Updated Leak Frequency Modelling Based on the UK Hydrocarbon Release Database

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This paper presents an overview of the process for revising correlations for the frequency of hydrocarbon leaks on offshore installations in the UKCS.

The UK HSE's Hydrocarbon Release Database (HCRD) is widely acknowledged as the most comprehensive source of information on loss of containment incidents in the UKCS. Results based on it are used in the risk assessment of both offshore and onshore facilities in many countries. Since the frequencies are effectively direct multipliers to the calculated end risk results, an upward or downward trend in the data could have a significant effect on safety related expenditure.

In June 2016, the UK HSE issued updated, and more comprehensive, information on incidents and equipment populations. The paper discusses a process for selecting the incidents in the database which are of relevance to risk assessment. In combination with the updated population data it allows the calculation of frequencies for a range of equipment types together with correlations describing their hole size distribution. The proposed method of achieving this is described.

The study demonstrated that when a number of factors are taken in combination, the frequencies used in risk assessments can be justifiably reduced by significant amounts with potential implications for the extent to which control and mitigation measures are required.

Key Words: Process Leak Frequencies, Hydrocarbon Release Database

Background

The oil and gas industry makes considerable investments to reduce the likelihood and consequence of loss of containment accidents. It is a complex task to assess the relative values of these investments to achieve an appropriate balance of financial expenditure and risk reduction. Knowledge of failure frequencies needs to be considered alongside the resulting consequences and the cost of implementing risk reduction measures.

While all hazards need to be considered in a risk assessment, the focus of attention will normally be on hydrocarbon loss of containment events and one of the key inputs to this analysis is the estimation of frequency of accidental releases of various sizes. These estimates are normally based on historical incidents which are used as the basis of a leak frequency model. Various sources of data are available but the Health and Safety Executive's (HSE) Hydrocarbon Release Database (HCRD) has become established as the prime source of data. Tables and mathematical correlations based upon it are used in many countries for onshore as well as offshore studies. This is because even though the environmental and operational conditions differ, there is a lack of data considered more appropriate. It could be argued that the database is the most significant source of information of this type available to the petrochemical as well as the oil and gas industries. The estimated leak frequencies are direct multipliers to the calculated risks and their accuracy can directly affect decisions on the provision of safety barriers and therefore costs.

Recent work has identified some areas for improvement in the way in which information in the HCRD is collected, collated and analysed. Some of these have been addressed and have been presented elsewhere (Bain, Wakefield, & Borresen, 2016). Two relevant developments are the issue of more detailed information on incidents in the UKCS (HSE, 2016#1) and improved estimates of the corresponding equipment populations (HSE, 2016#2). Both of these cover the period October 1992 up until December 2015 and were issued on the HSE's web site in June 2016. Using these data as a basis, a revised model for calculating suitable estimates for process equipment leak frequencies is being developed. This paper details the various stages in the analysis and suggests approaches that can be adopted. Results are presented using flanges as an example but these are subject to refinement and will vary as further years of data are added.

Source Data

Incidents

The latest publicly available information from the HCRD gives details of 4656 incidents until 31st December 2015. Each record has 118 fields of information the most important of which are;

- Date of incident
- Installation Type
- Process System Type
- Equipment Type
- Quantity of Hydrocarbon Released
- Equipment Size
- Equivalent Hole Diameter, and
- System Pressure at the time of the release

Other information provides more details on the installation, the module where the release took place, the cause of the leak, how it was detected, information on ignitions and any emergency action which followed as a result. While these are important and merit detailed analysis, the focus of this work is to establish mathematical correlations to describe the frequency distribution for various types of equipment. The information items referenced above are those of prime interest in deriving these. Some of the information has not previously been made available. Two items are particularly relevant to this study;

- Equipment sizes were not previously made available other that some items which were classified in size bands of; less than or equal to 3" (D <= 3"), larger than 3" but less than 11" (3" < D < 11") and greater than 11" (D > 11"). This new information may enable an analysis of the distribution of hole sizes as a ratio of the equipment size. In particular, it allows identification of releases which could be classed as full bore ruptures.
- In the information previously available, the size of holes with equivalent diameters greater than 100 mm was simply recorded as "> 100 mm" making the task of fitting a hole size distribution for these large holes more difficult. The information now available provides better estimates of the actual hole size.

Equipment Populations

Some users of the HCRD who had a need to obtain estimates of equipment populations in addition to incidents became aware, some years ago, that the recorded amount of equipment in any given year had become static. As an example, Figure 1 shows population of flanges[1] in the range 3" to 11" obtained from the HSE on-line system (HSE, 2016#3). The blue dotted line shows the total number of flanges which indicated that the population remained constant that from 2003-2004 onwards. This was the case for all other equipment types. This date coincides with a change in the way in which the data was collected whereby greater responsibility was placed on operators to update information on-line. This system appears to have been ineffective, with operators being unaware of their responsibility and insufficient oversight by the HSE to identify the problem and act. Thus, process systems were being modified, many installations constructed and a few decommissioned without the changes influencing the frequency analysis based on the HCRD. In recent years, the regulator and industry have worked together to understand this issue and to take steps to establish better estimates. The work, largely undertaken and financed by DNV GL, has resulted in better estimates of the equipment population over the period since 1992 and greater understanding on which installations and process systems were included in the data. The results are given in the updated estimates issued by the HSE in June 2016 (HSE, 2016#2) and are used as a basis, along with the incident data (HSE, 2016#1), for the modelling described in this paper. These show significant increases in the estimated populations as shown in Figure 1 for 3" - 11" flanges. The original data includes equipment counts from all types of installations whereas the plot for "original – fixed production" excludes certain types. The amended data shows the best estimate after taking account of missing information. Over the period from around 2004 this represents an increase of 33% for this equipment type. When incorporated into a frequency analysis this would result in a corresponding decrease in calculated values.

