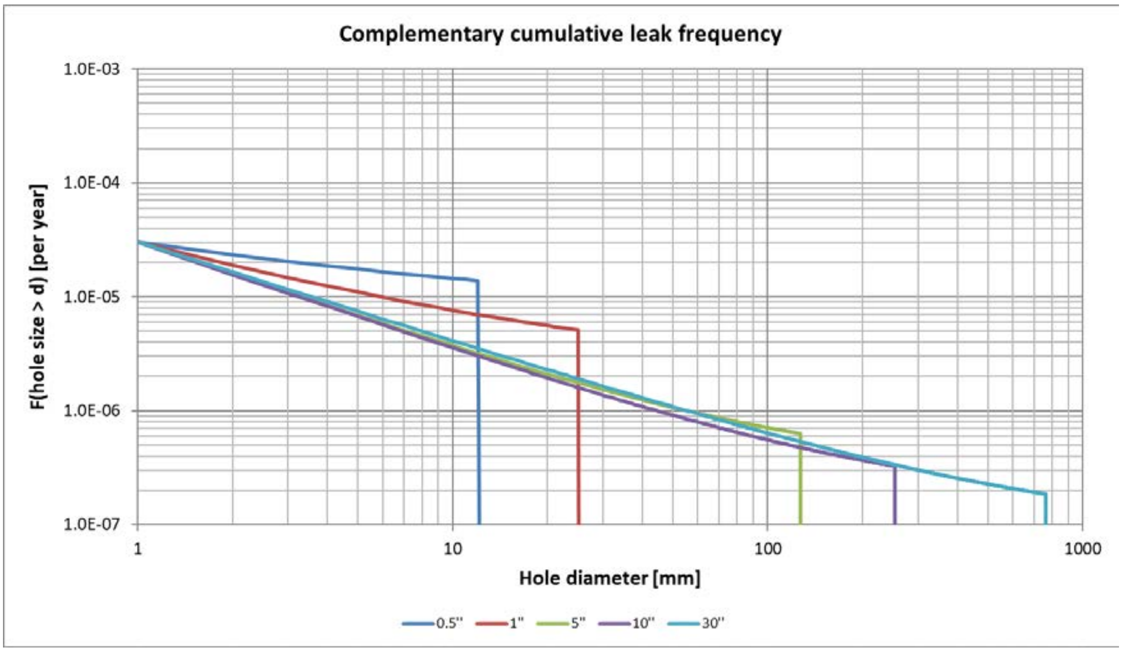


Figure 7.3 – Standard flange: hole size distribution for various equipment dimensions

The performance of the PLOFAM model for standard flanges with respect to the established targets is shown in Figure 6.5 and Figure 6.6. The results show that the model is able to describe the historical leak rate distribution and the number of leaks observed at installations on NCS.

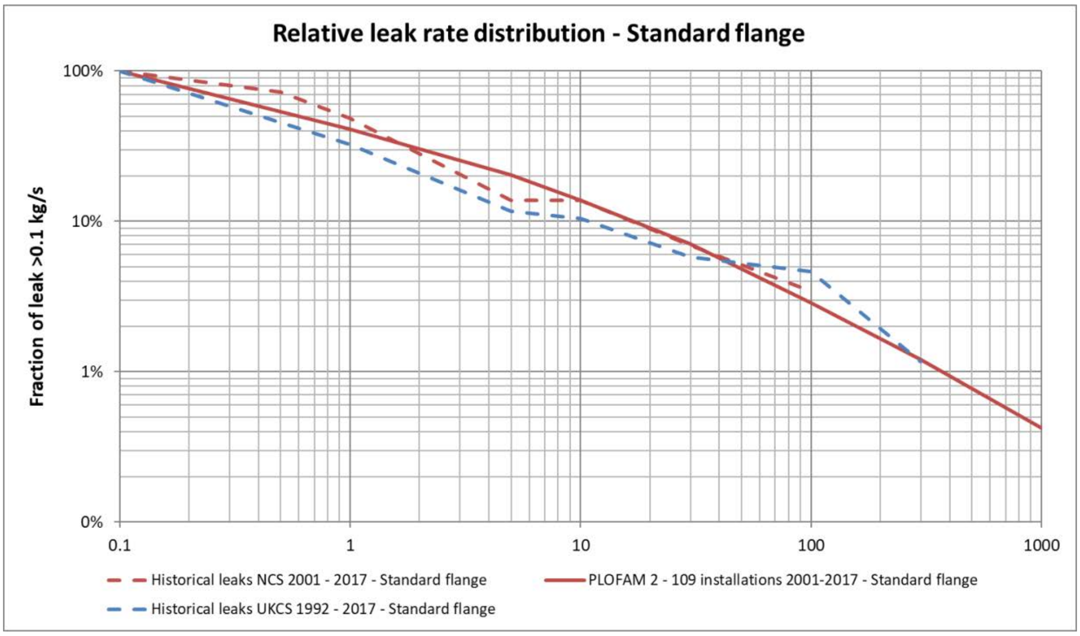


Figure 7.4 – Standard flange: complementary cumulative relative leak rate distribution

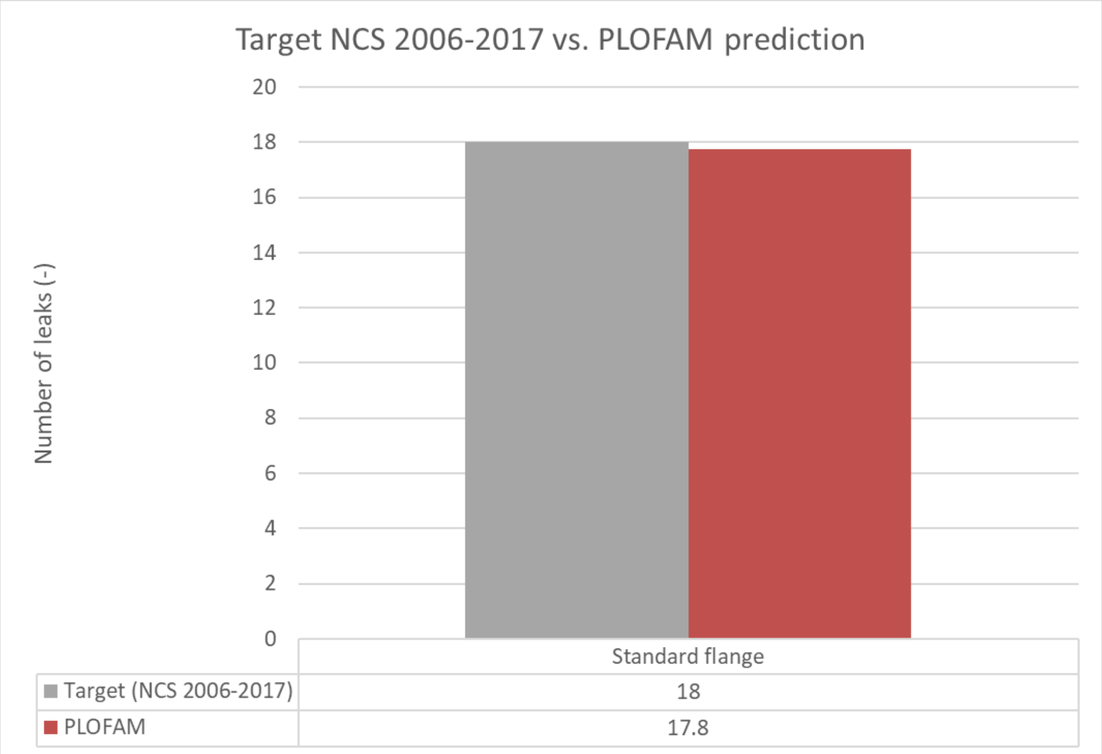


Figure 7.5 – Standard flange validation: prediction PLOFAM vs. observed leaks at NCS in same period

8 Compact flange

8.1 Compact flange equipment type

Compact flange covers all types of compact flanges.

8.2 Compact flange PLOFAM parameters

The following data are available with regard to establish specific model parameters for compact flanges:

- No population data on equipment years covering the use of compact flanges at installations located on the UKCS is available. It is not known whether any of the leaks associated with standard flanges in HCRD actually did stem from a compact flange
- No leaks in the NCS dataset (seen TN-2) are known to be originating from compact flanges. Furthermore, it is not known that leaks having an initial leak rate above 0.1 kg/s originating from compact flanges have occurred on land based facilities in Norway
- The total number of equipment years at NCS for compact flanges installed in riser systems, subsea systems and process systems (both offshore and onshore) since the first compact flange was installed is estimated to be in the interval 500,000 – 1,000,000 years (Ref. /4/). This figure is based on interview with vendors supplying compact flanges to industry in Norway

Based on this, it is concluded that the underlying leak frequency for compact flanges should comply with 0 leaks occurring in 500,000 equipment years at installations on the NCS. This is considered to be a conservative approach as the number of equipment years most likely is significantly larger than 500,000 equipment years.

Based on a brief review of causes for leaks it is judged that the probability for large holes arising compact flanges are limited. The probability for latent causes, which is important for standard flanges, is significantly less because correct installation can be visually inspected (a compact flange is only installed correctly if there is no visual opening between the flange surfaces). Opening of a pressurized bolted joint by mistake have caused some sudden large releases of fluids from standard offshore (ASME) flanges and clamp connectors. This event may also be possible with compact flanges, but it is highly unlikely because the design will provide a pre-warning small leakage far before a critical leakage will occur, and thus enable the operator to reverse the operation.

The compact flange is also judged not to be vulnerable in an over-pressurization scenario because when assembled, this bolted joint is normally designed to remain leak tight beyond the yield stress limit of the adjoining pipe.

Leakage can develop from bolt relaxation due to the dynamics of bolted joints with gasket, such as standard offshore (ASME) flanges, when exposed to severe vibrations or other cyclic loads. With "Non-gasketed" compact flanged joints this event is not possible because the assembled joint behave static through all load situations within allowable loads for the adjoining piping system. Analysis and destructive testing have demonstrated that welded joints outside the compact flanged connection will always fail before leakage can develop in the bolted joint when the piping system is subject to fatigue loads.

Based on operational experience, the failure mode thought to be the most likely cause for a future leak in a compact flange is degradation caused by a corrosive internal medium carving out a small hole in between the flange surfaces. Such a process will develop slowly over time and will most likely be detected. If a leak finally materializes, the hole is probably quite small, *i.e.* in the range of a few millimetres. Therefore, it is concluded to apply a rather high value for α. The probability for intermediate hole sizes are judged to be remote. α is therefore set to 0.9.

Based on the above (supported by Ref. /4/), the suggested model parameters are presented in Table 8.1. All leaks from compact flanges are considered to be significant leaks, which is based on that the most likely failure mode (small hole in between the flange surfaces due to corrosion) probably would result in a significant leak during normal operation. Figure 8.2 displays model result for various equipment dimensions. The model for standard flanges is included for comparison. The plot shows that the deviation between the models increase with increasing hole size. For big hole sizes, the relative difference between a standard flange and a compact flange approach a factor of 100. This is because the full bore hole fraction (*i.e.* $\theta(D)$) is judged to be considerably less for compact flanges opposed to standard flanges.

The stochastic uncertainty of the given data (0 leaks in 500,000 equipment years) can be assessed based on the Poisson distribution. Application of the Poisson distribution for this purpose requires that the leaks occur independently. This is not entirely true as it is reasonable to assume that lesson learnt from incidents will have some effect on the likelihood of leaks occurring in the future.

Figure 8.1 shows the cumulative Poisson distribution for 500,000 equipment years based on the standard flange failure rate in PLOFAM (F_{hist}= $2.6 \cdot 10^{-5}$ per year for significant and marginal leak in total, which applies for equipment dimension in the interval 3 - 4" for standard flanges (*i.e.* $\varphi(D) \approx 1$)). Using a correction factor of 10 for compact flanges, and rounding up to $3.0 \cdot 10^{-6}$ per year, results in a reasonable likelihood of observing zero leaks in 500,000 equipment years (*i.e.* about 20 %). The expected number of leaks using 20 % as the acceptable probability for being fortunate in 500,000 equipment years becomes 1.5. This is a more conservative approach than used to set the targets for the other equipment in PLOFAM (see Chapter 5), where a 50% probability is used. Using the standard approach, the expected number of leaks would be 0.69. This model accounts for unknown leaks from compact flanges. Note also that the actual number of compact flange years most likely is significantly higher than 500,000.

The methodology described above for setting the parameters for compact flanges is stricter than the approach used when setting the parameters for all other equipment types in PLOFAM. In general, best estimate is targeted. The rational for the conservative approach is that the uncertainty associated with the available data is more prominent. It is expected that an even lower F_{hist} for compact flanges can be justified in the future based on an improved quality of the data.

Table 8.1 - Model properties for compact flange based on NCS population dataset (see TN-2)

Parameter	Description
$\varphi(D)$	It is judged that there is no dependency with equipment dimension, which means that $\varphi(D)$ is set to 1
$\theta(D)$	No evidence for that $\theta(D)$ should be dependent on compact flange dimension has been identified. It is concluded to estimate $\theta(D)$ by setting A_D to zero and B_D to 0.001. 0.001 means that a full bore hole (*i.e.* rupture) will occur in 0.1 % of the cases
F_{hist}	Significant leak: $3.0\cdot10^{-6}$ per year Marginal leak: disregarded
α	0.9

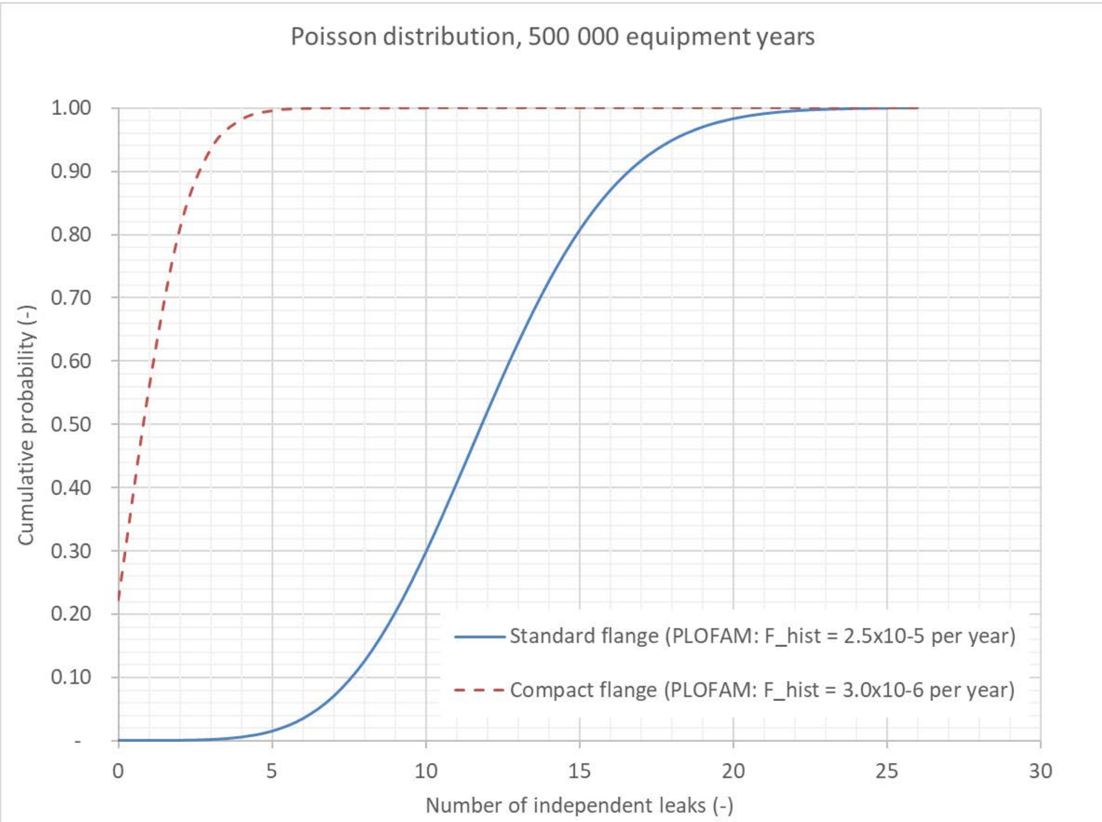


Figure 8.1 - Poisson distribution for 500,000 equipment years based on compact flange failure rate of F_{hist}= $3.0\cdot10^{-6}$ per year and standard flange failure rate of F_{hist}= $2.5\cdot10^{-5}$ per year. The calculation for a standard flange is based on a dimension in the interval 3 - 4"

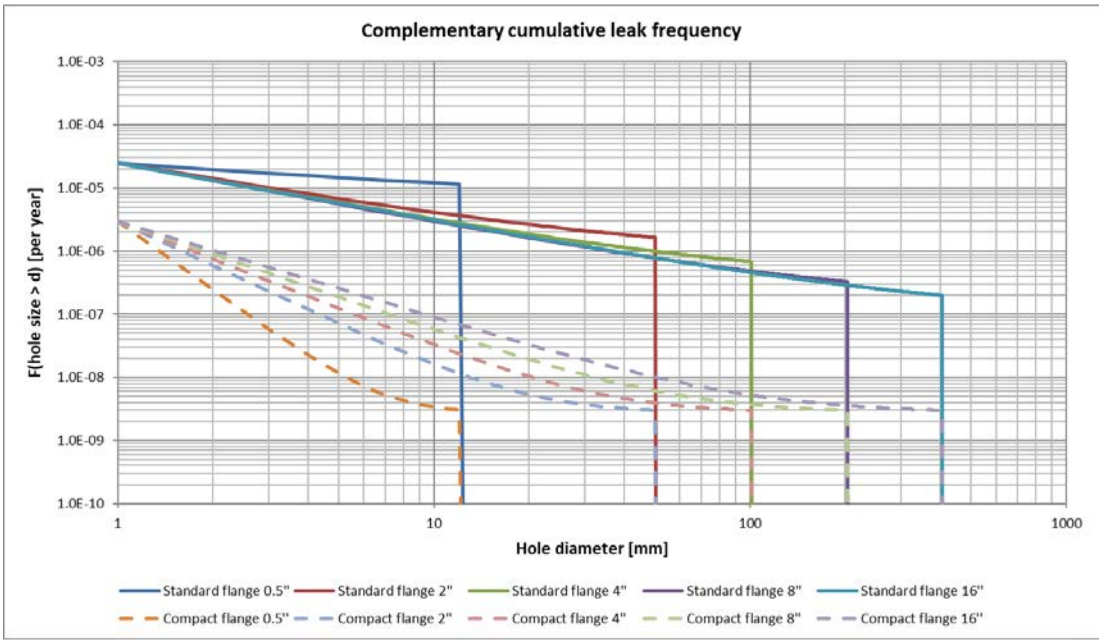


Figure 8.2 – PLOFAM model for significant leaks for standard flanges and compact flanges for various equipment dimensions

9 Instrument

9.1 Instrument equipment type

The equipment category ‘Instrument’ envelope all types of small scale instruments used at an offshore installation. There are many types of instruments measuring different parameters, such as pressure and temperature. Flow meters embedded in the main process flow is not regarded as an instrument in PLOFAM, and is should normally be counted as two flanges (one at each side of the flow meter).

Instruments are typically attached to process equipment and process pipes. A typical design is a ¾” connection where the instrument tubing is connected downstream a modular valve by use of a threaded connection. This is shown in Figure 9.1. The instrument tubing is typically 10 mm.

In PLOFAM, the model for instruments is simplified by fixing the dimension for instrument to ½”. This means that potential hole size related to ruptures in the modular valve (or more generally, the valves upstream the instrument tubing) is not directly covered by the model. On the other hand, the inner diameter of the modular valve and the instrument tubing is normally smaller than ¾” and ½” respectively. Also, based on experience from the observed events, leaks from the modular valve are judged to be rare. Hence, focusing the model on the dimension of the tubing is in accordance with observed failure modes. 10 mm could have used as the upper hole size, but ½” (12.7 mm) is used to embed a fraction of the bigger holes arising from leaks in the modular valve (¾”).

The valves isolating the instrument tubing from the process system is considered to be a part of the instrument in PLOFAM. This is to ensure that the model is consistent the equipment counts forming the basis for the NCS population data. In the future, one should try to establish equipment counts where the instrument tubing, the instrument itself, the valves and the flanges is counted separately. Then specific models for the different parts could be derived:

- instrument including tubing,
- the valves on the instrument connection
- couplings (*e.g.* threaded or flanged)

Based on above the generated hole size frequency distribution for instrument must be considered to represent the average distribution for all types of instruments. The available data does not allow for assessment of specific failure frequencies for the various types of instruments.

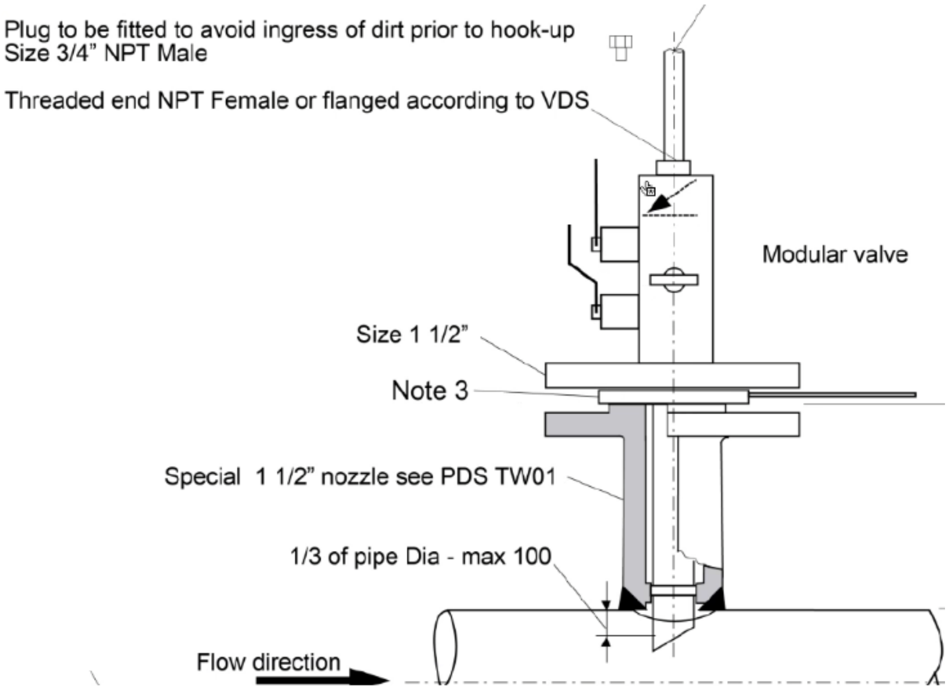


Figure 9.1 – Typical connection of instrument to a process system

9.2 Instrument PLOFAM parameters

Leaks in instruments is typically caused by failure of the instrument tubing due to technical causes, such as

- fatigue induced by vibration
- improper centre of gravity of the instrument and inadequate support of instrument
- erroneous mounting of equipment (*e.g.* excessive torque)

A common failure is shown in Figure 9.2, where the tubing has failed due to fatigue resulting from improper support of the heavy instrument.