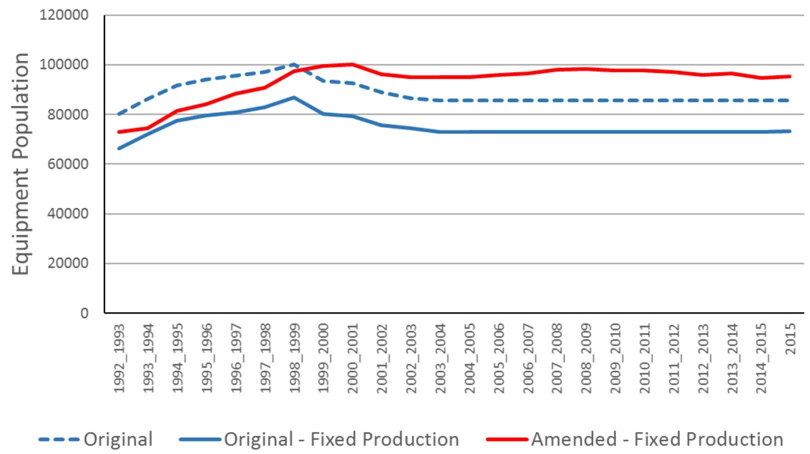


Figure 1: Variation in Population of 3" - 11" Flange Joints

Modifications to Incident Data

The first task in this analysis was to review the incident data and make amendments where errors could be readily identified. Several issues were identified but, of these, only two had a direct bearing on the analysis.

1. There are 163 incidents with an apparent equivalent hole size of 999 mm. It is understood that this was used as a numerical value surrogate to represent an incident for which an equivalent hole size was not available. These data were modified to "BLANK" to make this fact explicit. In analysing the data only those data with recorded hole sizes were used in determining the hole size distribution. This effectively means that the "BLANK" entries have

[1] Within this paper, a "flange" is taken to mean a "flange joint" rather than the "flange face" definition used in the HCRD. A factor of 2 has been used to convert from one definition to the other.

the same distribution as the recorded values. This is a potentially conservative assumption since the most likely reason for the hole size not being recorded was because it was too small to be able to measure accurately.

2. The incidents where the reported hole size was greater than the equipment sizes were modified to make the hole size equal to the equipment size. This was the case for 49 incidents.

Selection of Relevant Incidents

Not all the events recorded in the HCRD are appropriate for consideration in the determination of leak frequencies. This may be because of incompatibility with the population data or because the nature of the incident, even if it had ignited, would not have had consequences with the potential to cause significant damage or loss of life. This section describes the various reasons for filtering out incidents to arrive at a set used in the later analysis.

Installation Type: The population data (HSE, 2016#2) includes equipment counts only from fixed production installations[2]. Equipment data for mobile drilling units were removed from the population because it was not practical to determine the amount of time that the installation was in the UKCS. Equipment on sub-sea installations and non-production installations were also removed from the population data set. To be compatible with this, all incidents other than those on fixed production installations were removed.

System Type: Not all process systems have their equipment counted. Equipment counts are not generally available for systems associated with flaring, venting and utility systems. The study carried out to establish the equipment population data identified 37 system types which were normally counted and a further 17 which were not normally counted. The resulting data is an estimate of the equipment in those systems classed as "normally counted". To be compatible with this, all incidents from "not normally counted" systems were removed. In addition, loss of containment incidents from drilling and well operations were removed.

Equipment Types: There are two types of equipment which have no population counts. These are "Drain Openings" and "Drain Plugs". These have been designated as "Uncounted Equipment" whereas all other types are "Counted Equipment". Since there is no population data for these two equipment types it is not possible to calculate frequencies for these.

There are also 304 "BLANK" entries in the equipment type field. Incidents in "Counted Equipment" or recorded as "BLANK" are retained in the current study while incidents in "Uncounted systems" are filtered out. "BLANK" entries are subsequently redistributed as described later.

Hole Size: Prior to the 2001/2002 accounting period, there are no records of hole sizes less than 1 mm. It is not clear whether this is because such small holes were not recorded at all or because any holes smaller than 1 mm were recorded as "1 mm". A large proportion of holes are recorded as being exactly 1 mm in diameter. For the purposes of this study hole sizes less than 1 mm were filtered out to ensure consistency and because releases from holes of this size are of limited relevance to a QRA. While deselecting the small holes influences frequency it also changes the hole size distribution such that there are a greater proportion of selected incidents with hole sizes in the higher size categories. "BLANK" entries are subsequently redistributed as described later.

System Pressure: It is known that several reported incidents have occurred under very low system pressures. Typically, these have been due to deliberate breaking of containment of systems thought to have been purged of hydrocarbon gas. In many cases the hole sizes associated with these are large. In previous DNV studies (Spouge, 2006) and (Falck, Bain, & Rødsætre, 2009) these releases have been categorised as "zero pressure" leaks which were assigned their own leak frequency functions and associated with lower levels of consequence. These were leaks where the recorded "Actual Pressure" was less than 0.01 barg. Arguably it would be justifiable to disregard the "zero pressure" leaks altogether on the basis that their consequences would be negligible in comparison with leaks at normal system pressures. In the current study, incidents with recorded system pressures of less than 0.01 barg have been filtered out. Systems with no recorded pressure (35 in number) are conservatively assumed to have occurred at their operating pressure when it is likely that many were actually less than 0.01 barg.

Deliberate Releases Accidentally Ignited: All ignited events are required to be reported. In a few cases these may be incidents where a deliberate release, e.g. from a vent, was ignited. Although this is a valid incident it does not relate to an accidental release of hydrocarbons and so should be deselected. Most incidents of this type will be in systems categorised as "Not counted" and filtered out for this reason. However, an examination of the description of ignited incidents identified some which were attributed to "Counted Systems" but which either should more appropriately have been attributed to flare systems or turbine exhausts. Such incidents were filtered out.

Reporting Criteria: The criteria under which a release is considered reportable has varied over the years. Guidance from Oil & Gas UK (O&GUK) which included suitable criteria was first issued in 2008. The most recent version was issued in 2015 (Oil & Gas UK, 2015) in response to the introduction of European Union reporting requirements (European Union, 2013) and (European Union, 2014). Incidents should now be reported if they meet either the criteria for a RIDDOR reportable incident or those of the EU. A given incident may comply with both, RIDDOR only, EU only or neither of the criteria which are themselves dependent on the type of hydrocarbon being released. EU criteria have a classification of releases of "fugitive" and "non-fugitive". For incidents above a given release quantity but below a given release rate, whether or not a release is reportable depends on this categorisation. It is not practical in most cases to determine whether a historic incident is fugitive or non-fugitive but the purposes of this study incidents have been assumed as non-fugitive.

[2] The term "Fixed" in this context includes permanently moored floating installations.

Figure 2 and Figure 3 show the criteria that have been applied. This study has filtered out those incidents which meet the not-reportable criteria. This does not mean that they shouldn't have been reported at the time they occurred since different criteria may have applied at the time.

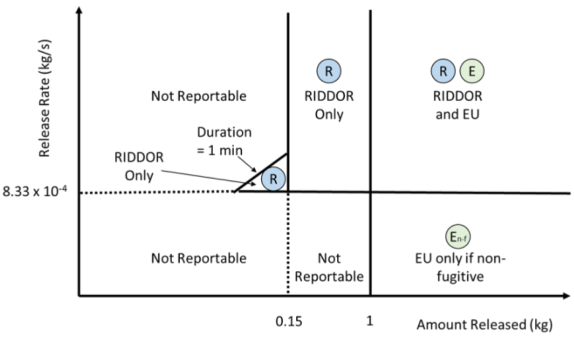


Figure 2: RIDDOR & EU Reporting Criteria for Gas Releases

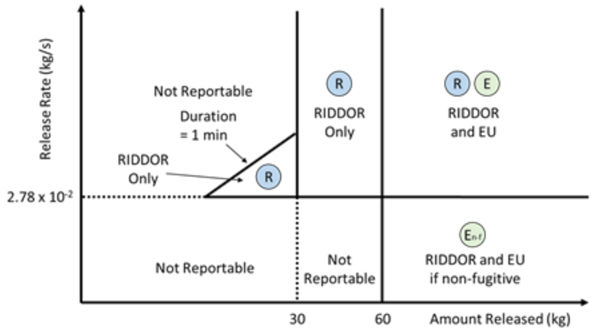


Figure 3: RIDDOR & EU Reporting Criteria for Oil Releases

Time Period : Calculation of frequencies based on the HCRD have typically used the whole period from when records were started in 1992. It is known that the number of reported incidents have been falling over this period and at some point it becomes appropriate to recognise this by giving more weight to recent experience. This could be achieved, for example, by considering only the last 5 years or 10 years in deriving the frequency. It may also be appropriate to use a different time period for deriving probabilistic distributions of hole size from that used for frequencies.

Within this study, frequencies have generally been calculated using the last 10 years of experience and this is discussed later. However, hole size distributions are based on the whole of the database. This would nominally cover the period from 1st October 1992 to 31st December 2015. Note that the first incident in the data base occurred on 26th September 1992 and is therefore before this period. Hence, it can be excluded from the analysis to be consistent with the equipment population data.

Criterion	Retained	Removed	Proportion Retained
Installation Type	4265	391	91.60%
System Type	3430	1226	73.67%
Equipment Type	4568	88	98.11%
Hole Size	3829	827	82.24%
System Pressure	4384	272	94.16%
Deliberate Releases	4652	4	N/A
Reportable	3386	1270	72.72%
Time Period	4655	1	99.98%
Overall	1968	2688	42.27%

Table 1: Incidents Retained and Removed During Filtering Process

Table 1 shows how many incidents were filtered out under the various criteria. The set of incidents used in the analysis are those which met all the criteria listed above. In many cases a given incident is filtered out by more than one of the selection criteria. Applying all the criteria in combination resulted in the deselection of 2688 of the incidents leaving 1968. This is 42.27% of the total.

Variation of Frequency With Time

An examination of the annual number of incidents in the HCRD reveals that there is a clear downward trend. This is shown in Figure 4 and Figure 5 using a combination of all equipment types[3].

[3] The accounting period for 1992-1993 is only 6 months (1/10/92 – 31/3/93) and the final period is 9 months (1/4/15 – 31/12/15). The number of incidents for these periods have been factored to annualise them.

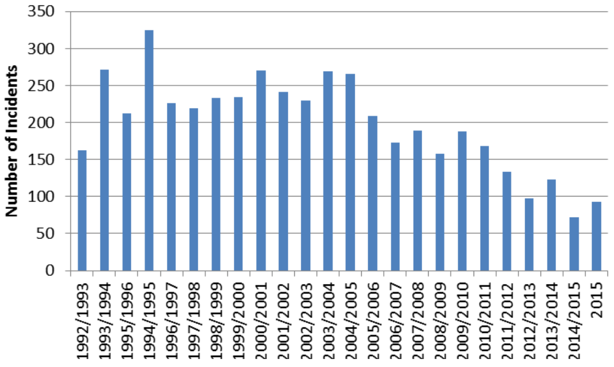


Figure 4: Reported Incidents by Reporting Year

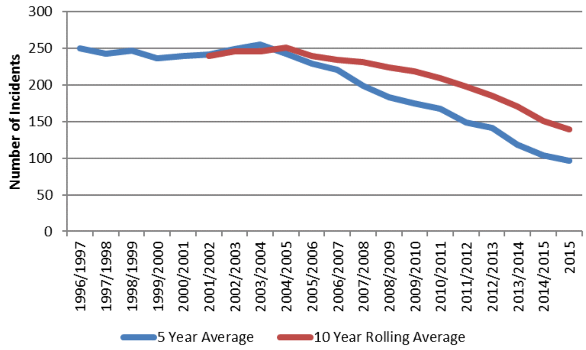


Figure 5: Rolling Averages of Reported Incidents

Since the population of equipment has generally grown over the period in which the HCRD has been operating the frequency based on equipment years has been falling at an even faster rate.

This trend can be further illustrated by using flanges as an example as shown in Figure 6 and Figure 7. Flanges have had a particularly sharp decline in the past decade which is more significant than most other equipment types.