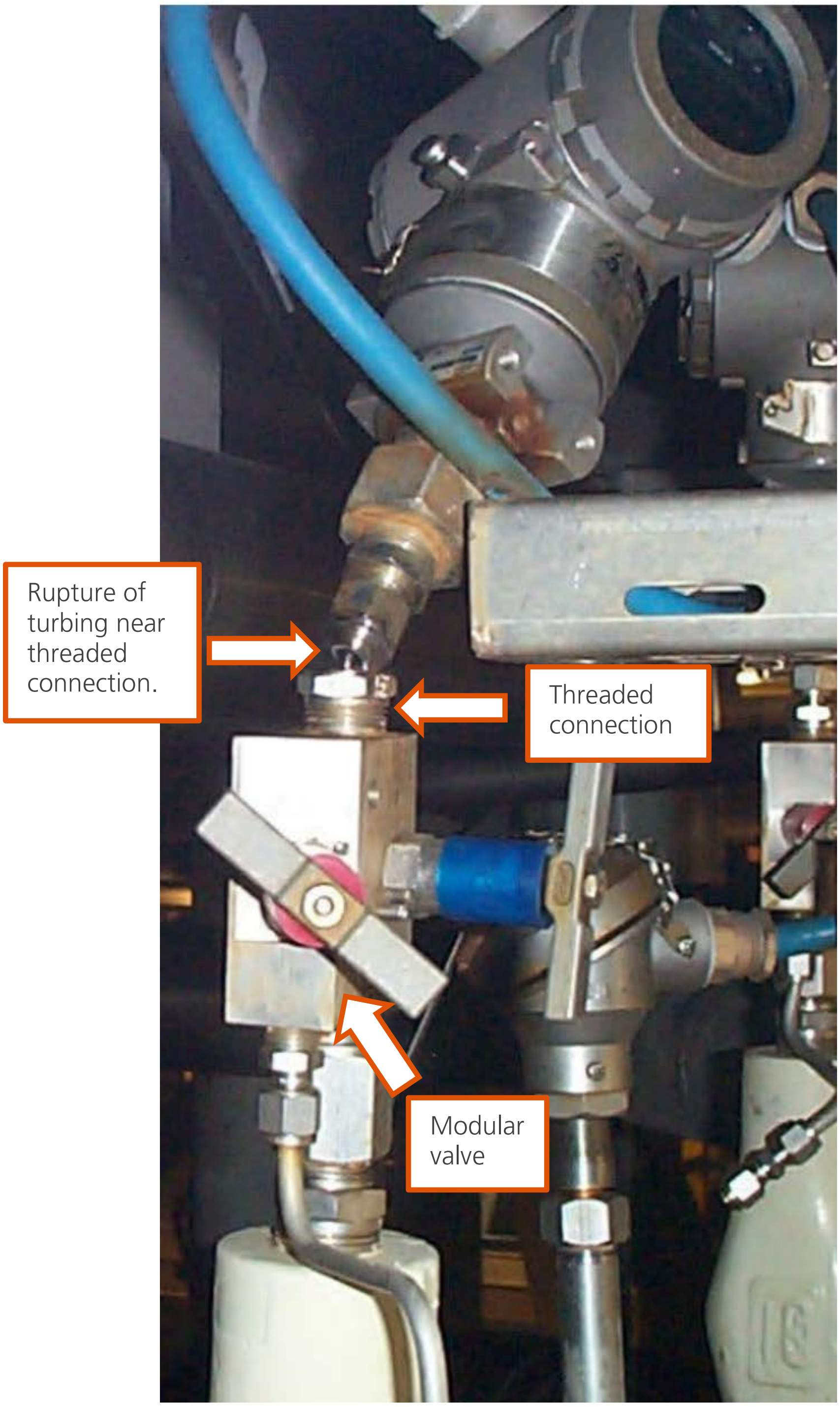


Figure 9.2 – Typical failure of instrument tubing

The resulting model parameters for instrument are summarized in Table 6.1.

In Figure 6.4, the resulting hole size frequency distribution is shown (dimension of½" to be used for all instruments). In special cases where the instrument has much higher equipment dimension than ¾" (> 1.5 inch) one should rather use the models for flanges and valves to model the leak frequency.

Table 9.1 – Instrument parameters (½" to be used for all types of instruments in PLOFAM)

Parameter	Description
F_{hist}	Significant leaks: $1.3{\cdot}10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.15
α	0

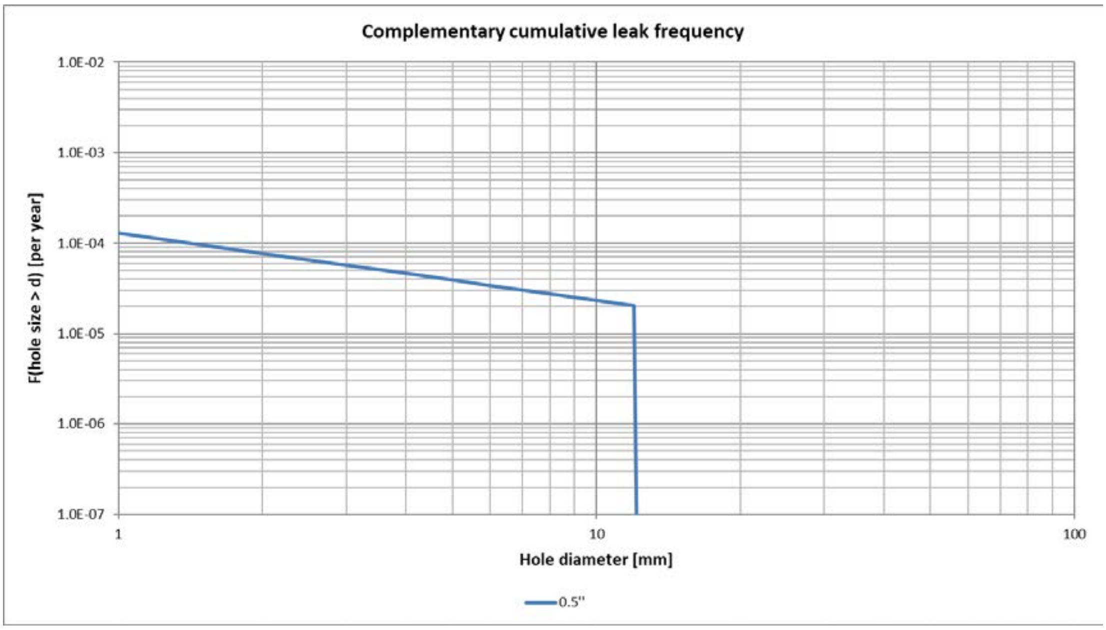


Figure 9.3 – Instrument hole size distribution to be used for all instruments

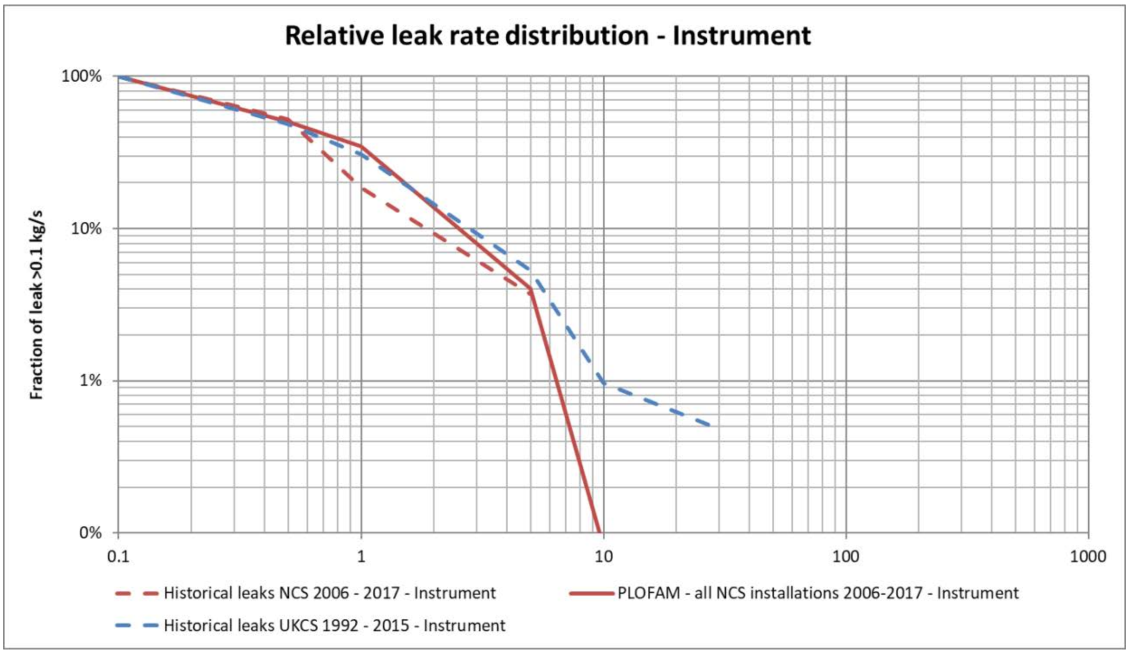


Figure 9.4 – Instrument: complementary cumulative relative leak rate distribution

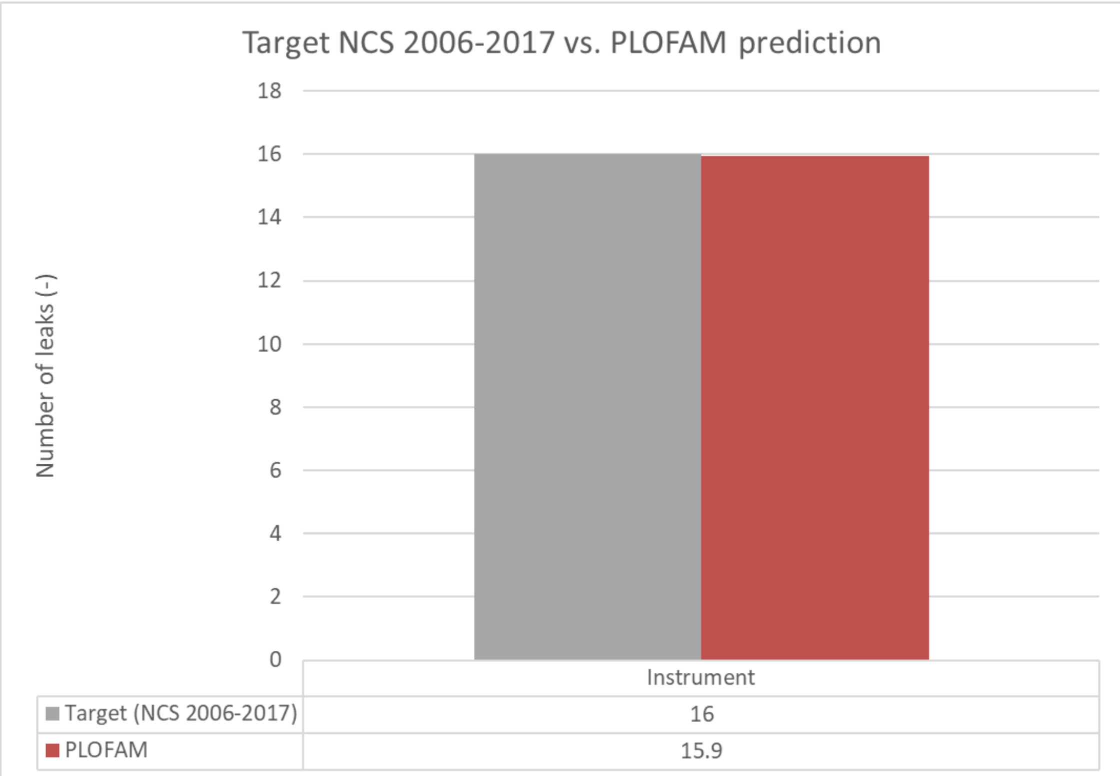


Figure 9.5 – Instrument validation: prediction PLOFAM vs. observed leaks at NCS in same period

10 Steel pipe

10.1 Steel pipe equipment type

Steel pipe are any steel pipe used in a process system except instrument tubing which is covered by the model for instruments.

Two models have been established;

- a model based on a generic fraction added to the total frequency estimate for the other equipment types. This model is to be applied if the steel pipes are not counted
- a specific model of the leak frequency per steel pipe meter

10.2 Steel pipe PLOFAM parameters

A generic fraction of 12% generates an estimate of the number of leaks in the period 2006-2017 balancing the number of observed leaks at NCS (see Figure 10.2). The leak frequency from steel pipes ($F_{steel\ pipe}$) is calculated by summing all other contributors and dividing by (1-0.12) according to the following expression:

$$F_{steel\ pipe} = F_{exclusive\ steel\ pipe} \cdot \left(\frac{1}{1-0.12} - 1\right) = F_{exclusive\ steel\ pipe} \cdot \left(\frac{3}{22}\right)$$

The relative leak rate distribution will be identical with the weighted average distribution for all equipment types. The distribution is shown in Figure 10.1 together with the historical distribution for NCS and UKCS. These distributions are sensitive to stochastic effects. For instance, the distribution for NCS for massive leaks is governed by the single incident in 2006 having an initial leak rate of 930 kg/s.

The same generic steel pipe fraction applies to both significant and marginal leaks.

F_{hist} for steel pipes (per meter steel pipe) have been estimated by utilizing the available equipment counts of steel pipes in the NCS population dataset. Equipment counts are available for 24 of the installations in the population dataset.

Using the average contribution from steel pipes (12 %), the number of predicted leaks by PLOFAM from steel pipes in the period 01.01.2001 – 31.12.2017 is 3.2 for those 24 installations, which becomes the target for deriving a model for steel pipes per meter.

Based on the observed causes for leaks from steel pipes, it is considered reasonable that the HCR data displays a decreasing trend with increasing equipment dimension (see TN-6 in Ref. /1/). Causes for leaks stemming from pipes are dominated by technical errors such as corrosion, failure of welds and fatigue (Ref. /3/). Generally, the wall thickness of pipes increases with increasing equipment dimension, which implies that the big pipes is more robust than small pipes. This argument also applies for external impacts. The behaviour of $\varphi(D)$ outside the range of the HCR data (*i.e.* below about 1.5" and above about 16") is considered more uncertain than within the range of the HCR data. The parameter values are therefore set to avoid large shift with increasing equipment dimension.

The casual arguments for a decreasing total frequency for leaks with equipment dimension for steel piping is judged to apply also for the full bore hole fraction. The general causal argument is that the robustness of the pipe increase with increasing equipment dimension.

Although identified causal arguments and data from HCRD are consistent, the uncertainty related to assessment of the specific parameter values of $\theta(D)$ for steel pipe is significant. However, the uncertainty is reduced considerably by the validation model. The validation model demonstrates that the defined parameters of $\varphi(D)$ and $\theta(D)$ result in an acceptable fit to the observed leaks originating from steel pipes at installations on the NCS.

The parameters are summarized in Table 10.1.

Running the validation model for the 24 installations results in an estimate of 3.2 leaks originating from steel pipes using the specific model, which equals the number of leaks applying the generic model (see Figure 10.4). The relative leak rate distribution for the 24 installations is shown in Figure 10.3, demonstrating that the specific model will generate about the same relative leak rate distribution as the generic model.

Table 10.1 – Steel pipe parameters

Parameter	Description
F_{hist}	Significant leaks: $1.4 \cdot 10^{-5}$ [year^{-1} meter^{-1}] Marginal leaks: $2.0 \cdot 10^{-6}$ [year^{-1} meter^{-1}]
A_0	4.20
M_0	-0.3
A_D	17.6
M_D	-1.75
B_D	0.001
α	0
$Generic\ steel\ pipe\ fraction$	0.12 Applies to both significant and marginal leaks

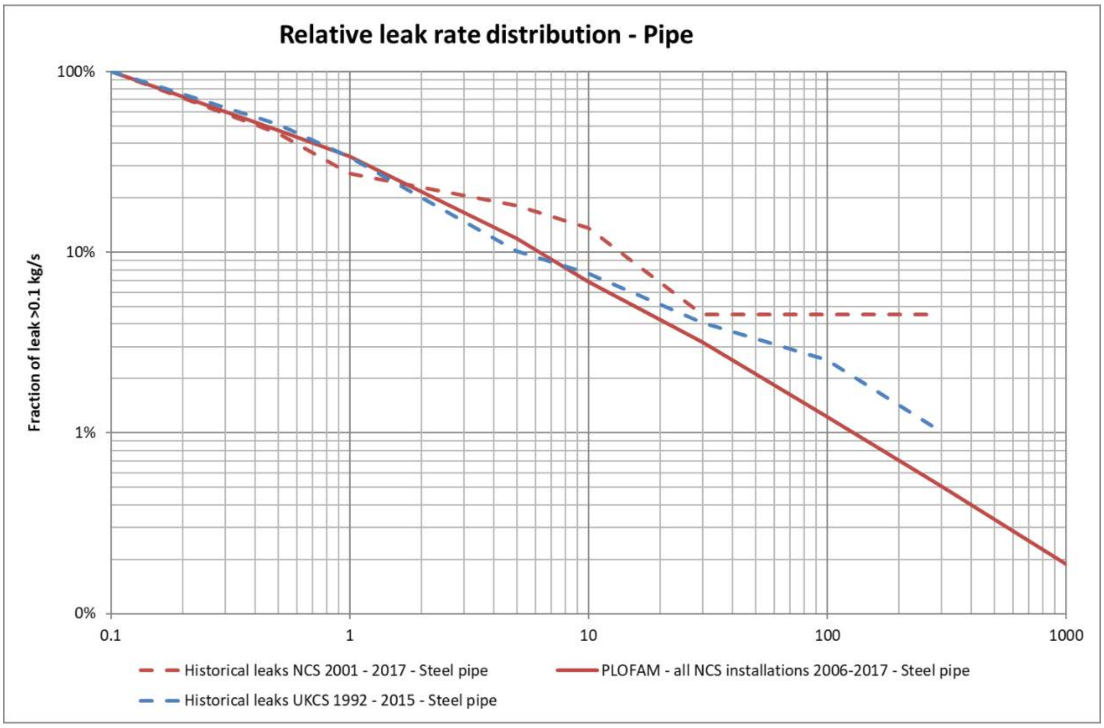


Figure 10.1 – Steel pipe: complementary cumulative relative leak rate distribution using average contribution of 12%

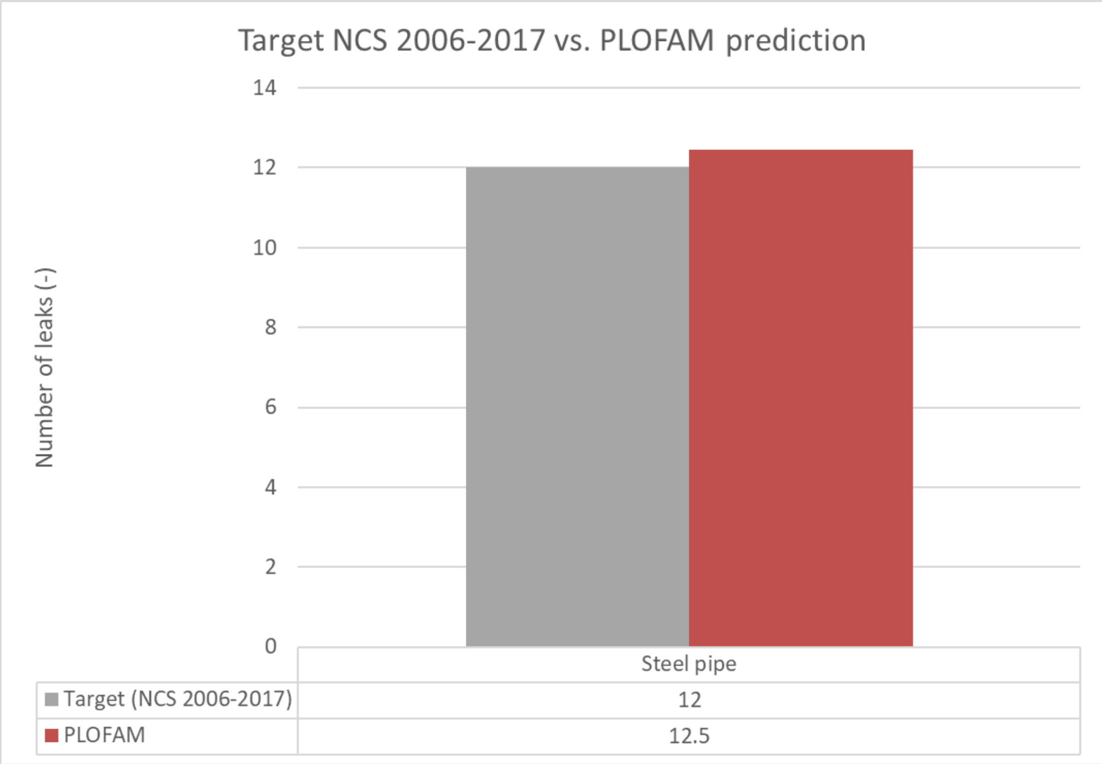


Figure 10.2 – Steel pipe validation: prediction PLOFAM vs. observed leaks at NCS in same period