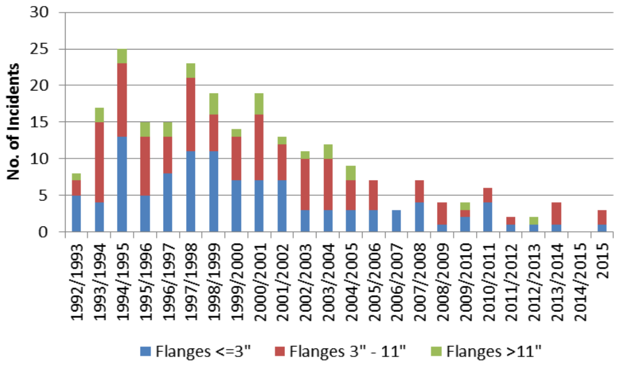


Figure 6: Reported Incidents for Flanges

by Reporting Period and Size Category

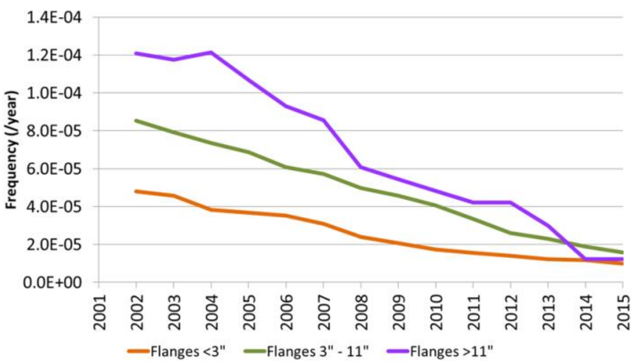


Figure 7: Rolling 10 year Averages of Frequency

for Flanges by Size Category

It is apparent that the oil and gas industry has been successful in reducing the frequency with which leaks occur and that risk assessments should take account of this. It is proposed that frequencies should be based on the previous 10 years of experience with the additional criteria that at least 10 incidents for that piece of equipment should have occurred within that period. If this is not the case, then the time period should be extended backwards until 10 incidents are available or the start of HCRD records is reached. Where 10 incidents are used, the period is taken as starting on the date mid-way between the 11^{th} and 10^{th} last incidents. An alternative approach for equipment with size categories is described below.

An adjustment is made to the number of incidents for each equipment type by redistributing the incidents for which an equipment type has not been specified, i.e. "BLANK" entries, in the proportions with which they have historically occurred. Of the 1968 selected events, 108 are for flanges in the <=3" category and there are there are 8 incidents with no equipment specified. The proportion of incidents from equipment in this category account for 108/1960 = 0.0551. In the last 10 year period, there have been 18 incidents in this category and 4 "BLANK" entries. Redistributing these incidents in proportion give 18 + (4 x 0.0551) =18.22 incidents. This equates to an average of 1.822 incidents/year. During this period the average population of <=3" flanges has been 182,187. The frequency is then calculated as 1.822/182187 = 1.00 x 10^{-5}. A similar calculation can be done for the flanges in the 3" – 11" category which has had 15 incidents in the last 10 years. However, there have only been 2 recorded incidents for >11" flanges in the last 10 years and the period of analysis is extended to 15.47 years to obtain the required 10 incidents. Table 2 provides details of the calculations as examples.

Equipment Category	Selected Incidents	Proportion of incidents	Incidents in last 10 years	Adjusted Incidents	Basis for Frequency	Average Incidents per Year	Average Population	Frequency
Flanges <=3”	108	0.0551	18	18.22	Last 10 years	1.822	182,187	1.00×10^{-5}
Flanges 3” – 11”	108	0.0551	15	15.22	Last 10 years	1.522	96,695	1.57×10^{-5}
Flanges >11”	26	0.0133	2	N/A	Last 10 incidents*	0.647	16,700	3.87×10^{-5}

*The last 10 incidents for flanges >11” have occurred in the period 12/7/2000 – 31/12/2015.

Table 2: Calculation of Leak Frequency for Flanges

A potential problem of using the period for the last 10 incidents is that different equipment will have calculated leak frequencies relating to different periods. This may be an issue for equipment which has different hole size categories and where there is a systematic change in the underlying frequency which should affect all the size categories.

An example of this is the case with flanges. The <3” and 3” – 11” categories each have more than 10 incidents in the 2006-2015 period but the >11” category only has 2. Extending back to 10 incidents gives a period of 15.47 years. This implies a higher frequency than may be appropriate given the general decrease in the last 10 years. Alternatively, basing the frequency for large flanges on only 2 incidents introduces large uncertainties. To overcome this situation the following approach is suggested for equipment types which have size categories.

If it is assumed that the ratio of frequencies between the three hole sizes is constant with time then we can use the long term average frequencies to establish these and then apply them to the overall frequency for the last ten years. We can calculate the following ratios;

$$R_s = F_{s\,all}/F_{all} \qquad R_m = F_{m\,all}/F_{all} \qquad R_l = F_{l\,all}/F_{all}$$

Where R_s, R_m and R_l are the respective ratios of frequency for the “small” (<3”), “medium” (3” – 11”) and large (>11”) equipment size categories to overall frequency taken over the whole period of the HCRD.

F_s, F_m and F_l are the frequencies for the “small” (<3”), “medium” (3” – 11”) and large (>11”) equipment size categories taken over the whole period of the HCRD respectively

and F_{all} is the overall frequency over the whole period of the HCRD.

The adjusted frequencies for the three categories over the last 10 years is then given by

$$F_{s\,10} = R_s\,F_{10} \qquad F_{m\,10} = R_m\,F_{10} \qquad F_{l\,10} = R_m\,F_{10}$$

Where $F_{s\,10}$, $F_{m\,10}$ and $F_{l\,10}$ are the adjusted frequencies for the “small”, “medium” and large equipment size categories over the previous 10 year period, and

and F_{10} is the overall frequency for the equipment type over the last 10 year period.

Using flanges as an example this gives the values shown inTable 3.

Equipment Size	Frequency over Whole Period	Frequency Ratio	Frequency over 10 years	Adjusted Frequency for 10 Year Period
<= 3"	2.685×10^{-5}	0.727	1.001×10^{-5}	8.777×10^{-6}
3" - 11"	4.991×10^{-5}	1.352	1.574×10^{-5}	1.631×10^{-5}
>11"	7.065×10^{-5}	1.914	1.220×10^{-5}	2.310×10^{-5}
Overall	3.692×10^{-5}		1.207×10^{-5}	1.207×10^{-5}

Table 3: Adjustment of Frequencies Example

An equivalent approach can be taken for different time periods, e.g. the most recent 5 years.

Calculation of Historic Frequency Exceedence Plots

The incidents remaining after the filtering process together with the relevant equipment population can be used to derive plots of frequency of hole sizes exceeding defined values. The process used in this study has used all of the available filtered data to derive hole size distributions and then to multiply this by the relevant frequency to obtain a frequency exceedance plot. Applying this process to the three categories of flanges, results in the plots shown in Figure 8. Figure 9 shows the probabilistic distribution for the hole sizes.