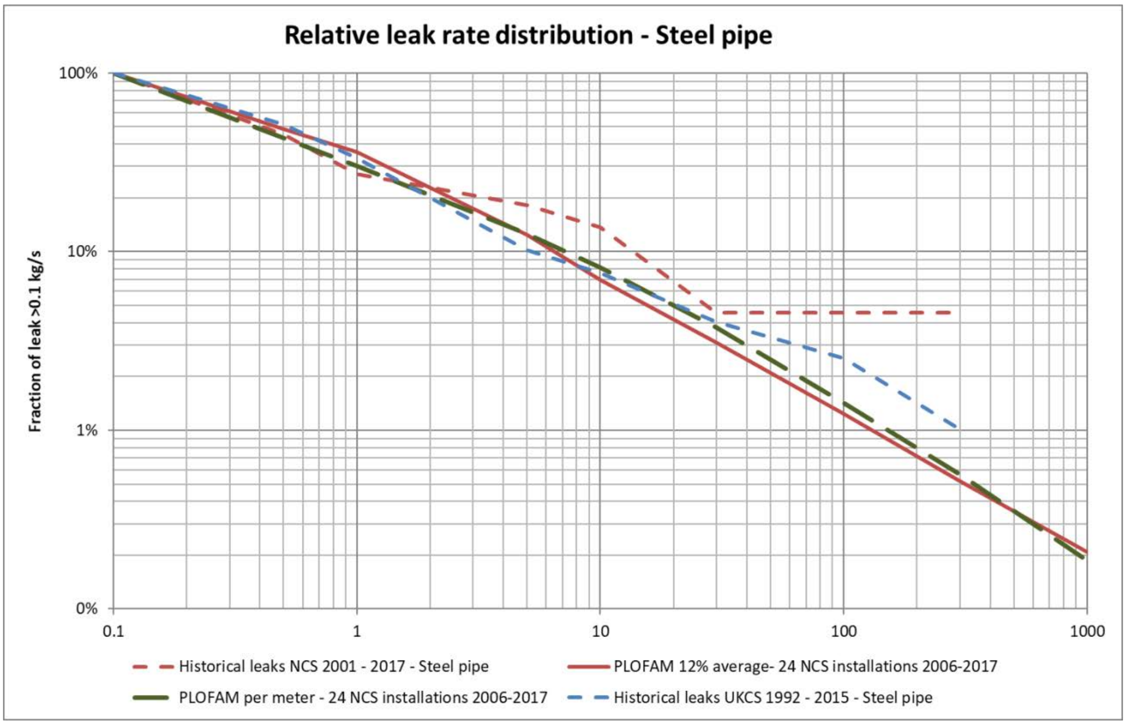


Figure 10.3 – Steel pipe: including complementary cumulative relative leak rate distribution using specific model per meter for 24 installations

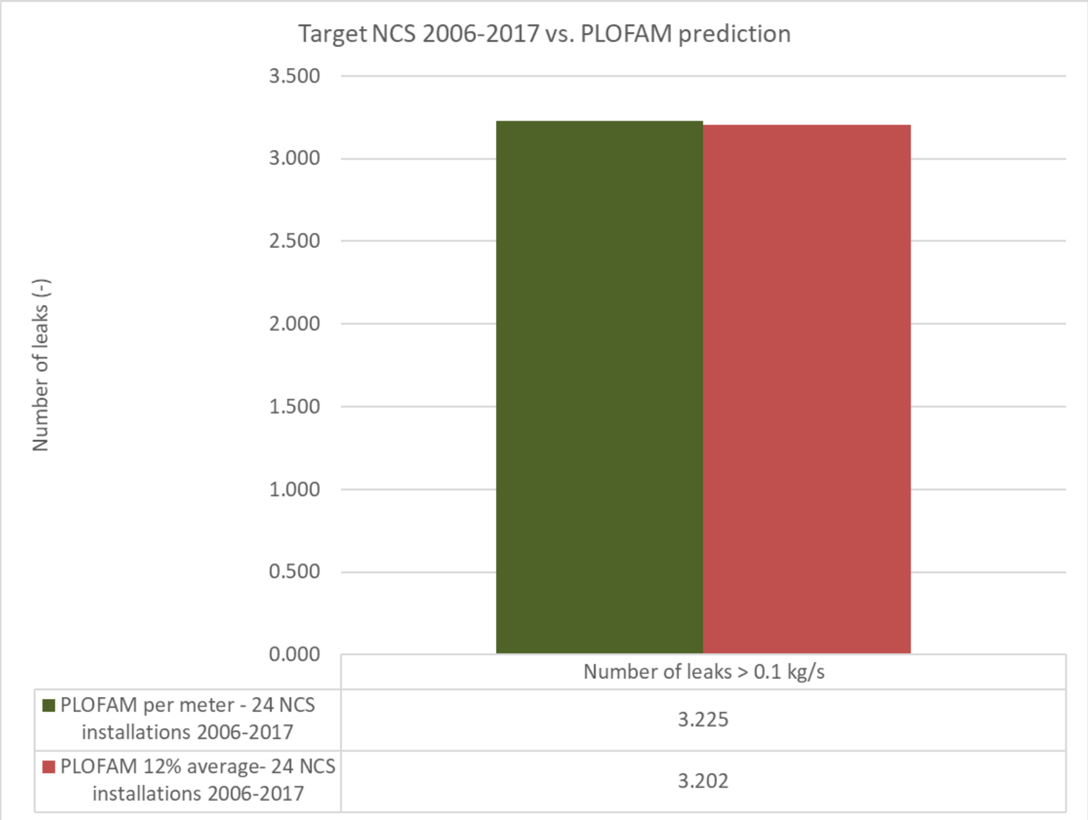


Figure 10.4 – Steel pipe: prediction generic model vs. specific model per meter for 24 installations in operation in the period 2006-2017

11 Compressor

11.1 Compressor equipment types

There are two types of compressors in terms of the technical function:

- Centrifugal compressors
- Reciprocating compressors

The UKCS data indicate that the leak frequency from reciprocating compressors is a factor of 10 higher than the frequency originating from centrifugal compressors (see Table 5.3). There have not been registered leaks from reciprocating compressors at NCS. Considering the limited number of equipment years for reciprocating compressors at NCS, no observed leaks is very likely despite the underlying failure frequency for reciprocating compressors being much higher than the failure frequency related to centrifugal compressors. In this regard, it should be noted that there is some uncertainty regarding the type of compressor recorded in the NCS population data set.

Based on the UKCS data (indicating a rather prominent difference between the two types of compressors), it has been concluded to derive different models for centrifugal and reciprocal compressors. This is supported by that the technical function is different for the two types of compressors. Reasons for the difference in leak frequency could be that a reciprocating compressor has more wearing parts (*e.g.* sliding parts), operates in general at higher pressures and generate more vibrations.

11.2 Compressor PLOFAM parameters

The parameters derived for compressors are shown in the table below. In lack of statistical data and analysis of failure modes related to compressors, the total leak frequency and rupture fraction is set to be independent of equipment dimension. The equipment dimension for compressors is defined to be the dimension of the inlet pipe.

The results show that the frequency for leaks from reciprocating compressors is significantly higher than the leak frequency originating from centrifugal compressors. This result is somewhat uncertain as it is based on limited statistical data for reciprocating compressors, and should be addressed further in future analysis. A failure mode analysis is recommended for qualitative assessment of the relative difference in expected failure modes for the two types of compressors. This means that a cost-benefit analysis trading off the application of either type must be used with care in the decision-making process.

The resulting validation with respect to the NCS data set is shown in Figure 11.3.

In Figure 11.1 and Figure 11.2, resulting hole size frequency distributions for a few compressor inlet dimensions are shown.

Table 11.1 –Compressor parameters

Parameter	Centrifugal compressors	Reciprocating compressors
F_{hist}	Significant leaks: $1.3{\cdot}10^{-3}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]	Significant leaks: $5.0{\cdot}10^{-3}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1	1
M_0	0	0
A_D	0	0
M_D	0	0
B_D	0.006	0.01
α	0	0

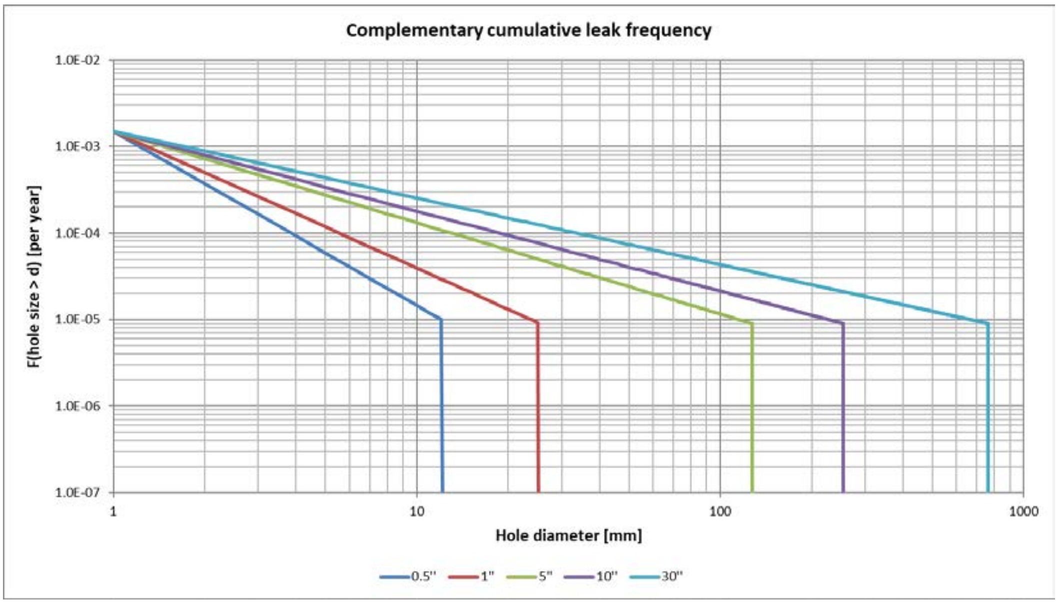


Figure 11.1 – Centrifugal compressor: hole size distribution for various equipment dimensions (pipe inlet)

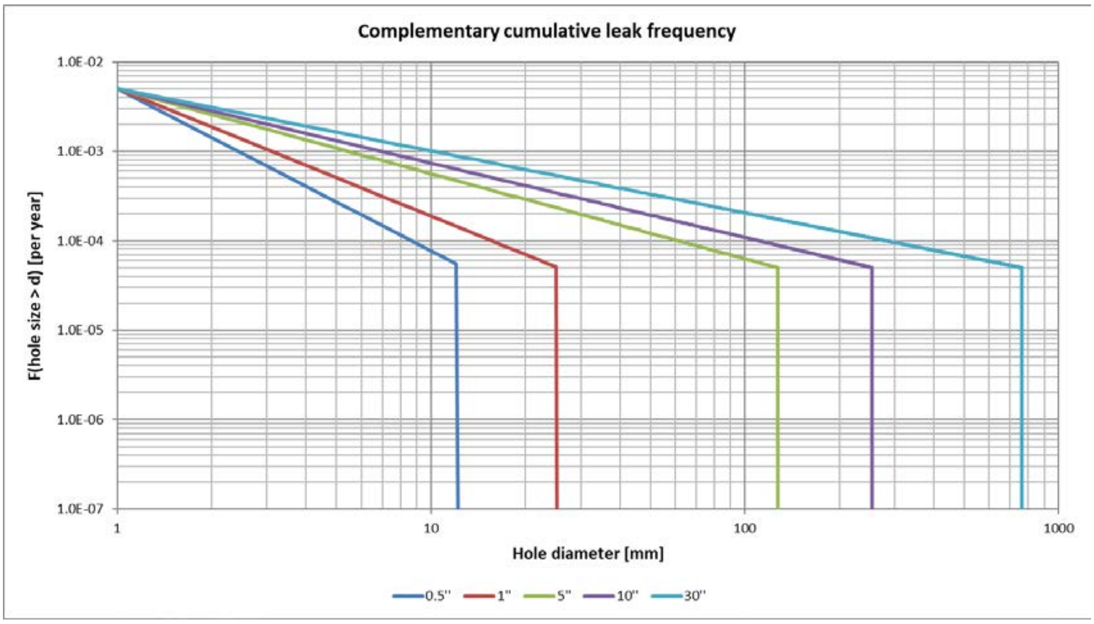


Figure 11.2 – Reciprocating compressor: hole size distribution for various equipment dimensions (pipe inlet)

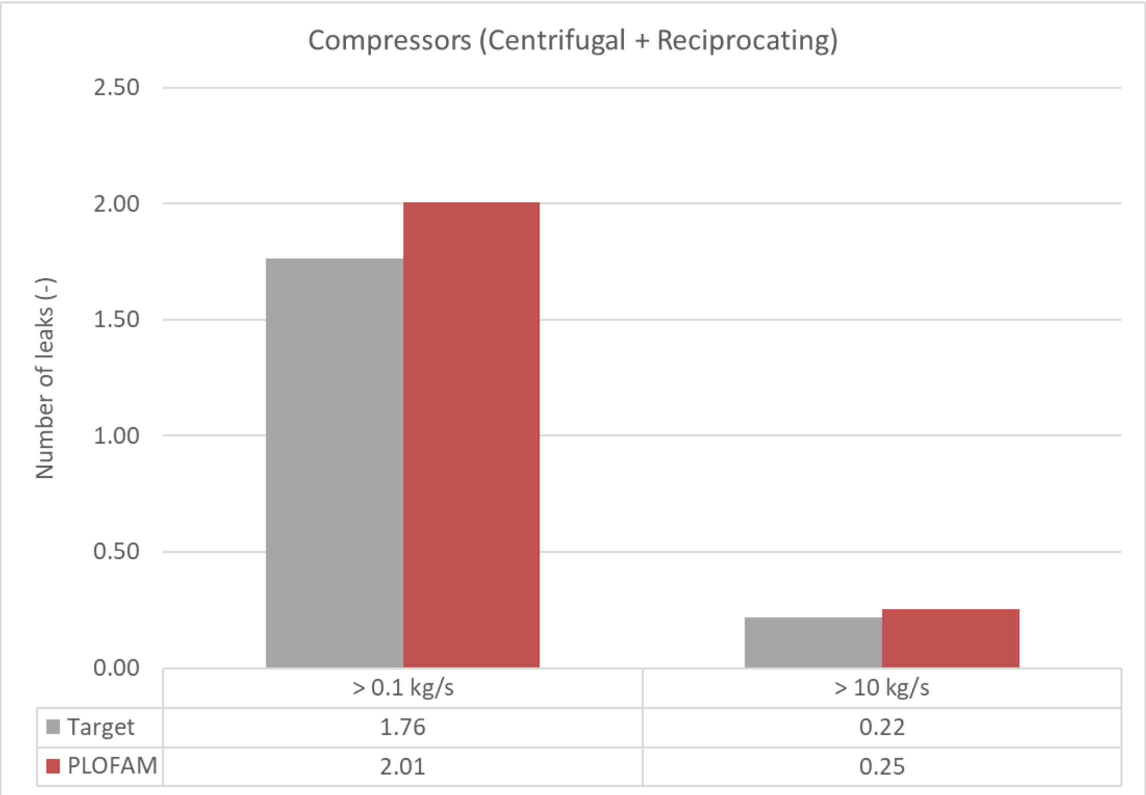


Figure 11.3 – Compressor validation (centrifugal + reciprocal compressors): prediction PLOFAM vs. observed leaks at NCS in same period

12 Pump

12.1 Pump equipment types

There are two types of pumps in terms of the technical function:

- Centrifugal pumps
- reciprocating pumps

The UKCS data indicate that the leak frequency from reciprocating pumps and centrifugal pumps are quite similar. There have not been registered leaks from reciprocating pumps at NCS. That could be due that the wrong type of pumps has been recorded in the data set or that all pumps are lumped into one class.

Based on the UKCS data it has been concluded to derive one common model for centrifugal and reciprocal pumps.

12.2 Pump PLOFAM parameters

The parameters derived for pumps are shown in the table below. In lack of statistical data and analysis of failure modes related to pumps, the total leak frequency and rupture fraction is set to be independent of equipment dimension. The equipment dimension for pumps is defined to be the dimension of the inlet pipe.

Note that the model applies for both reciprocating and centrifugal pumps. This joint model is somewhat uncertain as it is based on statistical data, and should be addressed further in future analysis. A failure mode analysis is recommended for qualitative assessment of a potential relative difference in expected failure modes for the two types of pumps.

The resulting validation with respect to the NCS data set is shown in Figure 12.2. The result shows that PLOFAM is over predicting the target for pumps. The overestimation is embedded to reflect that the UKCS data indicate a significant higher pump leak frequency than the NCS data. But more importantly, there is a strong correlation to the MISOF ignition model as there is a specific ignition probability related to immediate ignition of pump leaks. To ensure that the fire frequency is estimated consistently with the historical fire frequency believed to originate from pumps, the pump immediate ignition probability is scaled with the PLOFAM pump leak frequency model. This means that setting the leak frequency from pumps strictly in accordance with the NCS data, which gives a lower leak frequency than PLOFAM, means that the immediate ignition probability must be set considerably higher. It is judged that the pump immediate ignition probability should be set somewhat below 10%, which is obtained ramping up the frequency for pump slightly in PLOFAM. It is believed that one reason the frequency for leaks from pumps at UKCS installations appears to be higher is that leaks where the pump is the root cause (*e.g.* due to vibration) tend to be tagged to pump despite the leak originating from a neighbouring valve or flange. So the PLOFAM leak frequency is higher than the target value to account for this uncertainty, but the MISOF ignition probability compensates for this so the predicted fire frequency meets its target.

In Figure 12.1, the resulting hole size frequency distributions for a few pump inlet dimensions are shown.

Table 12.1 –Pump parameters

Parameter	Pump
F_{hist}	Significant leaks: $3.0{\cdot}10^{-3}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	$3.0{\cdot}10^{-5}$
α	0

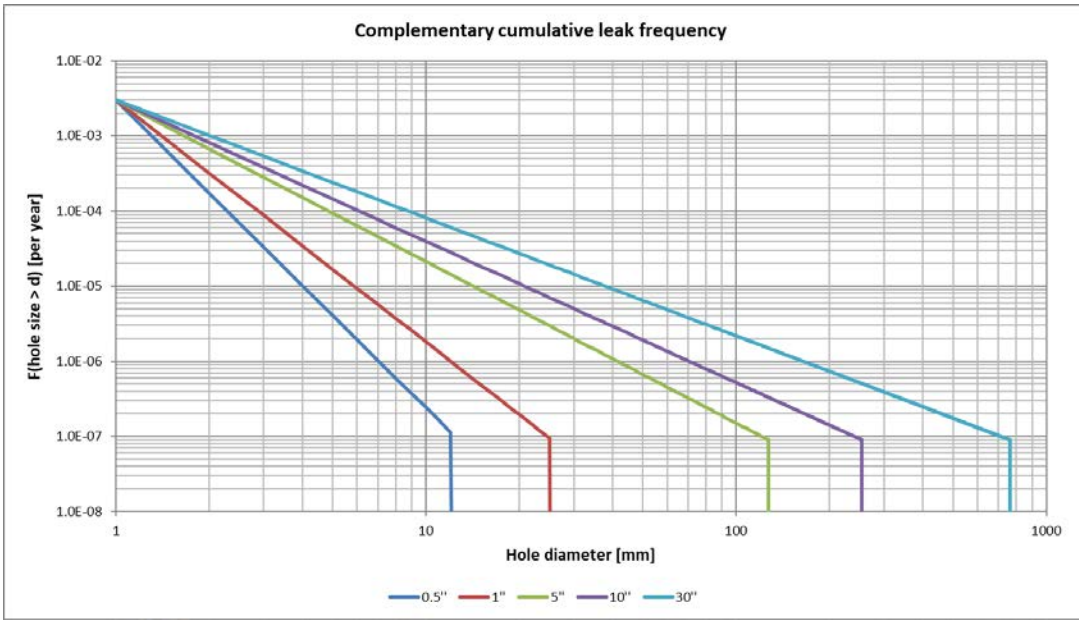


Figure 12.1 – Pump: hole size distribution for various equipment dimensions (pipe inlet)

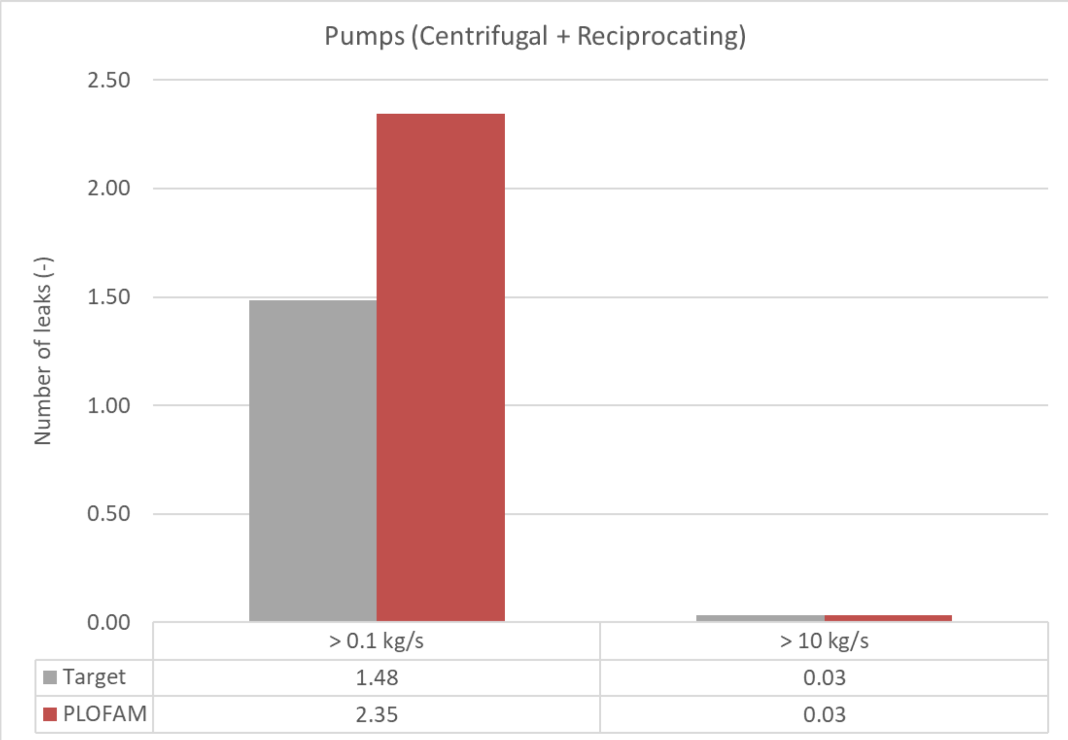


Figure 12.2 – Pump validation (centrifugal + reciprocating pumps): prediction PLOFAM vs. observed leaks at NCS in same period

13 Heat exchangers

13.1 Heat exchanger equipment types

There are two types of heat exchangers in terms of the technical function:

- Shell & tube heat exchangers
- Plate heat exchangers

Separate models have been derived for each type. The UKCS data (see Table 5.3) indicate that the total leak frequency is higher for plate heat exchangers than for shell & tube heat exchangers, but that the fraction large leaks (> 10 kg/s) is less (1 out of 25 for plate heat exchangers vs. 2 out of 10 for shell and tube heat exchangers). Hence, it is judged that two separate models should be developed.

13.2 Heat exchangers PLOFAM parameters

The parameters derived for heat exchangers are shown in the table below. The total leak frequency and rupture fraction is considered to be independent of equipment dimension. The equipment dimension for heat exchangers is defined to be the dimension of the inlet pipe.