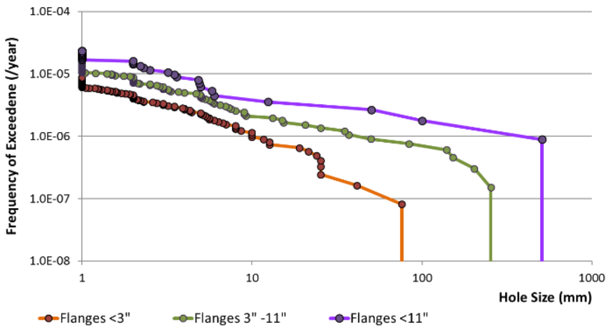


Figure 8: Historic Frequency Distribution of Flange Incidents

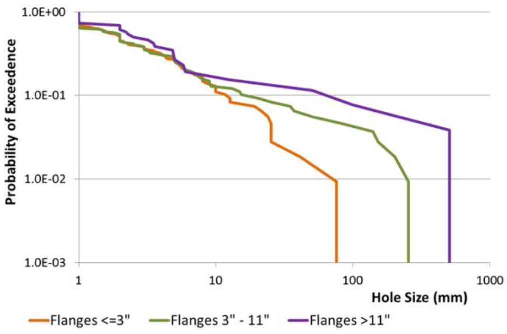


Figure 9: Hole Size Exceedence Probabilities for Flanges

Frequency Correlations

Various approaches have been suggested for specifying the frequencies to be used in risk assessments. These can range from simply reporting the frequency of releases within specific size bands to fitting mathematical functions to the historic plots. This latter approach is preferred given the relatively low number of releases within higher hole size categories which would then be subject to a large amount of uncertainty.

An established approach is presented in the IOGP Risk Assessment Data Directory (IOGP, 2010) and guidance issued by DNV (DNV, 2013). This is given using the following equation.

$$F = C(1 + aD^n)\, d^m + F_{rup} \qquad \text{for } d = 1 \text{ mm to } D \qquad (1)$$

$$F = 0 \qquad \text{for } d > D$$

Where d is the hole size
F is the frequency of a hole greater than or equal to d
D is the equipment size
and C, a, n, m and F_{rup} are parameters for each equipment type.
F_{rup} is referred to as the additional rupture frequency

The parameters a and n can be used to take account of the effect of equipment size. This can be applied to those items of equipment which are reported in different size categories. Where the equipment population does not provide this level of detail it is not practical to derive values for these parameters and the equation can be simplified to the following;

$$F = Cd^m + F_{rup} \qquad \text{for } d = 1 \text{ mm to } D \qquad (2)$$

$$F = 0 \qquad \text{for } d > D$$

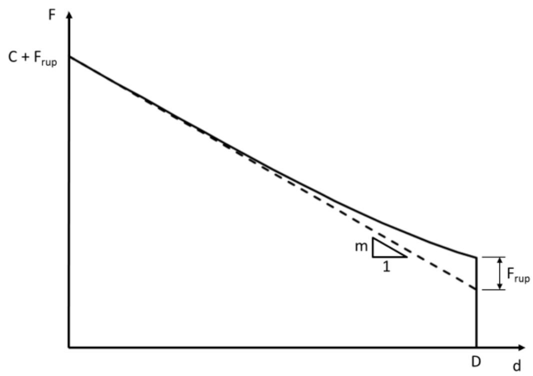


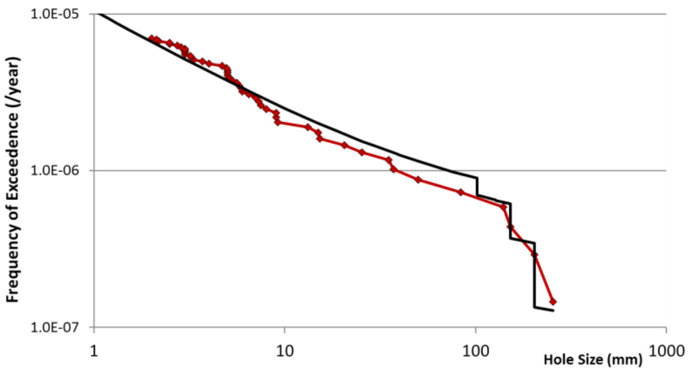
Figure 10: Parameters for the Exceedance Curve Correlation

Experience has shown that it is difficult to obtain good fits to all three size categories simultaneously using this formulation. This is largely because while the formulation effectively allows for variation of the C parameter with diameter, it does not allow for variation of the m parameter, which describes the gradient of the curve, or the additional rupture frequency parameter, F_{rup}. This study proposes an alternative way for accounting for the variation with equipment size. This is discussed later. The initial process is to find suitable values for C, m and F_{rup} to describe correlations for each of the three equipment size categories.

In fitting a curve, it should be borne in mind that part of the reason for the decrease in frequency of exceedance with hole size diameter is that the population of equipment capable of having a hole of that size decreases because of the limitation that the hole cannot be larger than the equipment. The 3" – 11" category, for example, is composed of a mixture of flanges of size 4", 5", 6", 8" and 10". Knowledge of the relative proportions of these would enable a composite curve to be produced from the contributions relating to each equipment size.

The population data in the HCRD does not provide this level of resolution, i.e. we have an estimate of the total in the 3" – 11" category but not a breakdown by equipment diameter. However, the PLOFAM study (Lloyds Register, 2016) reports proportions of equipment sizes for installations in the Norwegian sector. This gave the following distribution; 4": 22.075%, 5": 0.93%, 6": 30.748%, 8": 28.198% and 10": 18.049%. In the absence of UK data, it is proposed that this distribution is applied to installations in the UKCS on the assumption that the distributions are similar to those in Norwegian waters. The proposed correlation can be applied to each equipment size and an overall weighted average plot produced which can be compared with the historic data. Using this process means that the exceedance frequency for each of the 5 sizes drops to zero when the equipment size is reached. This results in a stepped plot as shown in Figure 11. This uses the equation;

$$F_{pred} = P_{equip}(Cd^m + F_{rup}) \qquad (3)$$



Where P_{equip} is a function of the hole size, d, and represents the proportion of equipment with a size greater than that of the given hole size.

Selecting values for the C, m and F_{rup} parameters allows a plot of the model prediction which can be compared with the historic evidence.