The results show that the total frequency for leaks from shell & tube heat exchangers and plate heat exchangers are quite similar, but that the rupture fraction is different. The difference in rupture fraction is in accordance with UKCS data. The UKCS data indicate that the total leak frequency is significantly higher for plate heat exchangers. The targets for heat exchangers are set based on NCS data, and the resulting model deviate somewhat from the picture seen at UKCS installations in terms of the relative difference in total leak frequency (*i.e.* F_{hist}). However, the target for the model is prone to randomness as it is based on limited statistical data. A failure mode analysis is recommended for qualitative assessment of the relative difference in expected failure modes for the two types of heat exchangers, especially with regard to rupture mechanisms that may be quite different for the two types of heat exchangers. (*e.g.* tube leak may result in shell rupture if the overprotection system fails). This means that a cost-benefit analysis trading off the application of either type of heat exchanger must be used with care in the decision-making process. The relative difference between the types of heat exchangers should be investigated further when the model is updated in the future.

The resulting validation with respect to the NCS dataset is shown in Figure 13.3 and Figure 13.4.

In Figure 11.1 and Figure 11.2, resulting hole size frequency distributions for a few heat exchangers inlet dimensions are shown.

When applying the model, the user must evaluate if the leak will result in release of hydrocarbons or heating/cooling medium and apply the model accordingly.

Table 13.1 –Heat exchangers parameters

Parameter	Shell & tube heat exchanger	Plate heat exchanger
F_{hist}	Significant leaks: $3.3 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]	Significant leaks: $3.5 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1	1
M_0	0	0
A_D	0	0
M_D	0	0
B_D	0.0075	0.001
α	0	0

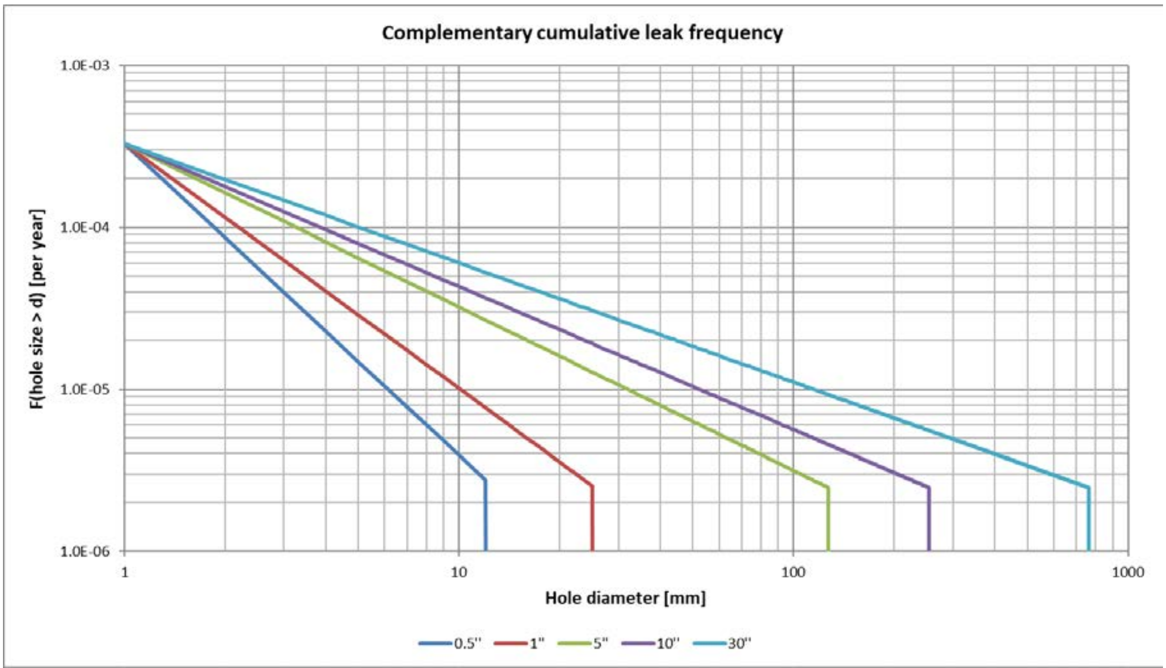


Figure 13.1 – Shell and tube heat exchanger: hole size distribution for various equipment dimensions

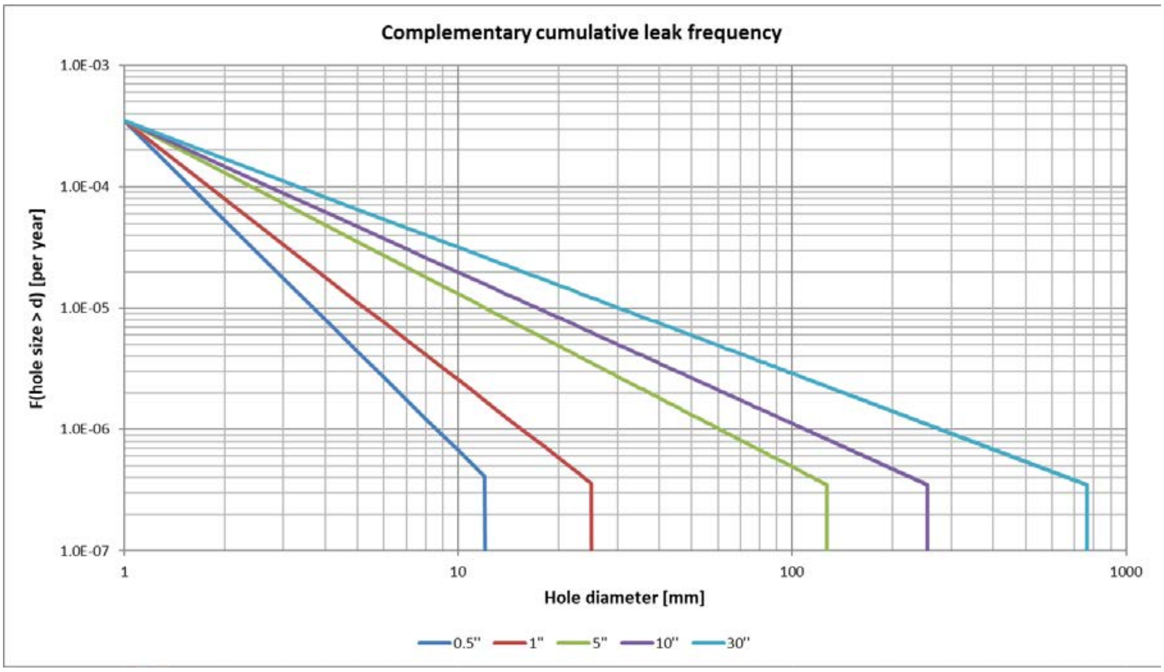


Figure 13.2 – Plate heat exchanger: hole size distribution for various equipment dimensions (pipe inlet)

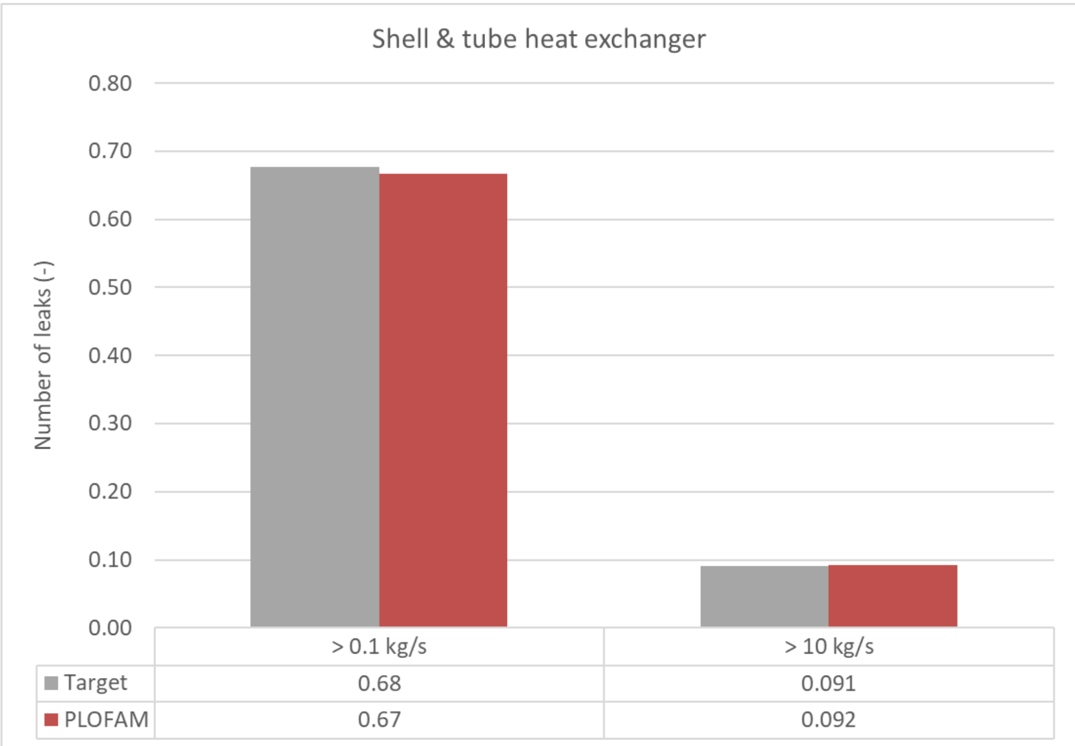


Figure 13.3 – Shell & tube heat exchanger validation: prediction PLOFAM vs. observed leaks at NCS in same period

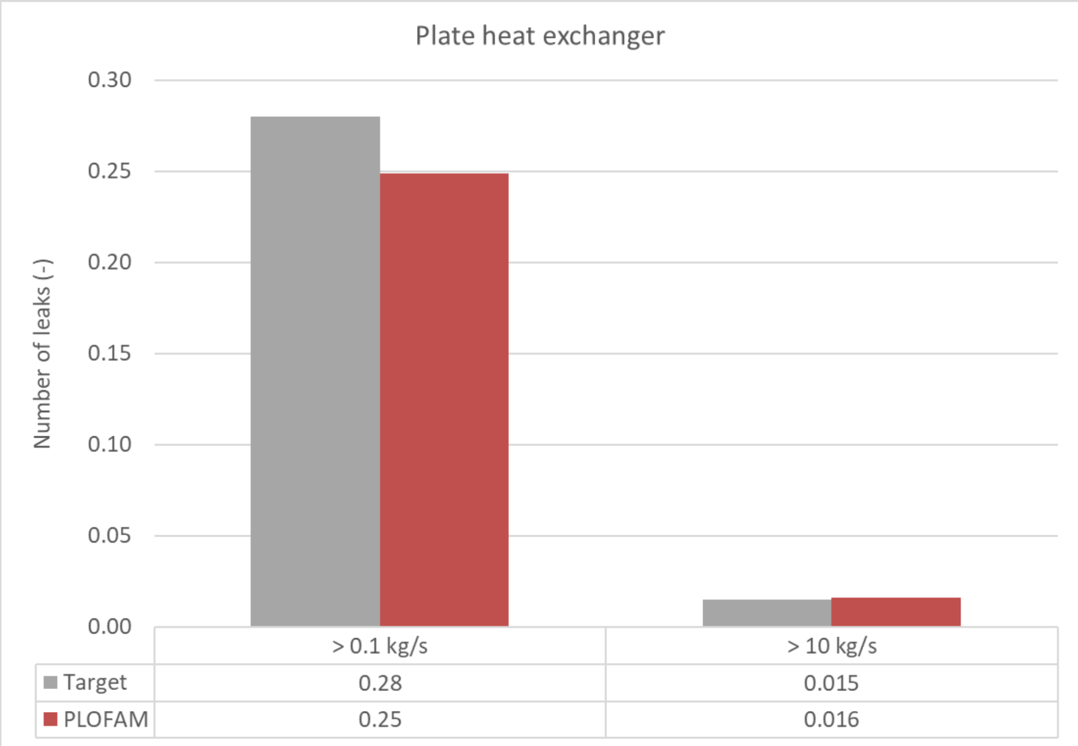


Figure 13.4 – Plate heat exchanger validation: prediction PLOFAM vs. observed leaks at NCS in same period

14 Process vessel

14.1 Process vessel equipment type

A process vessel is any type of pressurized vessel. The generated hole size frequency distribution for process vessels therefore must be considered to represent the average for all types of vessels, such as separators, scrubbers and knock out drums. The available data does not allow for assessment of specific failure frequencies for the various types of vessels. The leak frequencies apply to the shell and welded connections only, flanged connections must be considered separately.

14.2 Process vessel PLOFAM parameters

The parameters derived for process vessels are shown in the table below. The total leak frequency and rupture fraction is considered to be independent of equipment dimension. The equipment dimension for vessels is defined to be the dimension of the inlet pipe. This is a rough approximation as the physical dimensions of vessels are determined by other parameters as well, *e.g.* fluid retention time. Hence, two vessels with very different gross volume will possess the same hole size frequency distribution according to PLOFAM as long as the inlet dimension are the same. This may not be a reasonable modelling approach, and should be considered further in future studies.

The resulting validation with respect to the NCS data set is shown in Figure 14.2. The result shows that PLOFAM are able to reproduce the established targets for process vessel.

In Figure 14.1, the resulting hole size frequency distributions for a few process vessel inlet dimensions are shown.

Table 14.1 –Process vessel parameters

Parameter	Process vessel
F_{hist}	Significant leaks: $5.0 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	$6.0 \cdot 10^{-4}$
α	0

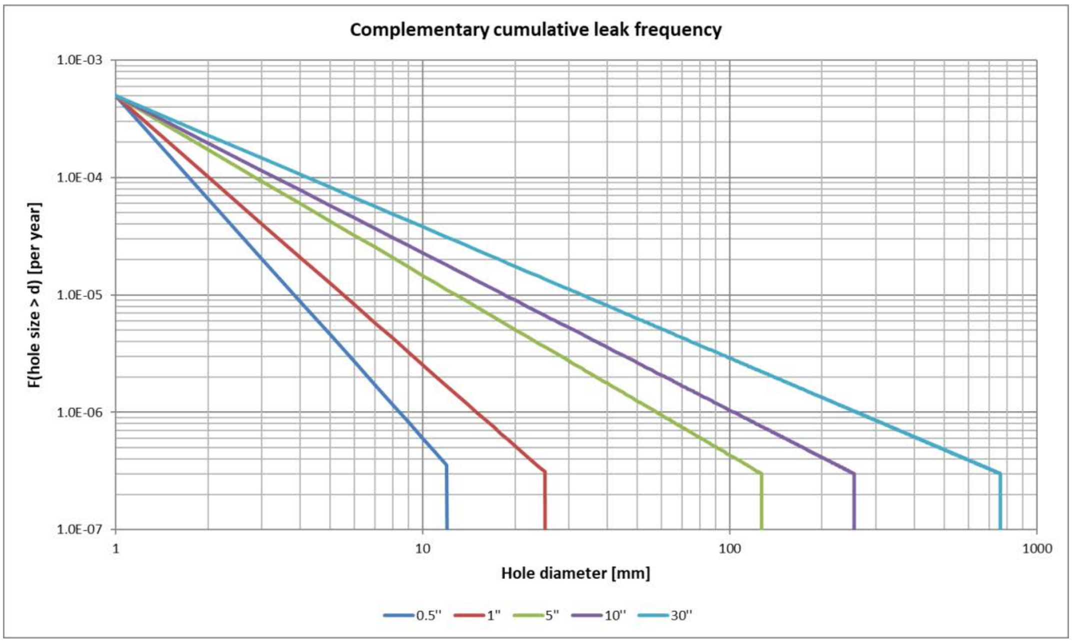


Figure 14.1 – Process vessel: hole size distribution for various equipment dimensions (pipe inlet)

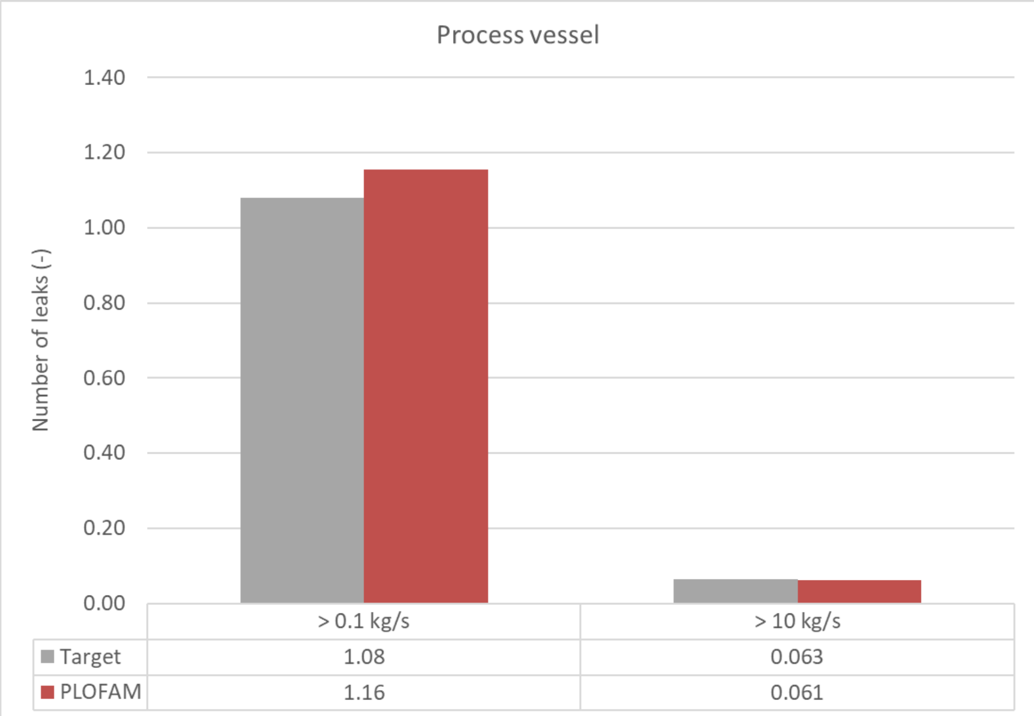


Figure 14.2 – Process vessel validation: prediction PLOFAM vs. observed leaks at NCS in same period

15 Filter

15.1 Filter equipment type

A filter is any type of filter.

15.2 Filter PLOFAM parameters

The parameters derived for filters are shown in the table below. The total leak frequency and rupture fraction is considered to be independent of equipment dimension. The equipment dimension for filters is defined to be the dimension of the inlet pipe.

The resulting validation with respect to the NCS data set is shown in Figure 15.2. The result shows that PLOFAM are able to reproduce the established targets for filters.

In Figure 15.1, the resulting hole size frequency distributions for a few filter inlet dimensions are shown.

Table 15.1 –Filter PLOFAM parameters

Parameter	Filter
F_{hist}	Significant leaks: $2.3 \cdot 10^{-3}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	$8.0 \cdot 10^{-4}$
α	0

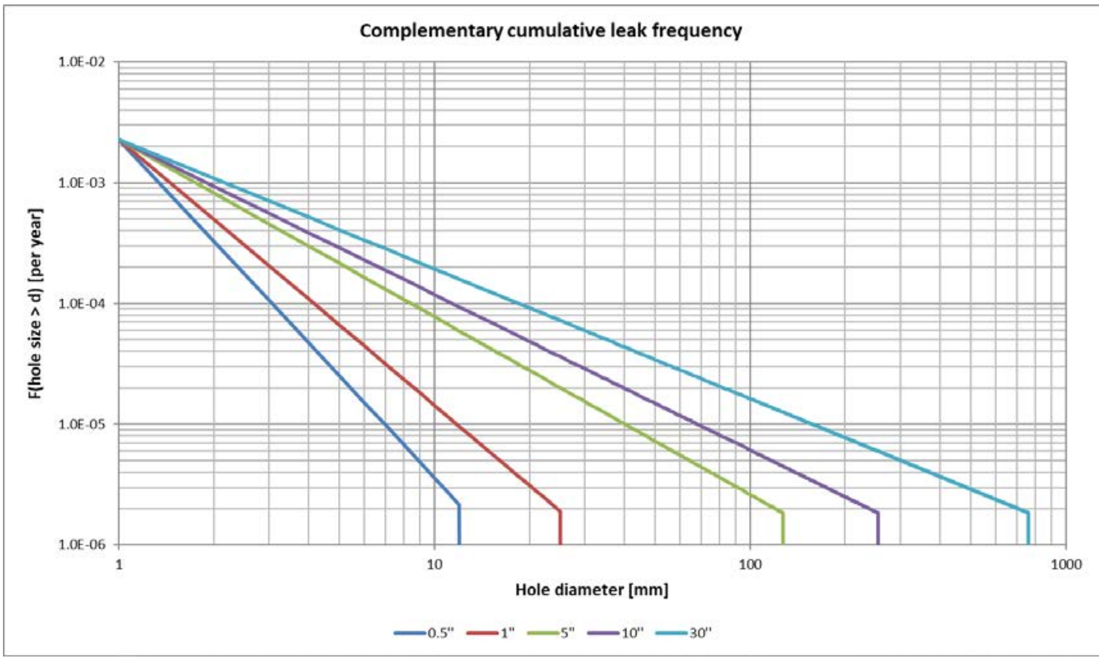


Figure 15.1 – Filter: hole size distribution for various equipment dimensions (pipe inlet)

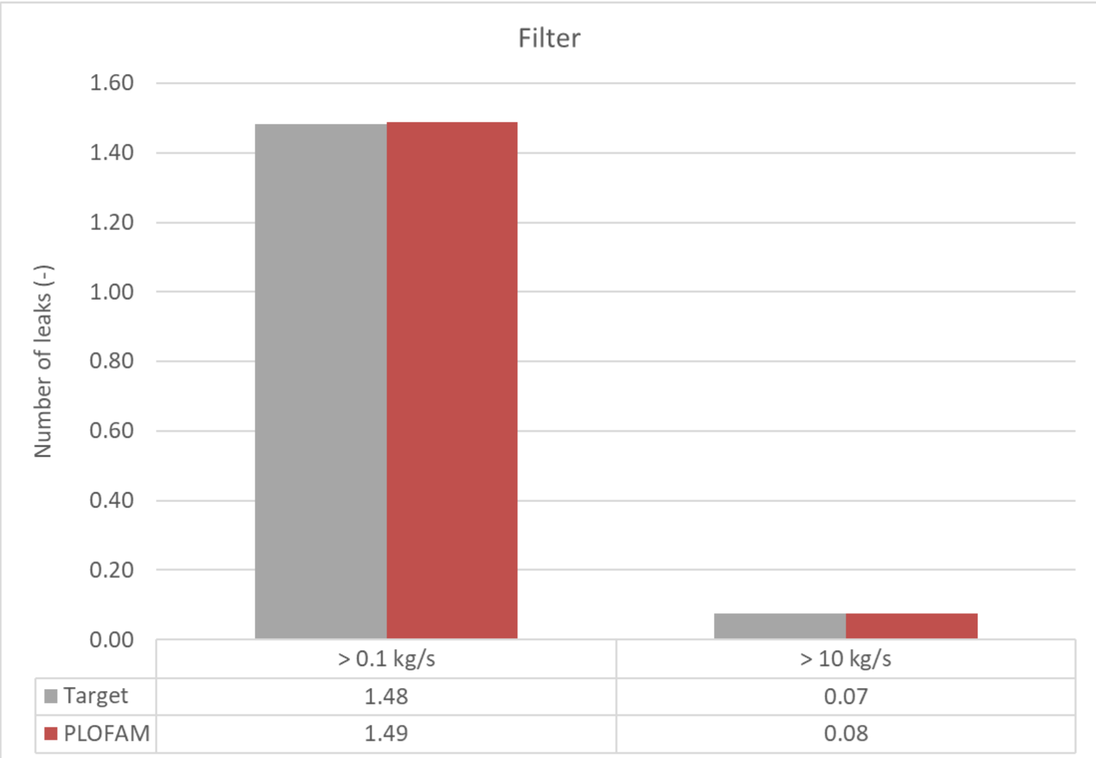


Figure 15.2 – Filter validation: prediction PLOFAM vs. observed leaks at NCS in same period

16 Pig trap

16.1 Pig trap equipment type

A pig trap is any type of pig trap (both pig launcher and pig receiver).

16.2 Pig trap PLOFAM parameters

The parameters derived for pig traps are shown in the table below. The total leak frequency and rupture fraction is considered to be independent of equipment dimension. The equipment dimension for pig traps is defined to be the dimension of the inlet pipe.

The resulting validation with respect to the NCS data set is shown in Figure 16.2. The result shows that PLOFAM are able to reproduce the established targets for pig traps.

In Figure 16.1, the resulting hole size frequency distributions for a few pig trap inlet dimensions are shown.

Table 16.1 –Pig trap (applies to both pig receive and pig launcher) PLOFAM parameters

Parameter	Pig trap
F_{hist}	Significant leaks: $1.7{\cdot}10^{-3}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.02
α	0

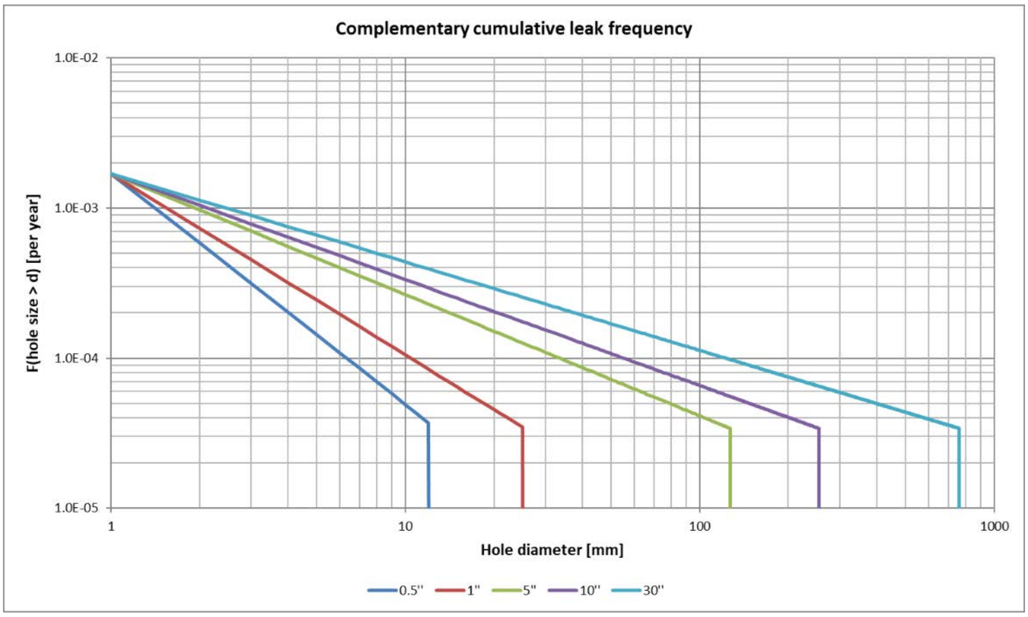
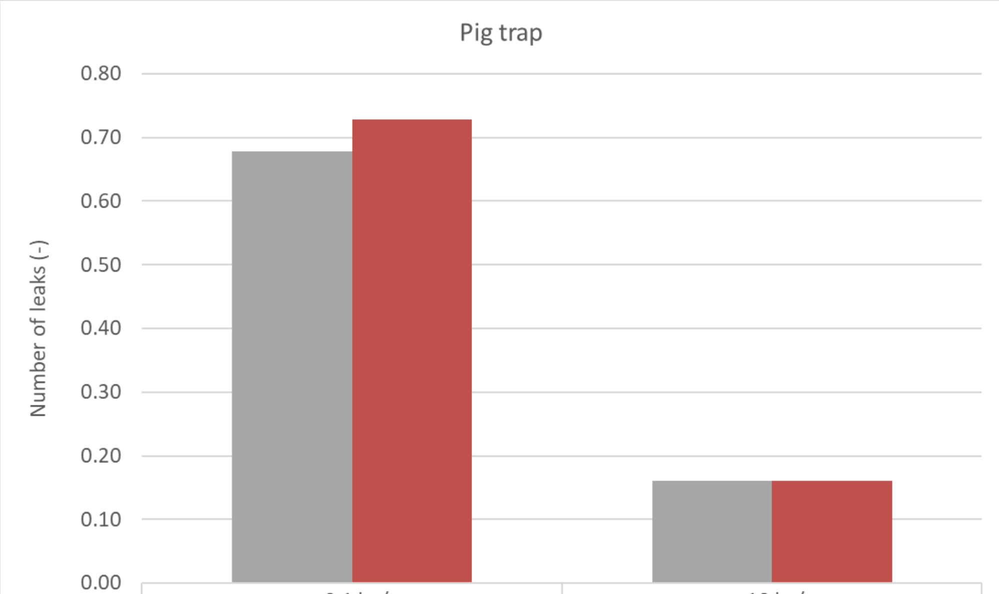


Figure 16.1 – Pig trap: hole size distribution for various equipment dimensions (pipe inlet)



	> 0.1 kg/s	> 10 kg/s
Target	0.68	0.161
PLOFAM	0.73	0.160

Figure 16.2 – Pig trap validation: prediction PLOFAM vs. observed leaks at NCS in same period

17 Producing well and gas lift well

17.1 Well equipment type

There are two types of leaks from wells covered by PLOFAM:

- Producing well which represent a topside well release where the inventory between DHSV and PWV is released during normal production
- Gas lift well which represent a topside well release where the inventory between the ASV and the barrier towards the process system is released

17.2 Well PLOFAM parameters

The parameters derived for wells are shown in the table below. The total leak frequency and rupture fraction is considered to be independent of equipment dimension. The equipment dimension for well is defined to be the dimension of:

- the production tubing for producing well
- the annulus wing valve for gas lift well

It is judged that full ruptures fraction is low. No ruptures scenarios have been recorded. The rupture fraction for producing well and gas lift well is set to 2% and 2.5% respectively. This evaluation is uncertain and should be reviewed in future update of the model.

The resulting validation with respect to the NCS dataset is shown in Figure 17.3 and Figure 17.4.

In Figure 17.1 and Figure 17.2, resulting hole size frequency distributions for a few dimensions are shown.

Table 17.1 –Producing well and gas lift well PLOFAM parameters

Parameter	Producing well	Gas lift well
F_{hist}	Significant leaks: $2.0 \cdot 10^{-5}$ [year^{-1} equipment^{-1}] Marginal leaks: $1.3 \cdot 10^{-4}$ [year^{-1} equipment^{-1}]	Significant leaks: $1.0 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: $1.0 \cdot 10^{-4}$ [year^{-1} equipment^{-1}]
A_0	1	1
M_0	0	0
A_D	0	0
M_D	0	0
B_D	0.02	0.025
α	0.5	0

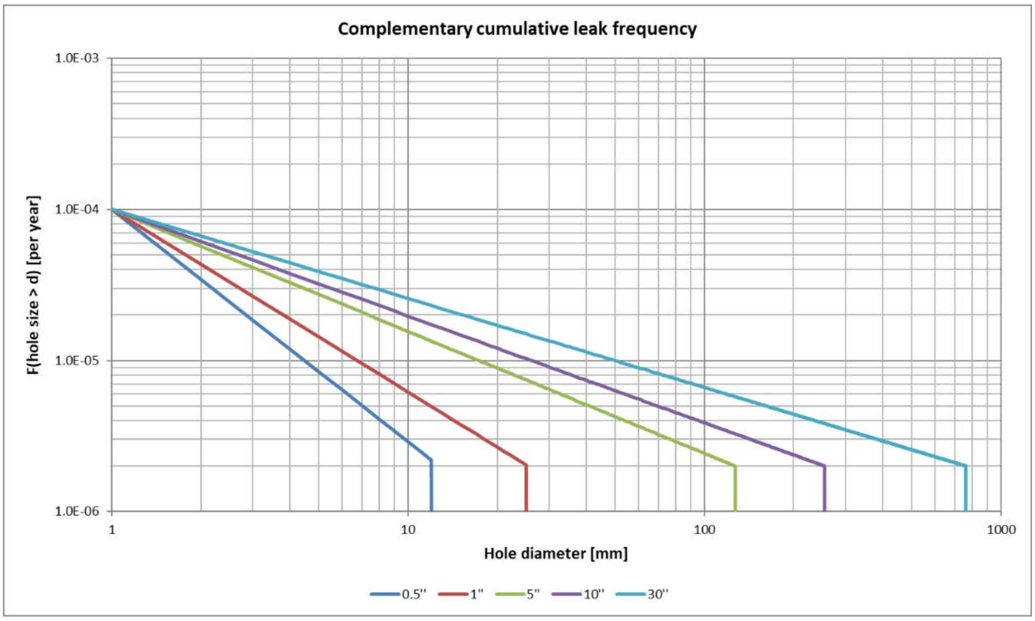


Figure 17.1 – Producing well: hole size distribution for various equipment dimensions

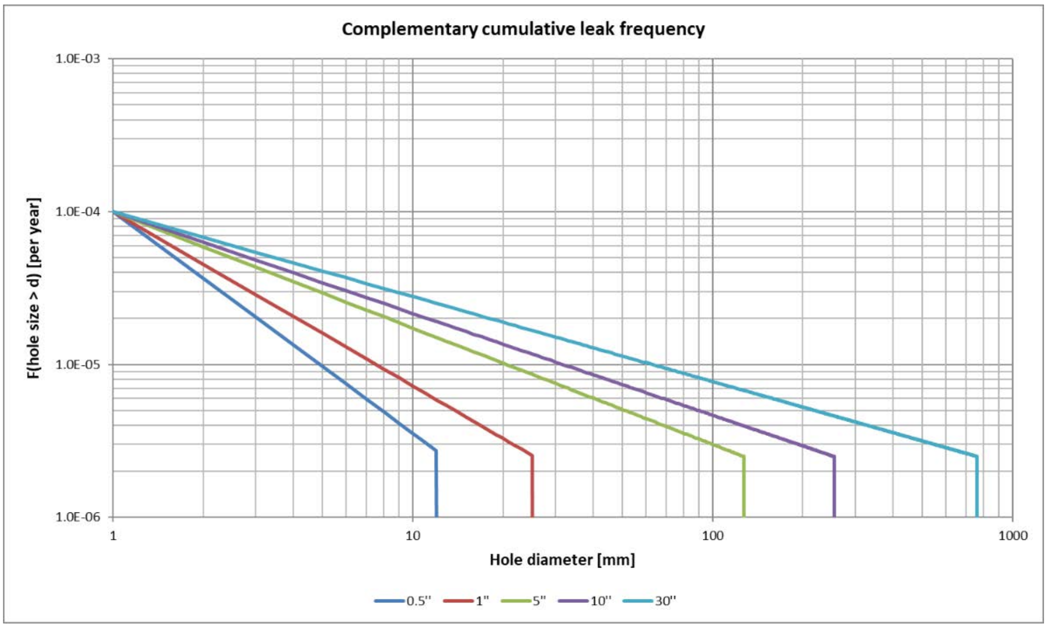


Figure 17.2 – Gas lift well: hole size distribution for various equipment dimensions (pipe inlet)

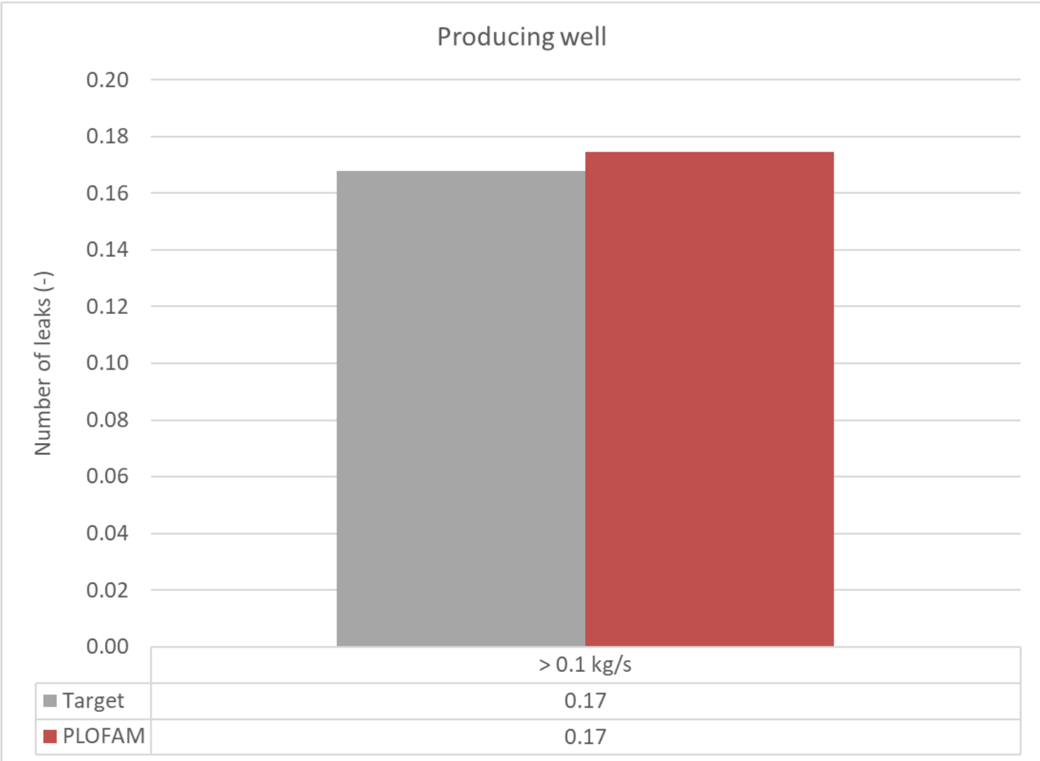


Figure 17.3 – Producing well validation of significant leaks: prediction PLOFAM vs. observed leaks at NCS in same period

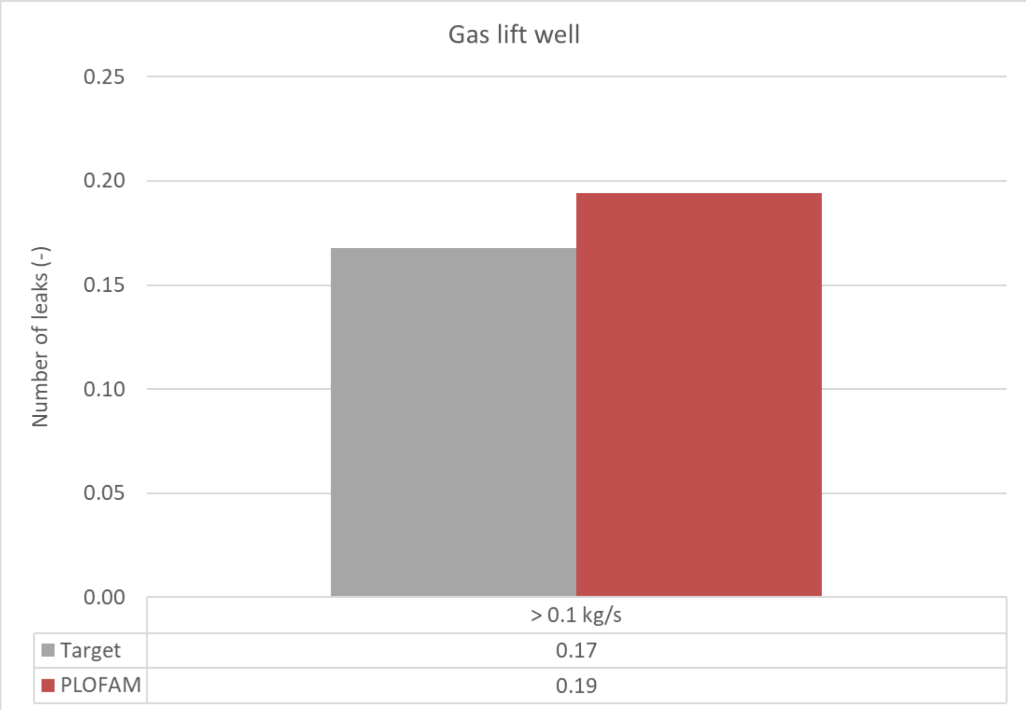


Figure 17.4 – Gas lift well validation of significant leaks: prediction PLOFAM vs. observed leaks at NCS in same period

18 Hose

18.1 Hose equipment type

A hose is any type of approved hose used for special temporary operations, such as flushing of a segment with a liquidous compound. The model does not apply for hoses that is not approved or certified for the particular operation.

18.2 Hose PLOFAM parameters

The key characteristics of hose leaks observed at NCS in the period 2001-2017 are presented in TN-2. The following are extracted from the historical data:

- The pressure is in all cases less than about 150 bar
- The quantity released is small or moderate (less than 100 kg) in most cases (only one incident where the inventory was more than 1 ton). The reason why the full inventory is not released in most cases is because the hose leak occurs typically during a special operation where the hose was not connected to a fully pressurized ESD segment. Also, manual intervention is common under hose leaks because personnel are often at the scene of the incident detecting the problem and terminates the unfolding scenario.
- The hole size was less than 1" in all cases where the hole size was known.
- Full rupture was recorded in about 1/3 of the incidents, which is explained by that a large fraction of the leaks is related to overpressurization resulting in full rupture.
- The initial leak rate was less than 10 kg/s in all cases

Based on above the parameters is set as follows:

- The rupture fraction is set to 40%, which is somewhat conservative
- The fraction of leaks being marginal is set to 20%
- α is set to 0.75 to reflect that intermediate holes in the hose is considered less likely. According to our understanding of the failure modes, it is reasonable to expect either a rupture (40% of cases) or a small hole in the hose.

The resulting parameters are shown in Table 18.1. The total leak frequency and rupture fraction is considered to be independent of hose dimension.

The resulting validation with respect to the NCS data set is shown in Figure 18.2 and Figure 18.3. The result shows that PLOFAM is slightly conservative, both in terms of the number of estimated leaks and the distribution (the predicted distribution is slightly shifted towards bigger leaks compared to the distribution of observed leaks). However, the population data (see TN-2) is rather uncertain and it is considered reasonable that the model is somewhat conservative.

In Figure 18.1, the resulting hole size frequency distributions for a few typical hose dimensions are shown.

As described above, the majority of the leaks originating from hoses are leaks with shorter duration and/or smaller quantities released than if they were connected to an ESD segment under normal operation. A threshold for the maximum released quantity is therefore set also for significant leaks. Based on the observed incidents, the maximum inventory released in hose leaks should be truncated to 250 kg unless when applied to special operations where it is known that the potential inventory may exceed 250 kg.