In this example, by using the coefficients; $C = 1 \times 10^{-5}$, $m = -0.7$, and $F_{rup} = 5 \times 10^{-7}$, we can predict a value for 10 mm holes of;

$$F(10) = 1 \times (1 \times 10^{-5} + 10^{-0.7} + 5 \times 10^{-7}) = 2.495 \times 10^{-6}$$

For a hole of size 175 mm (6.9") we will have a value for P_{equip} of 0.28198 + 0.18049 = 0.46248, i.e. the proportion of equipment in the category which have a nominal size greater than 175 mm.

So $F(175) = 0.46248 \times (1 \times 10^{-5} + 175^{-0.7} + 5 \times 10^{-7}) = 3.557 \times 10^{-7}$

Figure 11 and Figure 12 show the comparison with the predicted and historic plots for this selection of parameters. There are several steps in the plot representing the 4", 6", 8" and 10" equipment sizes. The step corresponding to 5" is not apparent because of the low proportion of this size of flange.

Process For Calculating Correlation Parameters

The objective for selecting values for the C, m and F_{rup} parameters is to find the combination which results in the best fit to the available historic data. This may be done in an iterative process where combinations of parameter are proposed, the resulting curve compared with the historic plot and progressively refined until a suitable fit is obtained. An alternative is to use a curve fitting algorithm to iterate automatically. The advantage of the latter is that the same result should be obtained by different analysts whereas the former will involve a degree of objectivity. In this study, a least squares curve fitting approach was used to establish the optimum values for the parameters.

It is also known that the accuracy to which holes in the range 1 mm to 2 mm can be measured is limited. Also, holes in this range are unlikely to contribute greatly to the overall risk. It is therefore proposed that, provided there are enough incidents greater than or equal to 2 mm, only these values are used in the curve fitting exercise. This is the case with all three size categories for flanges. Where the data for a given equipment item is sparse it may be appropriate to include holes between 1 mm and 2 mm.

Application of this process resulted in a refinement of the parameters to obtain a better fit as shown in Figure 12. Figure 13 also includes the fits for the other two size categories.

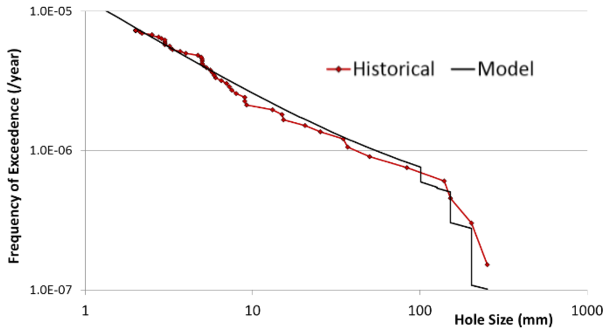


Figure 12: Correlation to Historic Data For 3" - 11" Flanges Following Least Squares Curve Fitting

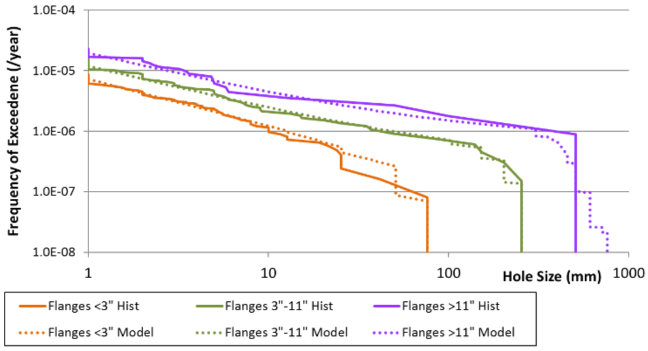


Figure 13: Correlations with Historic Data for Three Flange Size Categories

The correlations shown in Figure 13 have the following parameters and equations given in Table 4.

Equipment Type	C	m	F_{rup}	Equation	
Flanges <=3"	7.20 x 10^{-6}	-0.770	0	$F = 7.20 \times 10^{-6}\, d^{-0.77}$, F = 0,	d <= D d > D
Flanges 3"-11"	1.20 x 10^{-5}	-0.730	3.5 x 10^{-7}	$F = 1.20 \times 10^{-5}\, d^{-0.73} + 3.50 \times 10^{-7}$, F = 0,	d <= D d > D
Flanges >11"	2.00 x 10^{-5}	-0.700	8.0 x 10^{-7}	$F = 2.00 \times 10^{-5}\, d^{-0.70} + 8.0 \times 10^{-7}$, F = 0,	d <= D d > D

Table 4: Parameters and Equations for Three Flange Size Categories

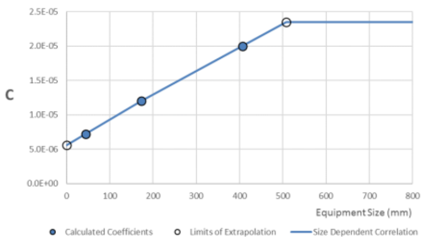
Various combinations of values for the three parameters can give visually acceptable fits to the historic data even though the values taken in isolation can be very different. This is particularly the case for the largest equipment size category where there are fewer data points. The correlations have greater uncertainties for larger hole sizes generally, but particularly for equipment types with small numbers of incidents.

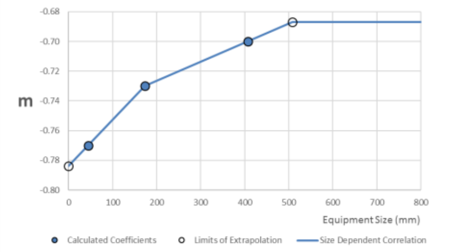
Process for Modelling Variation with Equipment Size

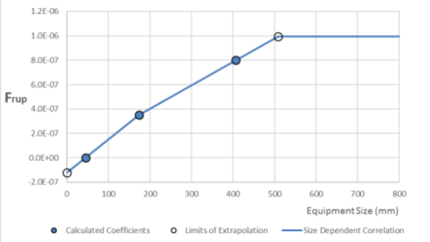
The equations presented above can be used for the corresponding range of equipment size. This will give step changes in the equations used as equipment size increases, e.g. the equation used for a 4" flange will be different from that for a 3" flange but the same for a 10" flange. An alternative approach is to develop a functional relationship between the equipment size and the parameters to enable size specific parameters to be obtained. This has previously been done for the C parameter by multiplying it by the factor $(1 + aD^n)$. The values for the parameters "a" and "n" are obtained by trial and error to match the available data. In some cases, selecting values for the parameters a and n, which gave good fits to the available data, could lead to very high predicted frequencies when extrapolated to large equipment sizes which are considered overly conservative. In this study an alternative approach is proposed.