Table 18.1 –Hose PLOFAM parameters

Parameter	Hose
F_{hist}	Significant leaks: $6.0\cdot10^{-5}$ [year^{-1} equipment^{-1}] Marginal leaks: $1.5\cdot10^{-5}$ [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.4
α	0.75

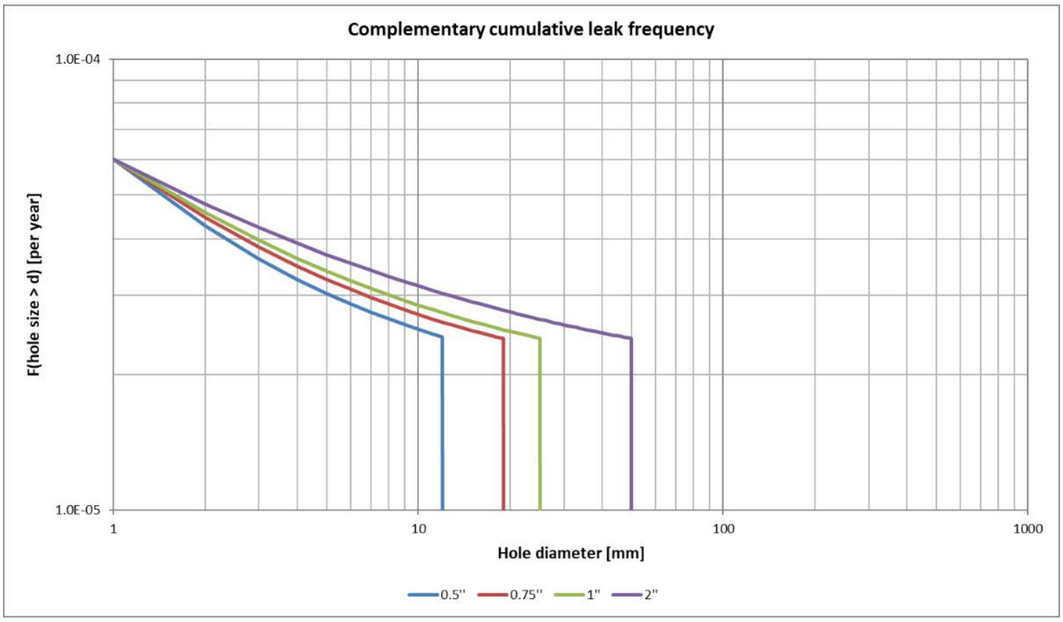


Figure 18.1 – Hose significant leaks: hole size distribution for various hose dimensions

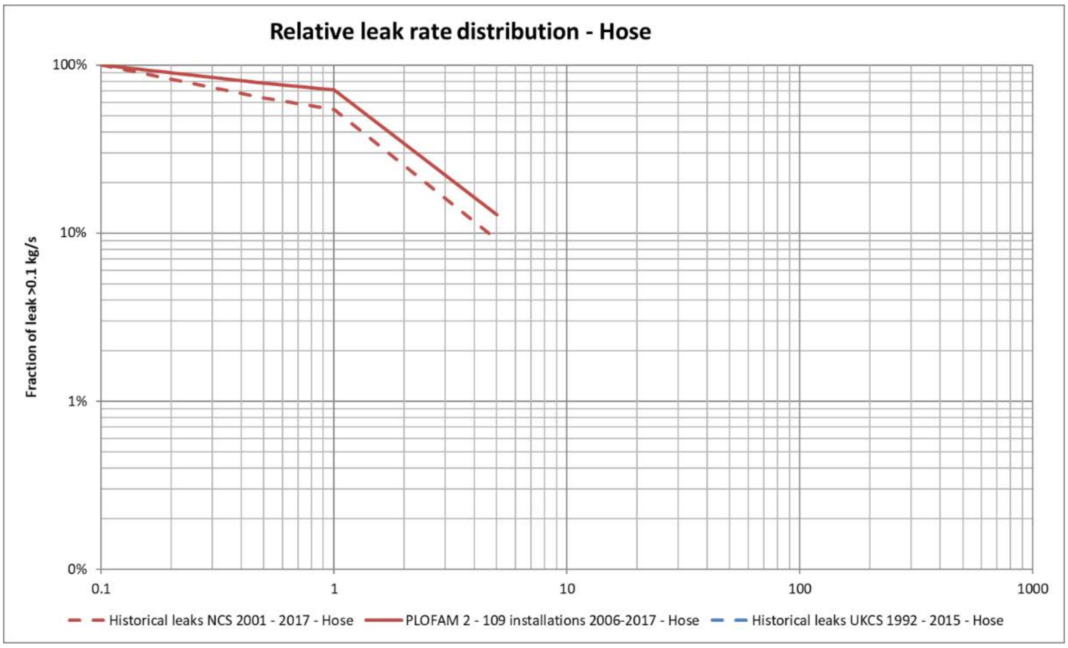


Figure 18.2 – Hose: complementary cumulative relative leak rate distribution

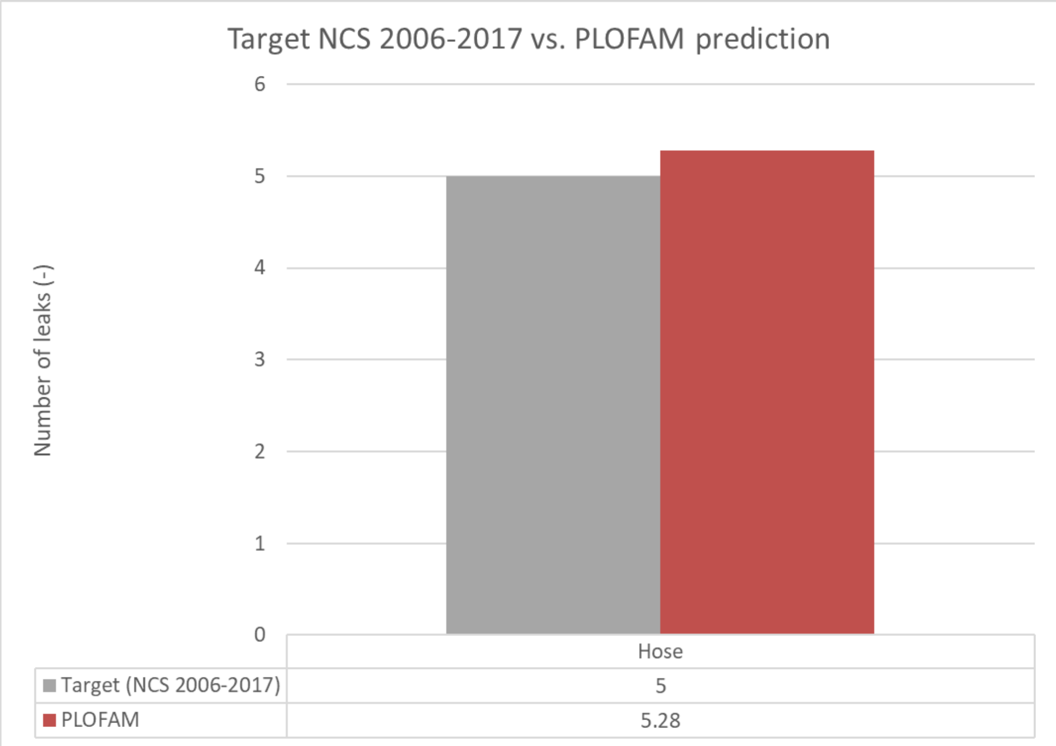


Figure 18.3 – Hose validation (significant leaks): prediction PLOFAM vs. observed leaks at NCS in same period

19 Air-cooled heat exchanger (Fin fan cooler)

The frequency for significant leaks from air-cooled heat exchangers (fin fan cooler) is derived based on 1 observed significant leak in about 2,000 equipment years at UKCS in the period 1992-2017. The frequency for marginal leaks is disregarded.

The rupture fraction is set to 3%, which is 4 times the rupture fraction for shell & tube heat exchangers (see Table 13.1). Due to the limited data, the model should be considered rather uncertain. A failure mode analysis is recommended for qualitative assessment of the potential failure modes in order to improve the basis for setting the model parameters.

Table 19.1 –Air-cooled heat exchanger (fin fan cooler) PLOFAM parameters

Parameter	Air-cooled heat exchanger
F_{hist}	Significant leaks: $5.0 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.03
α	0

20 Flexible pipe

The frequency for leaks from flexible piping is derived based on 25 observed significant leaks in about 175,000 equipment years (flexible piping meter years) at UKCS in the period 1992-2017. The frequency for marginal leaks is disregarded. The resulting frequency is about a factor of 10 higher than the frequency for leaks from steel pipe, which is considered to be reasonable.

In lack of data to derive the remaining model parameters directly, the parameters for hose are judged to be the most relevant parameters applicable to flexible piping.

Due to the limited data, the model for flexible piping should be considered rather uncertain. A failure mode analysis is recommended for qualitative assessment of the potential failure modes in order to improve the basis for setting the model parameters.

Table 20.1 –Flexible piping PLOFAM parameters

Parameter	Flexible piping
F_{hist}	Significant leaks: $1.4 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.4
α	0.75

21 Atmospheric vessel

In lack of data to set specific parameters for atmospheric vessels, the frequency for process vessels is recommended (see Table 14.1).The rupture fraction for process vessels is however very low compared to the rupture fraction assumed in SHLFM. The rupture fraction is therefore set to 10%.

Due to the limited data, the model for atmospheric vessel should be considered rather uncertain. A failure mode analysis is recommended for qualitative assessment of the potential failure modes in order to improve the basis for setting the model parameters.

Table 21.1 –Atmospheric vessel PLOFAM parameters

Parameter	Air-cooled heat exchanger
F_{hist}	Significant leaks: $5.0 \cdot 10^{-4}$ [year^{-1} equipment^{-1}] Marginal leaks: 0 [year^{-1} equipment^{-1}]
A_0	1
M_0	0
A_D	0
M_D	0
B_D	0.1
α	0

22 Overall validation and discussion

The parameters have been set in order to meet the requirements to the model described in TN-5 and the targets presented in chapter 5. Through this technical note (Chapter 6 – 18) the resulting complementary cumulative relative leak rate distribution when applying PLOFAM to all installations being in operation at NCS in period 2006-2017 has been shown for each equipment type. This chapter discusses how the model performs for all equipment types and for all installations, and whether the overall model performance is reasonable and within expectations.

Note that no population data has been compiled for Air cooled heat exchanger (most likely not a relevant equipment type at NCS), Flexible piping and Atmospheric vessels at NCS, and is therefore not included in the validation model. The contribution from these equipment types to the total leak picture are however expected to be negligible.

Figure 22.1 shows the PLOFAM prediction for all types of leaks (significant + marginal) relative to the number of leaks occurring at installations on the NCS in the period 2006-2017. The number of leaks is accurately predicted.

Figure 22.2 display the resulting overall distribution of significant leaks per equipment for all installations operating at NCS and UKCS compared with the PLOFAM prediction. The results show that PLOFAM reproduce the distribution observed at NCS. A significant difference with regards to the data from UKCS installations appear. The difference may be due to difference in the methodology for tagging the leak to the specific equipment type. The quality of the NCS data in this regard is deemed to be high because the database is established based on review of the accident investigation reports for the incidents.

Figure 22.3 gives the estimated and historical number of leaks with leak rate above or equal to 0.1, 0.5, 1, 5, 10, 30, 100, 300 and 1000 kg/s, while Figure 22.4 displays the number of estimated leaks within leak rate categories defined by the same leak rates. In both figures the ratio between the model prediction and historical number of leaks is given on the right y-axis. The results show that PLOFAM underpredicts the number of leaks in some intervals while overpredicts the number of leaks in other intervals. In particular the number of leaks in the interval 0.5 – 1 kg/s is underpredicted. This is regarded acceptable considering the high resolution in leak rate intervals and that both the number of leaks in the intervals 0.1 – 0.5 kg/s and 1-5 kg/s are overpredicted. Considering the cumulative number of leaks (*i.e.* the number of leaks with leak rate equal to or larger than the value on the x-axis), shows smaller fluctuations. The number of leaks with leak rate <30 kg/s is estimated with a deviation from the historical number of leaks of about 10 - 20% (both over and underprediction). For leaks with leak rate ≥30 kg/s, the number of leaks is however clearly underpredicted. This is however expected, as historical leaks in the period 2006 – 2017 show a high fraction of large leaks compared to other data periods, and is not defined as the target for the model. TN-2 (see Chapter 3.4) shows historical relative leak rate distributions for different data periods and also illustrates how different ways of plotting the data give different leak rate distributions. As explained in TN-2, the target for total complementary cumulative relative leak rate distribution for the model is defined by the relative leak rate distribution seen in the period 2001 – 2017. Applying PLOFAM to all installations on NCS in operation in the period 2001 – 2017, and multiply F_{hist}equally for all equipment types by a factor 1.32 to estimate the correct number of significant leaks >0.1 kg/s in the period (191), *i.e.* to account for a higher average leak frequency in 2001 – 2017 compared to 2006 – 2017, give the results presented in Figure 22.5. The figure shows that the model is able to reproduce the leak rate distribution seen in the period 2001 – 2017. Note that the relative leak rate distribution predicted by PLOFAM is the same for both periods.

In Figure 22.6, the resulting complementary cumulative relative leak rate distribution when applying PLOFAM to all installations being in operation at NCS in period 2006-2017 is shown together with the target for the model (black dotted curve). The relative distribution obtained from UKCS installations is also displayed, demonstrating that the data from NCS and UKCS installations are quite similar.

Figure 22.7 shows the relative leak rate distribution for the period 2001 – 2017 (blue curve) based on historical data categorized into number of leaks with leak rate larger than 0.1, 1, 5, 10, 30, 100 and 300 kg/s. The number of leaks in each category is divided by the total number of leaks >0.1 kg/s (see also TN-2). It is impossible to use the observation of very few leaks in a period to determine what the expected number of events in that period should be, which is the case for leak rates above about 30 kg/s, where only 4 leaks have occurred in the period 2001 - 2017. It could be that the expectation value actually is 8 and the industry has been fortunate to observe only 4, or it could be 2.4, but the industry was unfortunate when observing 4. Both the probability of observing < 4 leaks if the expectation value is 8 leaks or observing >4 leaks if the expectation value is 2.4 leaks, is 10% assuming that the number of leaks occurring in the period follows a Poisson process. This exercise is performed for all categories mentioned above and divided by the corresponding number of leaks >0.1 kg/s. The scenarios where the observed number of leaks represents a situation where the industry has been fortunate and unfortunate are shown Figure 22.7 together with the same relative leak rate distribution as given in Figure 22.6, *i.e.* the target for the model. The results show that the relative leak rate distribution predicted by PLOFAM gives results that are within the limits defined by the fortunate and unfortunate scenarios.

Figure 22.8 shows the same figure as Figure 22.7 but the leaks are not grouped in categories. This may indicate a slightly different picture where it may be claimed that the frequency of large leaks (> 100 kg/s) may be underestimated using PLOFAM. However, the result is very sensitive to the actual initial leak rate estimated for the historical leaks, which is associated with significant uncertainty as described in TN-2. Furthermore, as seen in TN-2, the relative leak rate distribution changes significantly between different data periods, as the number of large leaks is very few. Both historical data for the period 1992 – 2000, and 1992 – 2017 and also 2007 – 2017 shows a lower fraction of leaks >100 kg/s than the chosen data period.

Figure 22.9 display the complementary cumulative number of significant leaks for the entire period 1992-2017. The result shows that PLOFAM will underpredict the number of small leaks in the period 1992 - 2017, as expected (see TN-2), while it will replicate the number of leaks > 5 kg/s. Hence PLOFAM produce a good estimate for large leaks also for the entire data period.

Also recapping from TN-2 that targeting the average leak frequency for the period 2006 – 2017 gives 30% higher leak frequency than seen for any years after 2011, and about 50% higher leak frequency than recorded in 2017 gives important input to the total evaluation of the model. Having this in mind it is concluded that the overall leak rate distribution predicted by PLOFAM for all installations in operation on NCS in the period 2006 – 2017 is good and represents a reasonable and robust estimate for future leak frequency. Note also that the guidelines for use of PLOFAM in QRAs presented in TN-5 Appendix B are established from the conservative side. First of all it is recommended to model all Significant leaks as leaks occurring during normal operation where the full inventory is released (taking ESD and blowdown into account). Secondly the counting rules takes uncertainty in the population database used for model parametrization into account, by rather overestimate the leak frequency than underestimating it. This adds robustness to the frequency and risk estimates generated in QRAs using PLOFAM.

Figure 22.10 through Figure 22.13 show the overall results for gas and liquid leaks separately. The results show that the modelled relative leak rate distribution is broadly on target for gas leaks, but somewhat shifted towards smaller leaks for liquid leaks. Looking at the number of leaks, PLOFAM somewhat overpredicts the total number of recorded liquid leaks and underpredicts the total number of recorded gas leaks. A complete understanding of the causes for the difference in model prediction of leaks in terms of fluid phase has not been identified. An improved model prediction could have been obtained by defining separate PLOFAM parameters for equipment containing gas and liquid respectively. However, no apparent explanation has been found, and it has not been attempted to establish separate models for equipment containing gas and equipment containing liquids. It is recommended that future projects address this challenge. One objective could be to improve the simplified models used for estimation of initial leak rate for multi-phase leaks where estimation of the correct density is challenging. Uncertainty when classifying leaks in terms of fluid phase is also prominent. In total, considering these uncertainties, the prediction with respect to the fluid type by PLOFAM is considered acceptable. The main target is to predict the total number of leaks ensuring consistency in QRA's based on PLOFAM relative to what is observed in industry. The importance of the uncertainty in terms of predicting the frequency for the various leak types in a QRA will depend on the scenario driving the risk in the particular scenario. Looking at explosions, underprediction of gas leaks may be of most importance. However, considering fire risk, the situation may be the other way around.

To assess how the model performs for each installation in operation in the period 2006 – 2017, Figure 22.14 shows the number of estimated leaks versus the number of historical leaks for each installation (each data point represents a specific installation). The number of data points above (overestimated) and below (underestimated) the grey line is about the same, indicating that the overall prediction of the model is good, even though the model is obviously not able to predict the correct number of leaks for every installation. As discussed in TN-5 this is not expected as there are many factors influencing on the leak frequency that are not implemented in the model, but which basically cancel out when considering all installations together. However, there is a clear correlation in the data points indicating that the model is able to capture important factors influencing on the leak frequency. Over time as the number of installations with zero (and few) observed leaks will diminish, the overall correlation for all installations is expected to converge towards a symmetric distribution around the expected value predicted by PLOFAM (the grey line). The displayed variance of the distribution around the expected value will most likely not change much. Other explanatory variables in addition to the number of equipment are required to reflect the complexity of causes leading to external leaks at a specific installation. The OMT model (OMT = Organisation, Man & Technology) developed by Safetec (Ref. /3/) addresses this challenge. The OMT model combines PLOFAM with a methodology incorporating the human reliability and organisational factors quantitatively in order to achieve an improved estimate of the installation specific leak frequency. Hence, this uncertainty should be part of the overall assessment of the uncertainty associated with the risk picture in the risk management decision process based on the results from the QRA.

The model is mainly validated towards available data of leaks that has occurred at installations on the Norwegian Continental Shelf (NCS), but the data from the United Kingdom Continental Shelf (UKCS) indicate that the underlying hole size frequency distribution for equipment at installations located on the NCS is similar to the distribution for equipment located on UK installations. The differences may be explained by uncertainty related to the datasets (both the leaks and the population data, and the way equipment are counted and leaks are tagged to equipment types). Figure 22.5 displays the number of leaks (significant + marginal leaks) per equipment year (all types of pipes excluded) per year for NCS and UKCS. The plot shows that the leak frequency per equipment year and time trend in the leak frequency at UKCS is similar to the time trend seen on NCS. The average frequency appears to be slightly less at UKCS (the average frequency is about 25% less at UKCS over the period 2012-2016), but that may be due to uncertainty in the UKCS population data. The result presented in Figure 22.6 demonstrate that the relative distribution with regards to initial leak rate is equivalent for the two data sets.

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

The increasing spread of relative distributions with respect to initial leak rate for the unfortunate and fortunate scenario displayed in Figure 22.7 (and Figure 22.8) is important to consider when evaluating the accuracy of a QRA model based on PLOFAM. For leak rates above about 30 kg/s, the relative difference between the fortunate and unfortunate scenario constitutes a factor in the range 1.5 to 2.5. Here it must be noted that if the UKCS data is included, which indicate a similar relative leak distribution (see Figure 22.6), the uncertainty interval would be somewhat less. However, due to the uncertainties in the UKCS data, the uncertainty spectre including the historical leaks at UKCS has not been calculated. Qualifying the UKCS data for this application would thus add value to the evaluation of the overall uncertainty assessment. In total, adding the UKCS data, it is expected that a significantly less uncertainty can be documented.

Due to randomness, one cannot be totally sure about the exact underlying mean leak frequency distribution with respect to initial leak rate. The parameterisation process in PLOFAM targets the most likely underlying distribution, but we cannot rule out that the target frequency either is significantly lower or higher (illustrated by the fortunate and unfortunate scenario corresponding to 10% and 90% probability of exceedance, *i.e.* 80% confidence interval). This aleatory uncertainty should be taken into account in the decision-making process.

Increasing (or decreasing) the frequency for all leaks having initial leak rate > 30 kg/s with a factor of about two will in most cases have a decisive effect on the interpretation of the risk picture relative to the tolerance criterion typically applied in a QRA. Moreover, it is important to be aware of that a shift in leak frequency for large leaks results in a feedback effect on the total fire and explosion frequency resulting from delayed ignition as the probability for exposure to a potential source of ignition is proportional to the gas cloud size. In general, the gas cloud size increases profoundly with increasing leak rate, which implies that the probability for delayed ignition increases steeply with increasing leak rate. This implies that the overall uncertainty in a QRA is in many cases (*i.e.* in cases where large leaks drives the risk pictures) very much dominated by the uncertainty related to modelling of large leaks (> 30 kg/s). Accordingly, the uncertainty is considerably less in cases where the main risk contribution is stemming from small leaks compared to situations where large leaks drives the risk picture.

In MISOF, it was concluded that the equivalent relative factor between the upper and lower estimate for the underlying ignition probability is about a factor of 2.5. This means that the overall uncertainty spectre of the total fire and explosion frequency is even more significant than the uncertainty related to PLOFAM. Looking only at the contribution from large leaks, the uncertainty interval will be more prominent because the uncertainty related to estimation of the ignition probability stemming from large leaks is larger. Roughly, a generic factor of about 3 (relative to the best estimate at either side) is a fair estimate of the average uncertainty related to the fire and explosion frequency estimate generated by PLOFAM and MISOF, but should be considered specifically in each case (will depend on the type of leak (*e.g.* rate and composition) that drives the risk picture, which again will vary with module design parameters such as module size and global ventilation conditions).

It is important to bear in mind that the models target the most likely frequency. Since one cannot know the exact underlying frequency, the spread around the best estimate should be considered in the decision-making process. Adsorption of this aspect in the evaluation of the risk picture will mitigate the sensitivity of the decision to any large leaks (> 30 kg/s) occurring in the near future. Although a strict update of the PLOFAM model parameters after the occurrence of one future large leak at NCS would lead to a model that would predict a slightly higher frequency for leaks, the current model cannot be disregarded if one (or two) large leak occurs in the near future as the target value used for PLOFAM still would have a relatively high probability of occurrence. Likewise, a long period (> 5 years) without observing any large leak in the future does not imply that the current model is conservative in terms of estimation of the frequency for large leaks. According to PLOFAM, the probability for observing fewer large leaks per equipment year in the future than what has been observed so far is considerable. Decisions should therefore preferably be undertaken based on evaluating both the expected value generated by the models and the likely worst and best case described by an assessment of the uncertainty applicable to the situation at hand.

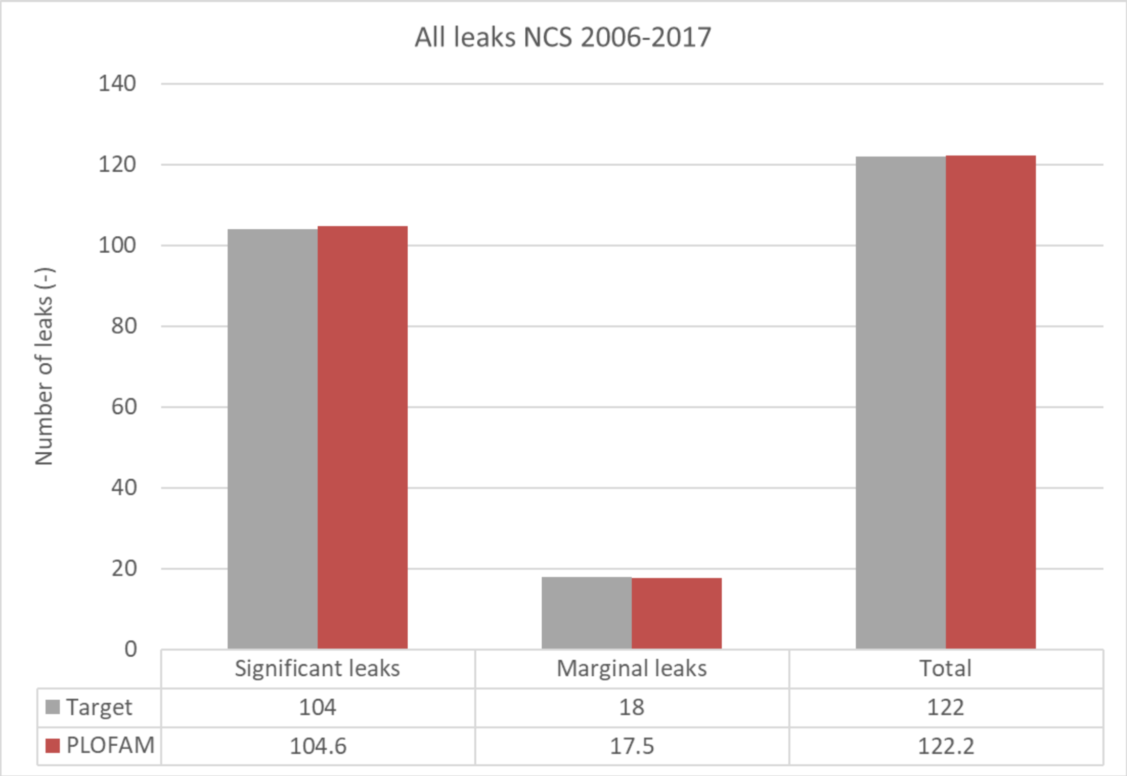
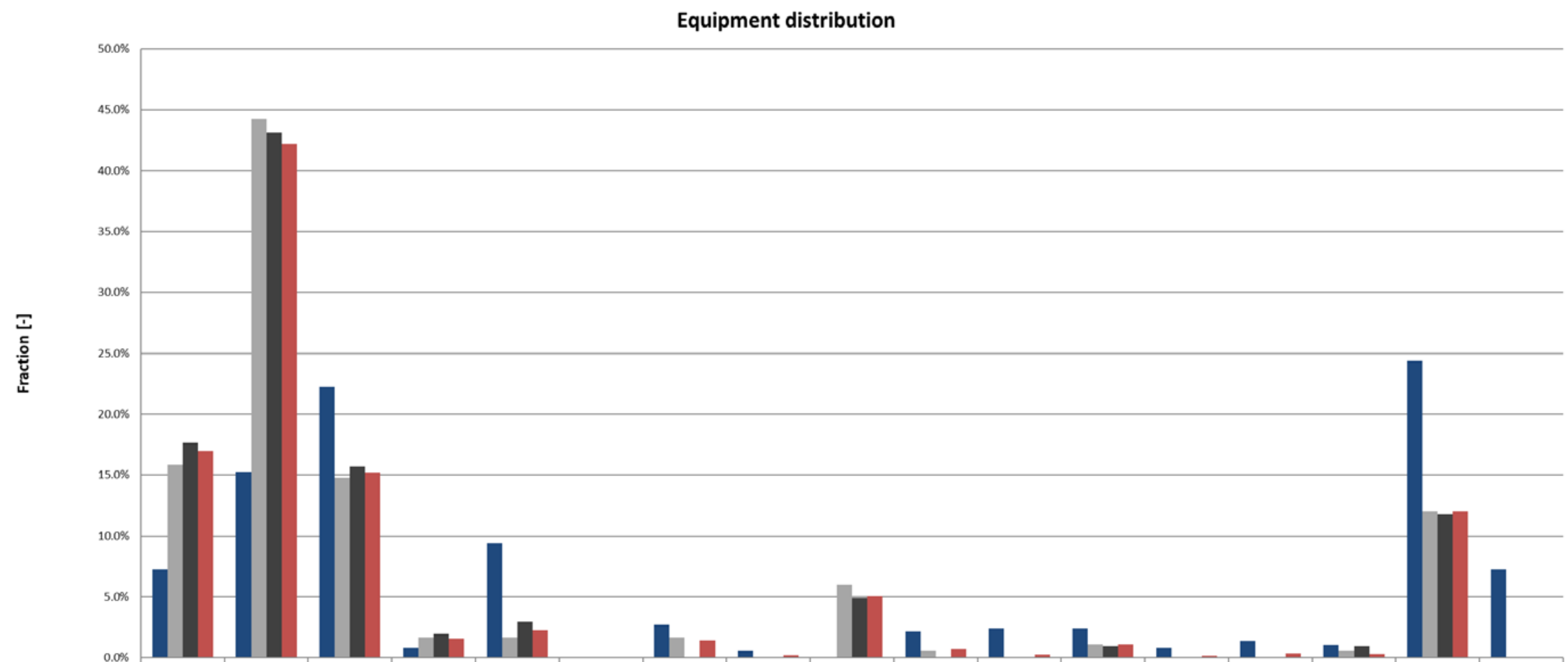
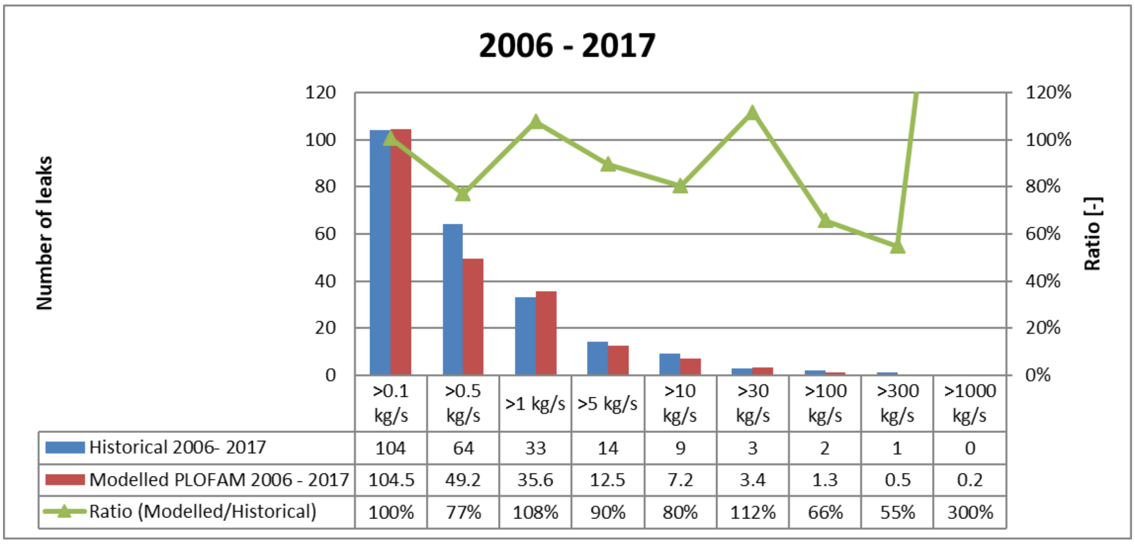


Figure 22.1 – Overall for all leaks (significant + marginal: total number of PLOFAM leaks for all installations operating at NCS in the period 2006-2017



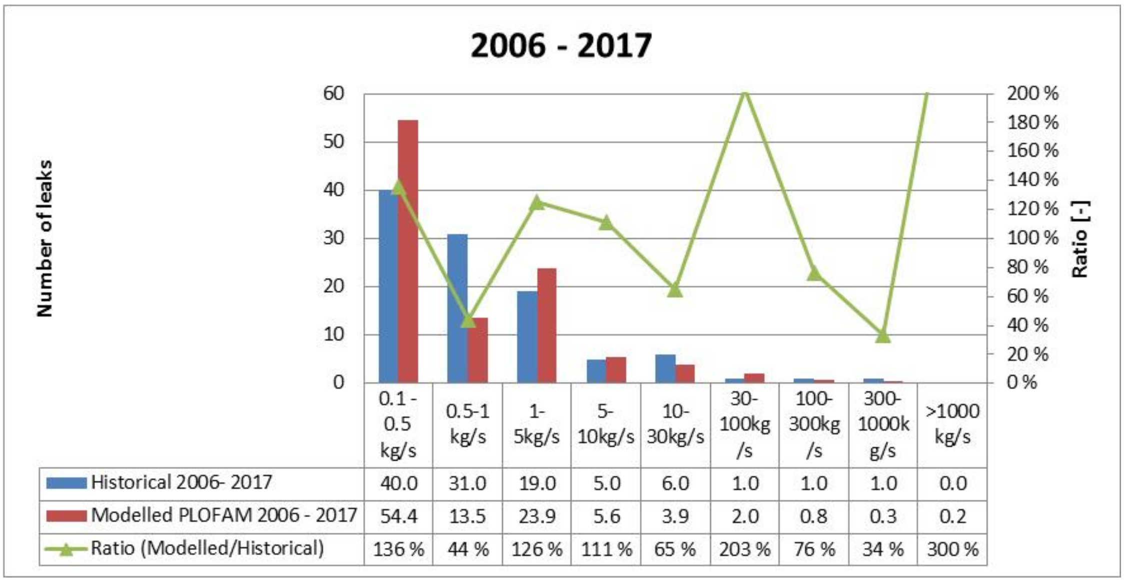
	Standard flange	Valve	Instrument	Centrifugal compressor	Pump	Compact flange	Filter	Gas lift well	Hose	Pig trap	Plate heat exchanger	Process vessel	Producing well	Reciprocating compressor	Shell and tube heat exchanger	Steel pipe	Other
UKCS historical	7.2%	15.3%	22.3%	0.8%	9.4%	0.0%	2.7%	0.5%	0.0%	2.1%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

Figure 22.2 – Historical (both for NCS and UKCS) and modelled equipment type distribution for Significant leaks. Both the historical equipment type distribution for the period 2001 – 2017 and 2006 – 2017 are given. The modelled result is achieved by applying PLOFAM to all installations at NCS being in operation in the period 2006 – 2017



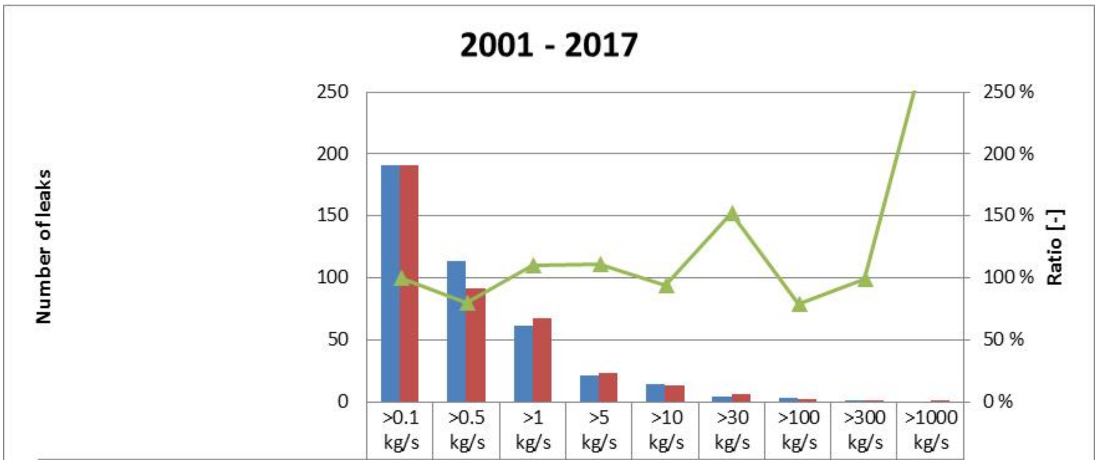
	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Historical 2006- 2017	104	64	33	14	9	3	2	1	0
Modelled PLOFAM 2006 - 2017	104.5	49.2	35.6	12.5	7.2	3.4	1.3	0.5	0.2
Ratio (Modelled/Historical)	100%	77%	108%	90%	80%	112%	66%	55%	300%

Figure 22.3 – Overall significant leaks: complementary cumulative leak rate distribution for all installations operating at NCS in the period 2006-2017



	0.1 - 0.5 kg/s	0.5-1 kg/s	1-5kg/s	5-10kg/s	10-30kg/s	30-100kg/s	100-300kg/s	300-1000kg/s	>1000 kg/s
Historical 2006- 2017	40.0	31.0	19.0	5.0	6.0	1.0	1.0	1.0	0.0
Modelled PLOFAM 2006 - 2017	54.4	13.5	23.9	5.6	3.9	2.0	0.8	0.3	0.2
Ratio (Modelled/Historical)	136 %	44 %	126 %	111 %	65 %	203 %	76 %	34 %	300 %

Figure 22.4 – Overall significant leaks: leak rate distribution for all installations operating at NCS in the period 2006-2017



	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Historical 2001 - 2017	191	114	61	21	14	4	3	1	0
Modelled PLOFAM2 2001 - 2017	191.0	91.6	66.9	23.3	13.1	6.1	2.4	1.0	0.4
Ratio (Modelled/Historical)	100 %	80 %	110 %	111 %	94 %	152 %	79 %	99 %	300 %

Figure 22.5 – Overall significant leaks: leak rate distribution for all installations operating at NCS in the period 2001-2017

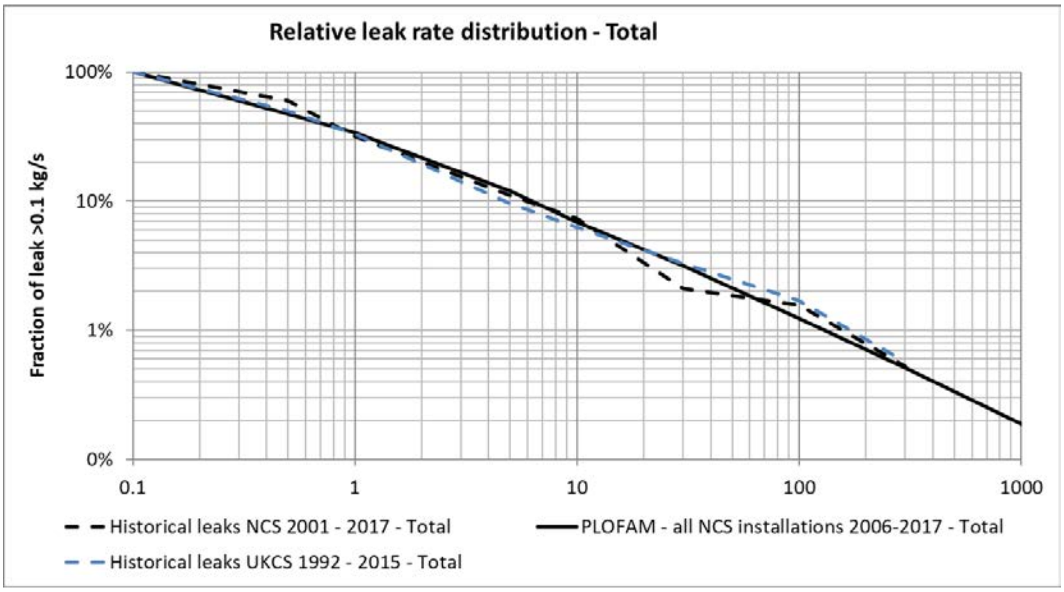


Figure 22.6 – Overall significant leaks: complementary cumulative relative leak rate distribution for all installations operating at NCS in the period 2006-2017

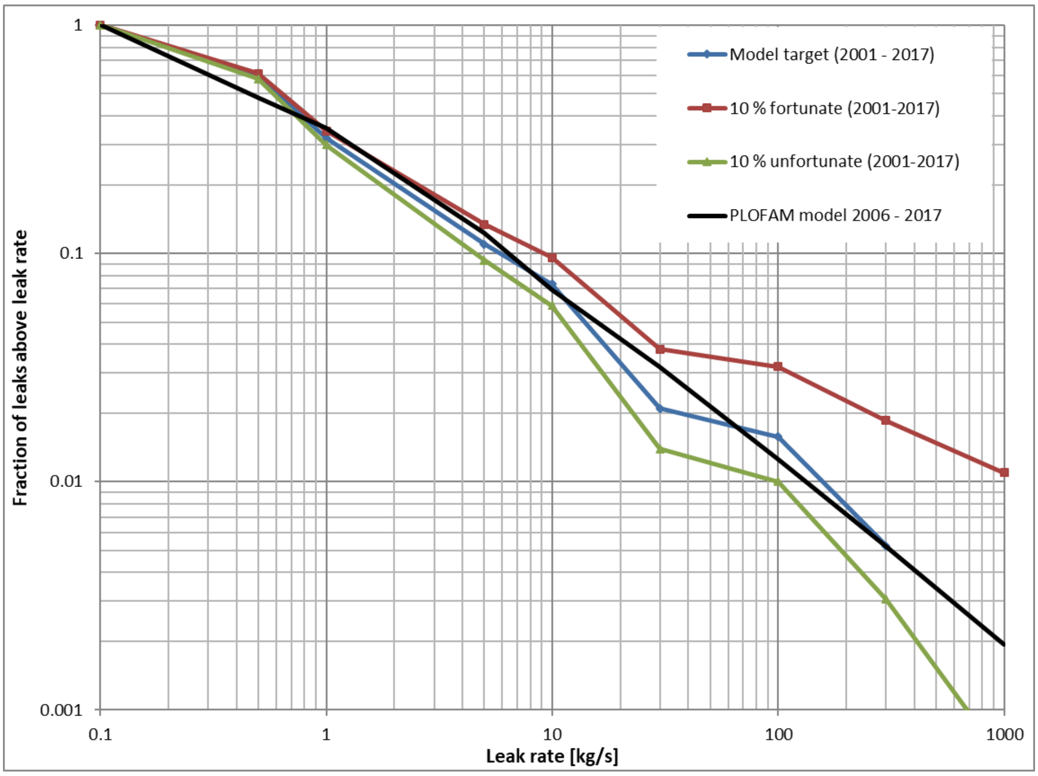


Figure 22.7 – Relative leak rate distribution based on historical leaks for the period 2001 - 2017 (blue curve, representing the target for the model) together with the curves representing a scenario where the expected number of leaks is higher and the actual observed number of leaks were fortunate (red curve) and a scenario where the expected number of leaks is lower, and the observed number of leaks were unfortunate (green curve). The black curve shows the resulting leak rate distribution when applying PLOFAM to all installations in operation in the period 2006 – 2017

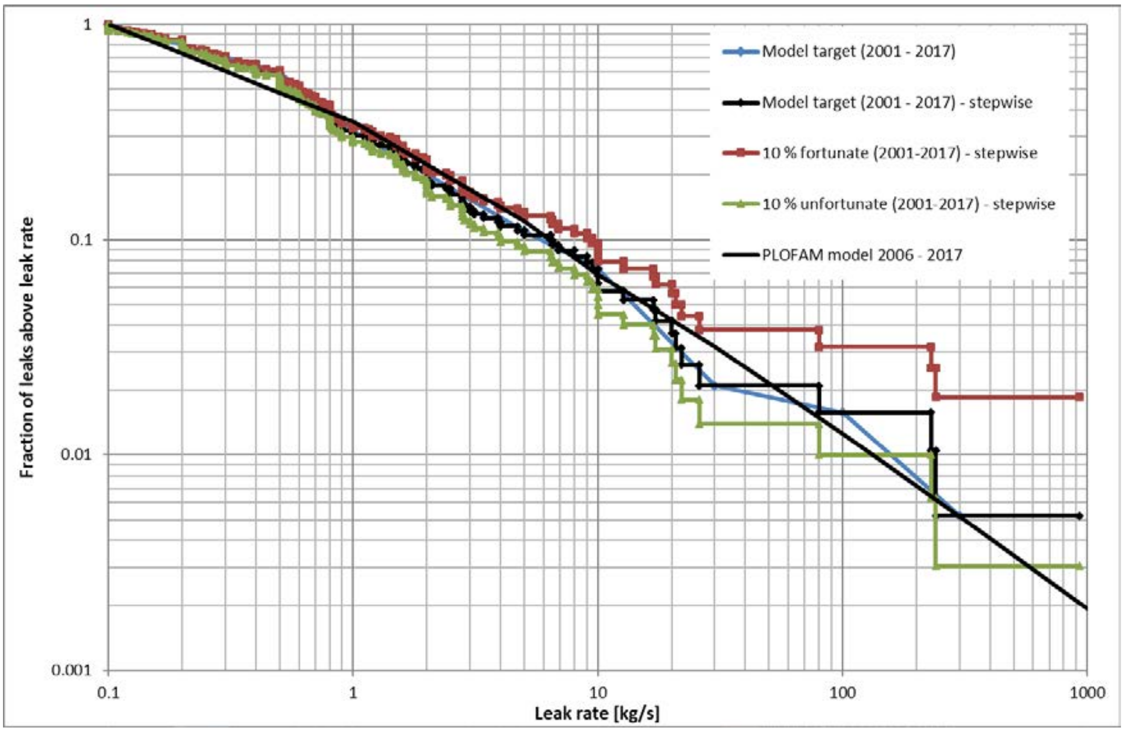


Figure 22.8 – Similar as Figure 22.7 but the actual leak rate registered in the database is used, *i.e.* the leaks are not grouped into categories

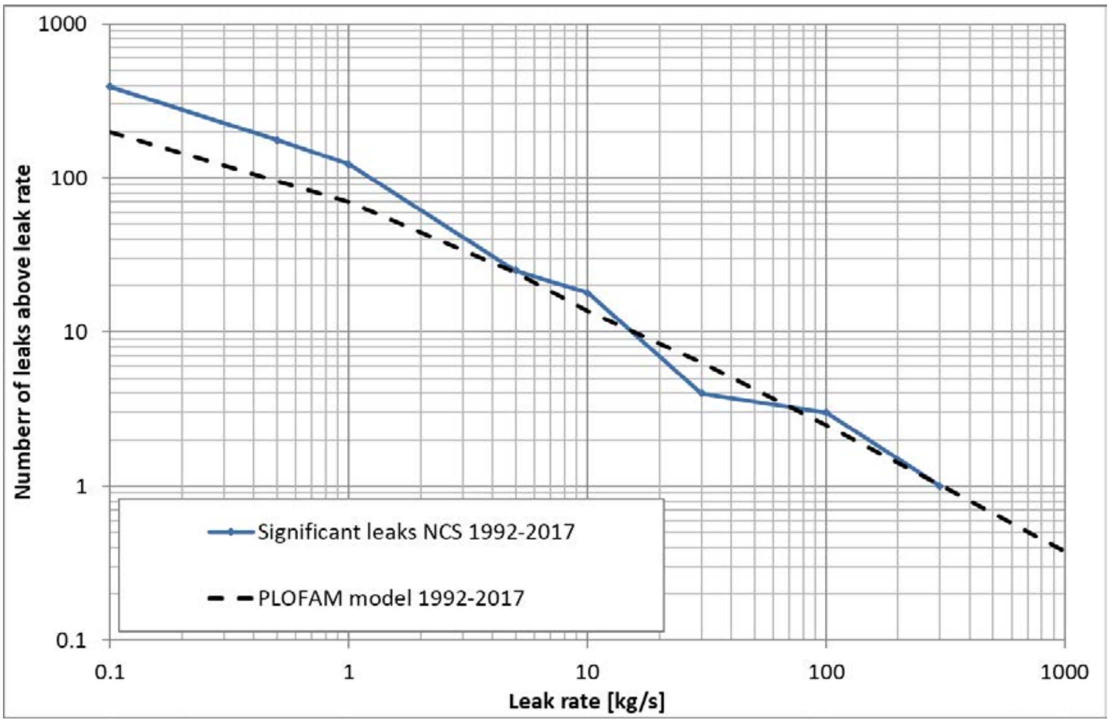


Figure 22.9 – Overall significant leaks: complementary cumulative leak rate distribution for all installations operating at NCS in the period 1992-2017