The above analysis produced three values for the C parameter corresponding to the three equipment size ranges. Analysis of the equipment size distribution data from the PLOFAM study provides average sizes for these ranges of 44.90 mm, 173.61 mm and 406.83 mm respectively. Assuming that the C parameter values are most representative of equipment at these notional equipment sizes we can plot the information as shown in Figure 14. In this model it is proposed that values for the coefficient for other sizes can be obtained by interpolation or extrapolation. This appears appropriate for small diameter equipment but there is more uncertainty for very large equipment sizes since these are rare within North Sea offshore installations and there is therefore insufficient information to allow robust conclusions to be drawn. In this model it is proposed that equipment sizes above a prescribed value will be taken to be constant. In this study a limiting equipment size of 20" (508 mm) is proposed. This choice is significant because it will greatly influence the estimated leak frequencies for large pieces of equipment such as may be found in onshore LNG plant. Making these assumptions provides a function which correlates the value of C to the equipment size, D, as shown in the first graph in Figure 14. This interpolation/extrapolation process can be applied on a linear basis or a logarithmic basis and it may be appropriate to use one basis some parameters and the alternative for others. The decision is reasonably arbitrary and depends on the judgement of the analyst. In this study, it has been decided to use a linear correlation for the each of the parameters. While this choice makes a difference to the overall model, it is not too significant given the uncertainties involved in the overall process.

Figure 14 show the graphs correlating the three parameters with equipment size together with the equations derived.







Correlation for C Parameter	Correlation for m Parameter	Correlation for F_{rup} Parameter
$C = 3.706 \times 10^{-8} D + 5.566 \times 10^{-6}$ for D <=173.61 mm	$m = 3.108 \times 10^{-4} D - 0.784$ for D <=173.61 mm	$F_{rup} = 2.719 \times 10^{-9} D - 1.221 \times 10^{-7}$ for D <=173.61 mm
$C = 3.430 \times 10^{-8} D + 6.045 \times 10^{-6}$ for 173.61 < D <= 508 mm	$m = 1.286 \times 10^{-4} D - 0.752$ for 173.61 < D <= 508 mm	$F_{rup} = 1.930 \times 10^{-9} D + 1.501 \times 10^{-8}$ for 173.61 < D <= 508 mm
$C = 2.347 \times 10^{7}$ for D > 508 mm	$m = -0.687$ for D > 508 mm	$F_{rup} = 9.952 \times 10^{-9}$ for D > 508 mm

Figure 14: Equipment Size Correlations for C, m and F_{rup} Parameters

These equations can then be applied to each of the nominal pipe sizes to produce equipment size specific correlations as shown in Figure 15 for equipment sizes ranging from ½" to 40". The information can also be tabulated as shown in Table 5.

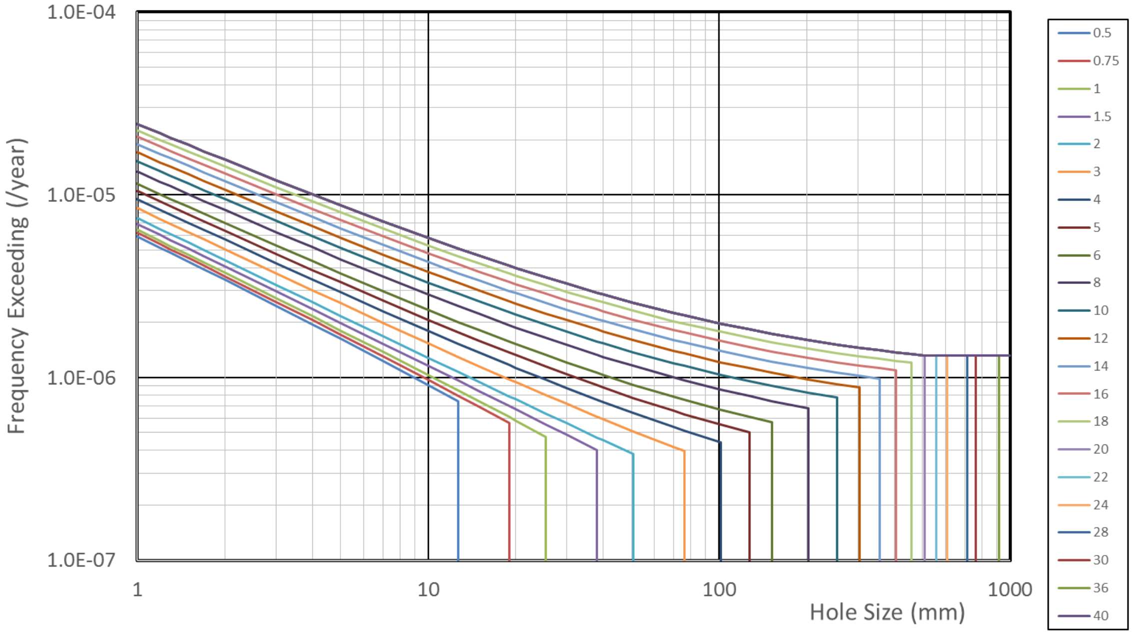


Figure 15: Leak Frequency Exceedance Curve for Nominal Flange Sizes

		Equipment Size		
		2"	6"	18"
	C	7.45×10^{-6}	1.12×10^{-5}	2.17×10^{-5}
	m	-0.77	-0.74	-0.69
	Frup	1.60×10^{-8}	2.92×10^{-7}	8.97×10^{-7}
Frequency in Range	1 mm - 3 mm	4.25×10^{-6}	6.22×10^{-6}	1.16×10^{-5}
	3 mm - 10 mm	1.93×10^{-6}	2.94×10^{-6}	5.74×10^{-6}
	10 mm - 30 mm	7.24×10^{-7}	1.14×10^{-6}	2.35×10^{-6}
	30 mm - 100 mm	5.62×10^{-7}	5.38×10^{-7}	1.16×10^{-6}
	>100 mm	0	6.70×10^{-7}	1.79×10^{-6}

Table 5: Leak Frequency Tabulations for Selected Flange Sizes and Hole Size Categories

Comparison With Previous Correlations

The exceedance curves produced in this study can be compared with previous correlations. DNV have previously published leak frequency tables based on an analysis of the data available up to March 2010 (DNV, 2013). More recently the PLOFAM study has proposed an alternative formulation for frequency exceedance correlations (Lloyds Register, 2016). Figure 16 compares the correlations from this study for a 2" flange with the equivalent correlations from the DNV 2010 and PLOFAM studies. Figure 17 and Figure 18 show the comparisons for 6" flanges and 18" flanges respectively.