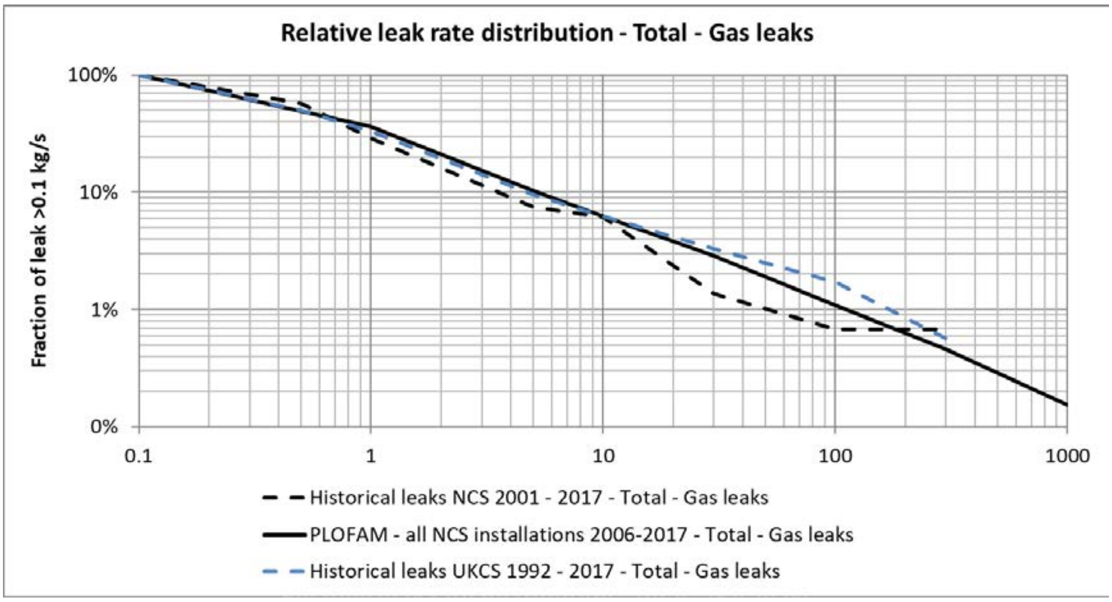


Figure 22.10 – Overall significant **gas** leaks: complementary cumulative relative leak rate distribution for all installations operating at NCS in the period 2006-2017

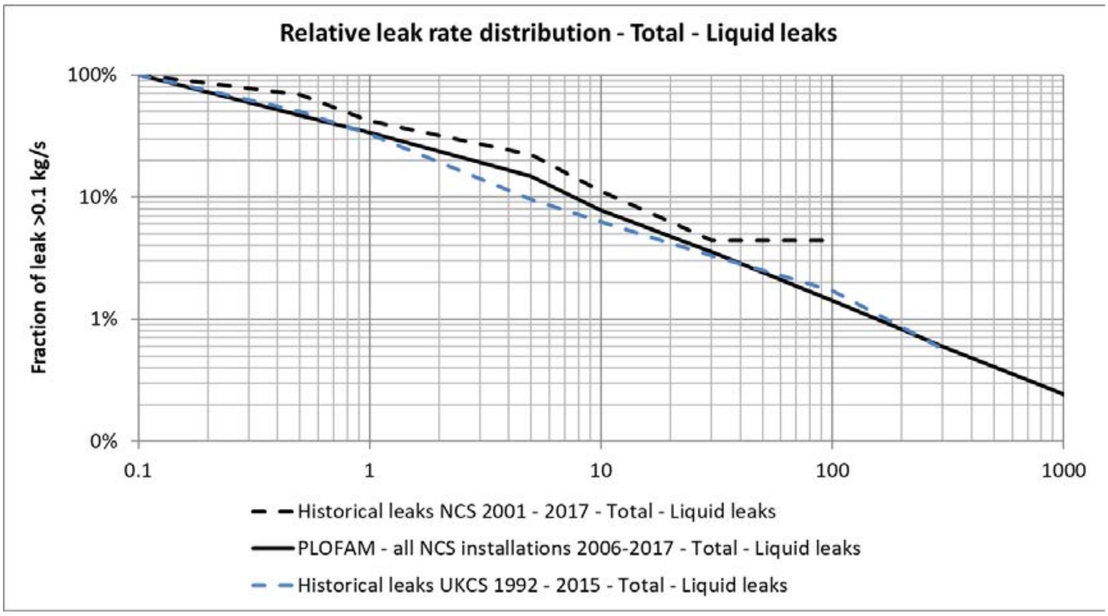
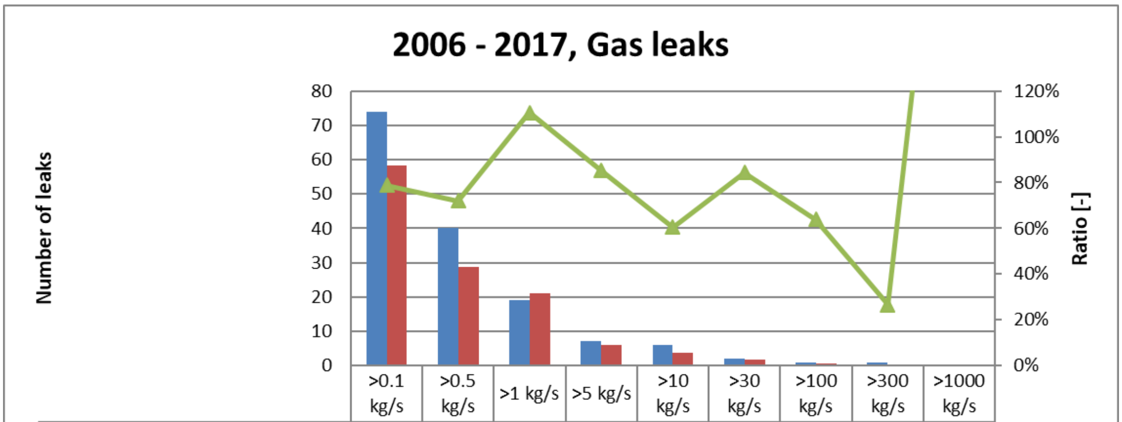
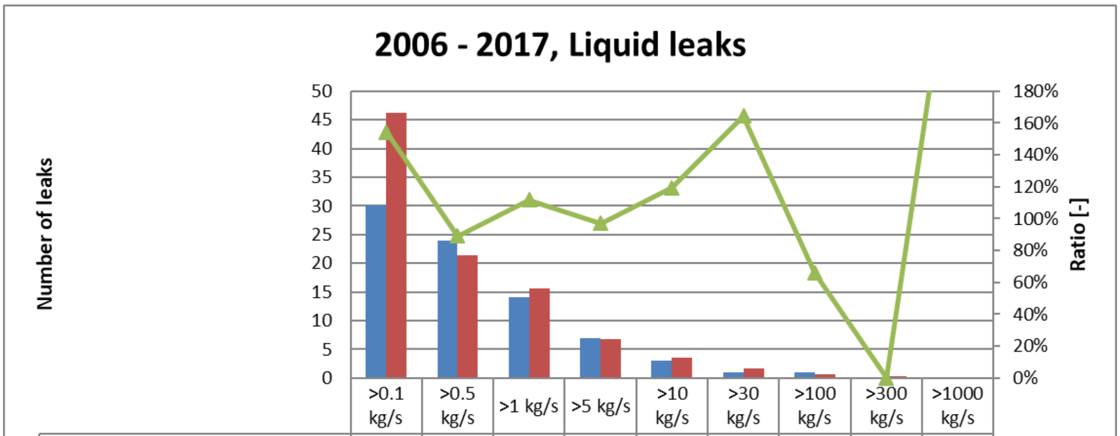


Figure 22.11 – Overall significant **liquid** leaks: complementary cumulative relative leak rate distribution for all installations operating at NCS in the period 2006-2017



	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Historical 2006- 2017	74	40	19	7	6	2	1	1	0
Modelled PLOFAM 2006 - 2017	58.3	28.8	21.0	6.0	3.6	1.7	0.6	0.3	0.1
Ratio (Modelled/Historical)	79%	72%	111%	85%	60%	84%	64%	27%	300%

Figure 22.12 – Overall significant **gas** leaks: leak rate distribution for all installations operating at NCS in the period 2001-2017



	>0.1 kg/s	>0.5 kg/s	>1 kg/s	>5 kg/s	>10 kg/s	>30 kg/s	>100 kg/s	>300 kg/s	>1000 kg/s
Historical 2006- 2017	30	24	14	7	3	1	1	0	0
Modelled PLOFAM 2006 - 2017	46.3	21.4	15.6	6.8	3.6	1.6	0.7	0.3	0.1
Ratio (Modelled/Historical)	154%	89%	112%	97%	119%	164%	66%	0%	300%

Figure 22.13 – Overall significant **liquid** leaks: leak rate distribution for all installations operating at NCS in the period 2001-2017

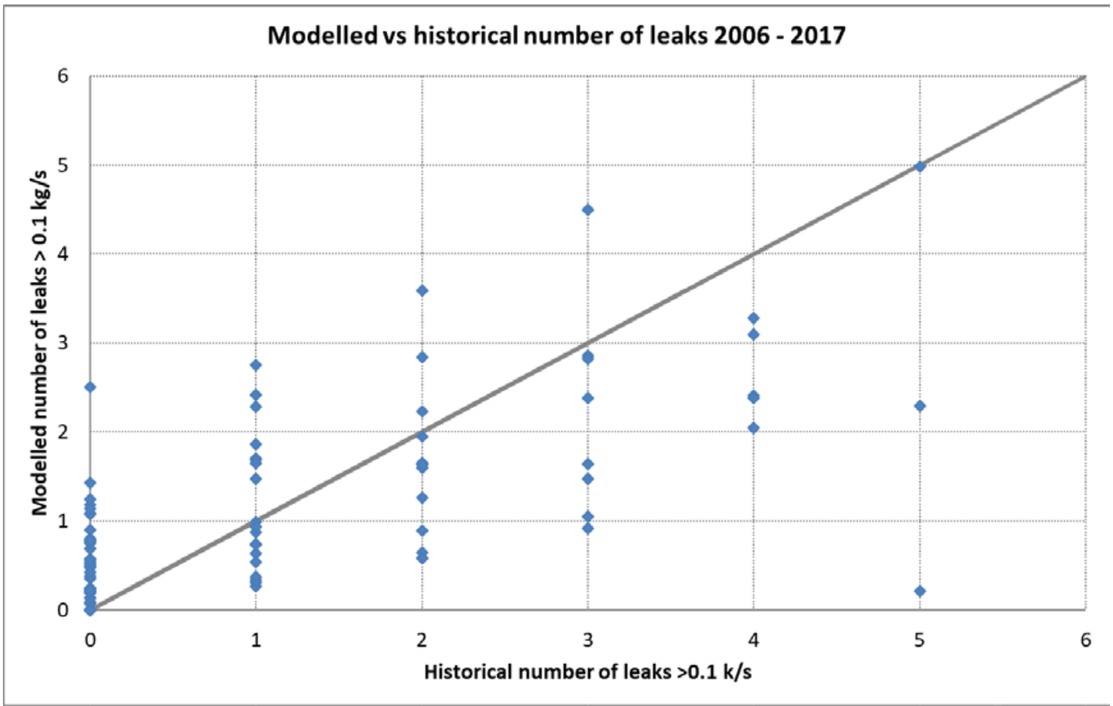
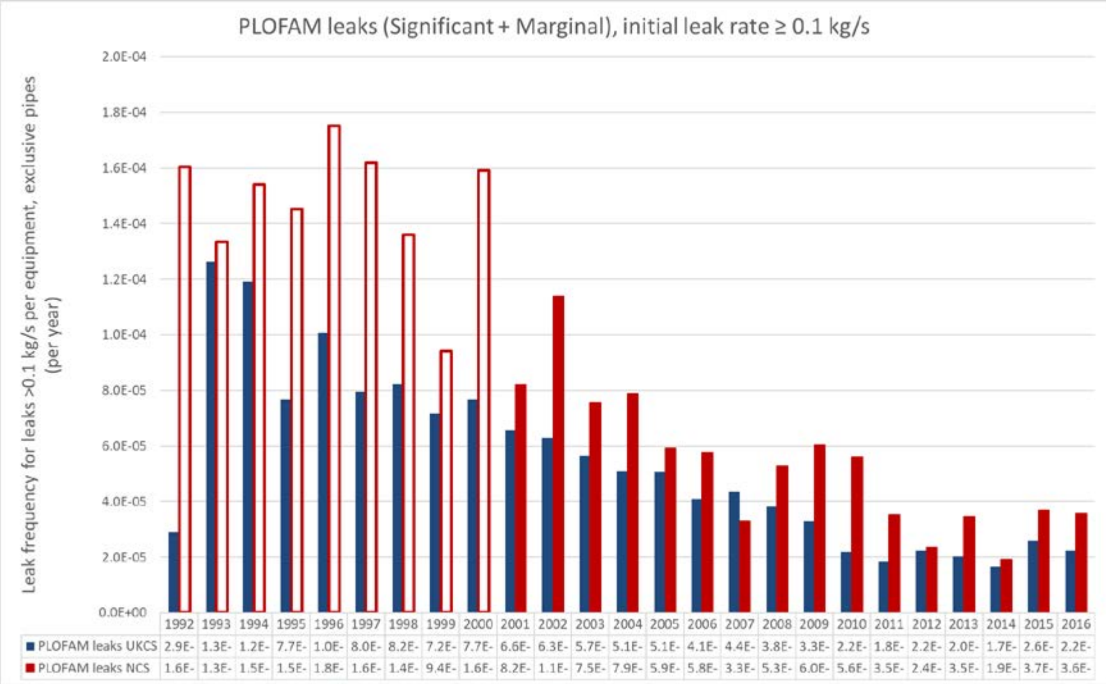


Figure 22.14 – Overall significant leaks: observed number of leaks vs. predicted number of leaks for all installations operating at NCS in the period 2006-2017. Datapoints below the grey line indicate underprediction. Datapoints above the grey line indicate overprediction



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
PLOFAM leaks UKCS	2.9E-	1.3E-	1.2E-	7.7E-	1.0E-	8.0E-	8.2E-	7.2E-	7.7E-	6.6E-	6.3E-	5.7E-	5.1E-	5.1E-	4.1E-	4.4E-	3.8E-	3.3E-	2.2E-	1.8E-	2.2E-	2.0E-	1.7E-	2.6E-	2.2E-
PLOFAM leaks NCS	1.6E-	1.3E-	1.5E-	1.5E-	1.8E-	1.6E-	1.4E-	9.4E-	1.6E-	8.2E-	1.1E-	7.5E-	7.9E-	5.9E-	5.8E-	3.3E-	5.3E-	6.0E-	5.6E-	3.5E-	2.4E-	3.5E-	1.9E-	3.7E-	3.6E-

Figure 22.15 – Number of historical leaks per equipment year (exclusive any type of piping) for leaks at NCS and UKCS. The correct exponent belonging to the figures in the table must be read from the second axis (the font size is maximized to enhance readability of the numbers below the bars).

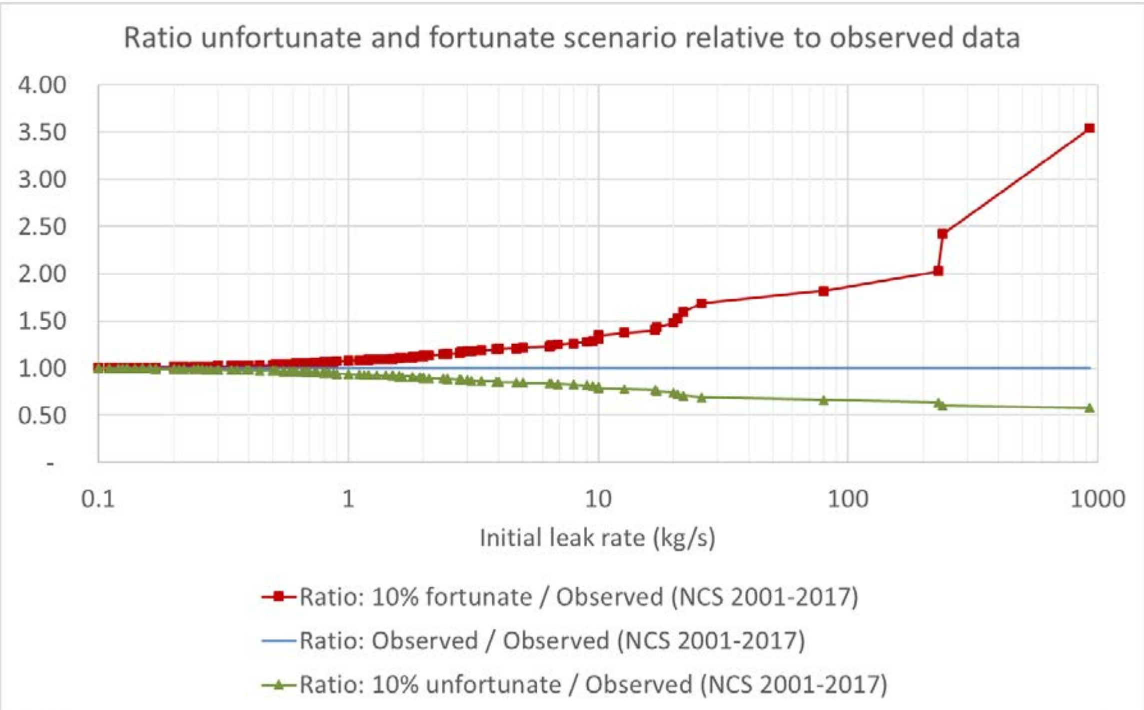


Figure 22.16 – Ratio unfortunate and fortunate scenario (10% percentiles used) with respect to observed data (NCS 20017-2017) versus initial leak rate. These ratios are derived directly from the relative leak rate distributions shown in Figure 22.8, but linear interpolation is used instead of plotting the steps

23 Further work

A model that is expected to predict leaks at installations on the NCS has been developed. During development of the model some unresolved challenges have been identified that are suggested to be addressed in future projects.

1) PLOFAM apply for estimation of leaks having an initial leak rate above 0.1 kg/s. In some cases, *e.g.* leaks in small enclosures with poor ventilation rates, even smaller leak rates should be assessed. It is judged that PLOFAM could be used for estimation of the leak frequency associated with smaller leak rates as well, but the estimate is more uncertain as no data is available for validation in this region. The capability of the model to estimate the leak frequencies for leaks with an initial leak rate less than 0.1 kg/s ought therefore to be investigated further to reduce this uncertainty

2) Although the quality of the NCS population dataset is considered to be high, there are aspects of the data that would increase the precision of the leak frequency model if they are improved. Elements of particular interest in addition to general quality assurance and update of equipment counts from QRAs are the effect of modifications implemented at installations, number of equipment in standby mode (*e.g.* redundant pumps and compressors), number of hose operations, wells in operation, equipment counts of flanges and valves associated with instrument connections and equipment counts of length of steel piping. The population data basis for development of the model for leaks stemming from hoses used in temporary operations is particularly uncertain. It is believed that the applied number of average hose operations per installation used as basis for the validation of PLOFAM is somewhat low, which implies that the frequency for leaks from hoses most likely is conservative. It is recommended that a future project upgrade the accuracy of the population dataset of hose operations in order to improve the precision of the leak frequency originating from hoses

3) A complete understanding of the causes for the difference in model prediction of leaks in terms of fluid phase has not been identified. An improved model prediction could have been obtained by defining separate PLOFAM parameters for equipment containing gas and liquid respectively. However, no apparent explanation has been found, and it has not been attempted to establish specific models for equipment containing gas and equipment containing liquids. It is recommended that future projects address this challenge. One objective could be to improve the simplified models used for estimation of initial leak rate for multi-phase leaks where estimation of the correct density is challenging. Uncertainty when classifying leaks in terms of fluid phase is also prominent, which calls for an improved methodology to be used under classification of leaks in the accident investigation work

4) Many aspects of the model lack support in causal arguments. For instance, the trends in the available data that describes the difference between various types of valves in terms of leak frequency is not fully understood (*e.g.* the difference between actuated and manual valves). It is recommended that future work seek to establish a better understanding of the correlation between failure modes and the observed statistical data of leaks. FMEA (Failure Mode and Effect Analysis) is suggested as tool for analysis of failure modes. Such studies would be very useful for all equipment types to improve the fundament for the leak frequency model, but in particular for inhomogeneous equipment categories consisting of equipment with variable technical properties. This applies in particular to the equipment type standard flange, valve and instrument (*e.g.* the dominant failure modes associated with an ASMA RJ and ASME RF flange is expected to be different)

5) The established mathematical framework is believed not completely to describe the behaviour of the underlying frequency hole size distributions. For the data available in this project, the mathematical formulation has been proven to be adequate. Future studies should look into possible improvements of the mathematical formulation. It is suggested that this is done in parallel with studies of failure modes (see previous item 4)) that can enable an understanding of the fundamental properties of the underlying hole size probability density function for the various equipment types

6) The general discrepancy between the estimated initial leak rate and hole size for leaks in HCRD has not been understood. This should be investigated further in the future, which probably also would increase understanding on how to improve modelling of initial leak rates in general (see also item 3) above).

7) The fraction marginal leaks of leaks at the NCS are considered uncertain. The fraction should be revised when more data is available. The updated version of HCRD (see item 6) above) will also improve the basis for setting the split between the significant and marginal leak scenario

8) Considerable work has been put into establishing the leak frequency data for installations on the NCS. It is recommended that the established data is updated (both the database of leaks and the corresponding population data) on a regular basis by a dedicated entity to ensure effective studies in the future

9) It is recommended that the procedures for investigation of leaks is updated to ensure that data parameters useful for modelling of leak frequencies are captured as part of the accident investigation process (*e.g*. pressure, temperature, hole size, composition, inventory etc.). In particular it would prove to very useful if the incidents are attributed to the correct equipment type.

10) As described in TN-2 there is uncertainty related to what extent operational time has been taken into account in the equipment count database. This adds uncertainty to the parameterisation process, but the effect is judged to be small (*i.e.* somewhat overestimation of the leak frequency). It is recommended to verify that operational time is not taken into account before new equipment counts are added to the population database in the future.

11) Leaks related to the flare system (see TN-2) appears to generate larger leaks (on average) than leaks stemming from other systems. This aspect should be explored further for potential implementation of a model specifically for flare system leaks

12) The rupture fraction for producing well and gas lift well is based on an engineering judgement and should reviewed in future updates of the model.

24 References

/1/ Lloyd's Register, Process leak for offshore installations frequency assessment model – PLOFAM, March 18th 2016.

/2/ Minutes of meeting PLOFAM project meeting with Equinor domain experts, "Leak frequency failure modes for valves, flanges and piping", 8 June 2018.

/3/ Safetec/Statoil, Guideline for application of the OMT model, technical note ST-11411-2, Rev. 6.0, 20.04.2017.

/4/ Personal communication with Tor Eriksen, independent consultant specialist on compact flanges.