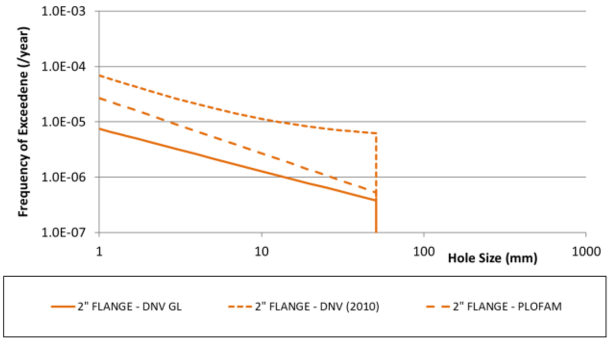


Figure 16: Comparison of Leak Frequency Exceedance Functions for 2" Flanges

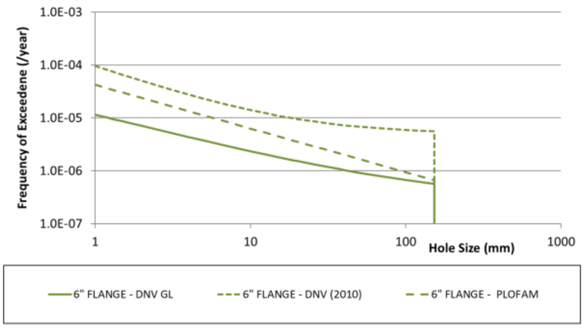


Figure 17:Comparison of Leak Frequency Exceedance Functions for 6" Flange

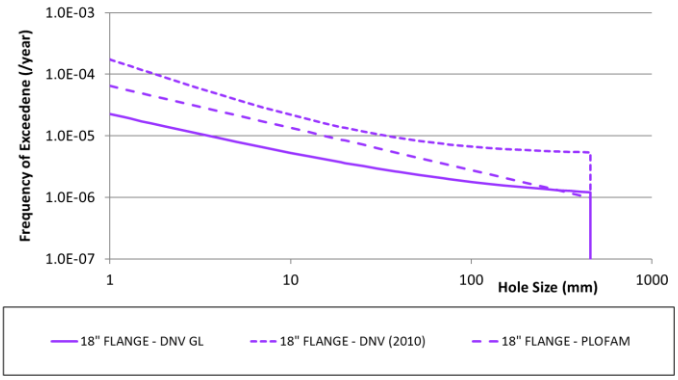


Figure 18: Comparison of Leak Frequency Exceedance Functions for 18" Flange

The difference between the "DNV GL" and "DNV (2010) curves is substantial and represents a change approaching an order of magnitude. This is due to several factors;

- Basing the frequency on the last 10 years only instead of the period 1/10/1992 to 31/3/2010.
- Filtering of incidents as described above.
- The increase in the population data relative to previous estimates.

The differences for flanges are more pronounced than for other equipment types. However, the reduction from the DNV (2010) values will still be significant when applied to typical sets of equipment comprising isolatable sections.

There is a closer correlation between the PLOFAM correlations and those found in this study. Generally, the DNV GL model produces lower estimates for small hole sizes and small equipment. The larger the hole size and equipment the smaller the difference between the two.

The difference between the distributions used in the DNV GL and PLOFAM studies as shown can be explained by several factors;

- The PLOFAM study is based on incidents and equipment populations on installations in Norwegian waters. The PLOFAM study did, however, apply their methodology to UK data and found it to be broadly comparable.
- The differences in historical period on which they are based; The PLOFAM study correlations are based on data from 1/1/2001 to 31/3/2015 whereas this study uses a more recent period; 1/1/2006 to 31/12/15.
- Different criteria were used to select the relevant incidents.

Application of Models

The data on which this model is based is entirely from fixed production platforms in UK waters. There are some areas where some small conservatisms have been included in the analytical process but the values derived from the correlations should be regarded as best estimates rather than conservative estimates. It is considered appropriate to use correlations derived using these methods in the risk assessments of these installations provided they are maintained and operated to a similar standard as prevailed for the period in which the frequencies are based, i.e. 2006 - 2015. If this is not the case, a suitable multiplying factor should be considered, either as a matter of judgement, based on the historic record of the installation itself, or the historic record of the group of installations under the control of given operator.

The data may also be used for mobile drilling units provided again that these are maintained and operated in a way manner commensurate with normal UK standards.

Leak frequencies based on the HCRD are regularly used for the analysis of installation outwith the UK and for process equipment onshore. This is due to the lack of alternative models based on incident and population data for these regions. If the approach given in this study is applied to such installations, consideration should be given to applying a multiplying factor to take account of maintenance and operating practices relating to that installation and to make allowance for the greater degree of uncertainty in applying the models to an installation type which may differ from those from which the data was collected.

Implications for Offshore Industry

As has been stated earlier, the estimation of hydrocarbon leak frequency is one of the most significant inputs to a risk assessment of an offshore installation. It is a direct multiplier to the risks levels from hydrocarbon loss of containment hazards. The obligation on operators is to reduce risks to ALARP. This can be achieved by the introducing barriers which either reduced the frequency of accidents occurring, reduce the adverse consequences or both. Examination of the occurrence of loss of containment incidents in the UKCS clearly indicates that the industry has been successful at reducing the frequency of leaks. On the assumption that risk levels were already ALARP, this should mean that less expenditure is required on the control and mitigation barriers than was previously the case. One example are blast walls designed to fail with a frequency of less than 10^{-4} per year. A combination of explosion and frequency analysis is used to find the design overpressure which the wall should be constructed to achieve this. A change in the calculation of the leak frequency will lead to a reduction in the required design overpressure and hence a reduction in costs. Such savings, particularly on new build installations may be considerable.

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