Modelling of Accidental Hydrocarbon Releases in QRAs: Hole Size Versus Initial Release Rate Basis

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In the Quantitative Risk Analysis of offshore installations, much of the effort is expended in modelling of hydrocarbon releases. The size of the release can vary from a pin hole to full bore. To cover this range of outcomes it is traditional to subdivide the spectrum of possibilities into a number of categories and to calculate the consequences of each of these using a representative release size.

Intuitively, the basis for subdividing the range would be on the basis of equivalent hole diameters with some lower limit but an alternative approach is to use release rates. Subdivision of the range of releases also raises questions that relate to how many categories are required and how the representative sizes for these should be selected.

This paper describes and compares the alternative approaches and in particular addresses the "hole size basis versus release rate basis" question. Many advocate the hole size basis since the tables giving the distribution of leak sizes are invariably quoted on this basis. Others prefer to use a release rate basis since this means that the consequence for a given release size category is then largely independent of the system pressure of the equipment from which the release emanates. This paper also investigates the effect of the number of ranges used in the analysis on the accuracy of the results and how the choice of representative value can influence the results.

The study on which this paper is based concludes that there is no reason to assume that adopting an "initial release rate" approach results in a decrease in accuracy of the analysis and that using it can often reduce the amount of computational effort involved. This is especially true when the consequence analysis includes expensive techniques such as CFD where it is not cost effective to model numerous scenarios.. The study also demonstrates the level of inaccuracy that may result from using a limited number of release size ranges and different strategies for deciding on a representative value for that range.

The paper uses hypothetical examples to examine the effect of different approaches on the accuracy and cost of a QRA. These examples use offshore QRA as a basis, but the same principles are applicable to onshore studies.

Keywords: QRA, Leak Frequency, Hydrocarbon Releases

Introduction

The calculation of frequencies and consequences of loss of containment incidents is an important part of the quantitative risk assessment (QRA) for both onshore and offshore studies. Other hazard types, ship collision, transportation, etc. are analysed but a significant part of the total effort is expended on the analysis of loss of containment. The general approach is to consider a series of release scenarios in the process plant and to calculate frequencies and consequences for each. The overall risk is then obtained by summing up the contributions from the representative releases. The determination of the scenarios to examine is largely influenced by the following:

- The physical layout of the structure, e.g. the presence of walls and decks or simply separation by distance.
- The isolation of different parts of the overall process plant, primarily by the positioning of isolation valves, and
- The material which would be released in the event of a loss of containment, e.g. gas from the top of a separator and liquid from the bottom.

The consequences of a loss of containment accident are very dependent on the size of the release; small holes are likely to be more frequent but their consequences may be negligible, larger holes are less likely but can present bigger consequences of higher severity. The analysis needs to consider the whole spectrum of possibilities and this has traditionally been done by dividing the range of possible release sizes into a number of subdivisions, calculating the frequency for each of these and estimating the consequences based on a representative release size from within that range. A typical example of this is to adopt three hole size ranges; "Small" (1 – 10 mm) represented by a 7 mm hole, "Medium" (10 – 50 mm) represented by a 35 mm hole and "Large" (> 50 mm) represented by a 100 mm hole. There are many possible variations in practice; some studies use 4 hole sizes and the NORSOK standard specifies 9 release sizes be considered as a minimum (NORSOK, 2010).

An alternative approach is to define the three ranges in terms of initial mass release rates; "Small" (0.01 – 1 kg/s) represented by 0.5 kg/s, "Medium" (1 – 10 kg/s) represented by 5 kg/s and "Large" (> 10 kg/s) represented by 50 kg/s.

Some observers consider this second approach to be fundamentally flawed on the basis that release size data collected in the Hydrocarbon Release Database (HCRD) (Health and Safety Executive, 2014) is given in terms of hole sizes rather than release rates and that different internal process conditions will generate different release rate sizes from the same hole size. However, it is the preferred approach of other analysts who claim that this provides efficiencies in the overall calculation process without necessarily having to compromise on accuracy. For example, the NORSOK procedure for probabilistic explosion analysis (NORSOK, 2010) is based upon initial release rates and is a prescribed approach for many explosion assessments. Using a hole size approach in other parts of the overall QRA", aside from the probabilistic explosion analysis, can make the process more complex..

The question of "Hole Size Basis" versus "Release Rate Basis" is an important one to resolve in order to give users of the results of QRAs confidence in the results produced. Other questions which arise when considering the selection of ranges and representative values are;

- How many release size ranges should be used?
- How should the ranges be distributed over the range of possibilities?
- What is the most appropriate representative value for a given release size range?

The answer to these questions will be dependent on the specifics of the release case being considered but we can use an example of a typical scenario to give some insights into the problem even though determining a robust set of rules that can be applied universally may not be practical.

In this paper a simplified example is used to illustrate the problem and provide some awareness of the issues, particularly the relative merits of a "hole size" and "initial release rate" approach. While this example relates to an offshore QRA the same principles will be applicable to onshore studies.

Definition of the Example Case and Model

For the purposes of this study a simplified example of a QRA was developed in order to analyse multiple variations in the approaches with regards to the setting up of release size ranges and representative values. The model is based on release from one single process segment in one relatively large module. The model used the process equipment items from an actual isolatable section in order to generate a graph of hole size against frequency of exceedance. Further correlations were developed in order to relate various parameters which collectively allowed the calculation of the Potential Loss of Life (PLL) for the example. In a complete QRA there will be several process segments assessed representing differences in internal segment conditions.

The simplified model used a much larger number of release size ranges than would be practical in a real QRA study. This formed a reference basecase against which the results produced using a smaller number of release size ranges could be compared. This effectively allows a series of numerical experiments to be carried out. Table 1 shows the list of equipment for the isolatable section used in the study.

Equipment Type	Size of largest Connection (in)	Number
Process Vessel	14	1
Centrifugal Compressor	10	1
Heat Exchanger	8	1

Equipment Type	Size (in)	Number
Manual Valves	0.75	5.5
	1	1.5
	2	6
	3	5.5
	4	3
	8	2
	10	2
Actuated Valves	1	1
	2	1
	3	2.5
	6	1
	8	0.5
	10	0.5

Equipment Type	Size (in)	Number
Flanges	0.75	11
	1.0	6
	1.5	2
	2.0	14
	3.0	22
	4.0	11
	6.0	2
	8	12
	10	12
	14	4
Small Bore Fittings	1	6
	2	5
	2	6

Equipment Type	Size (in)	Total Length (m)
Process Pipework	3	2
	4	4
	8	45.17
	10	41.5

Table 1 : Equipment Parts Count for Exemplar Study.

From Table 1 it can be seen that the largest equipment size is nominally 14" (355.6 mm). In the release modelling it is assumed that the equipment size is the same as the nominal size although in practice the internal area of the pipework and equipment would be smaller. The frequency analysis for this set of equipment was carried out using the software code LEAK (DNV GL Software, 2014) which uses mathematical correlations derived by DNV GL using information from the HCRD up to March 2010 (DNV, 2013 and Falck 2009). For the current study, an analysis using a large number of release size ranges was performed in order to produce in fine detail the calculated leak frequencies within the various ranges. The ranges used were 1 mm ranges starting at 1 – 2 mm for holes up to 100 mm, 2 mm ranges between 100 mm and 200 mm and 5 mm ranges for hole sizes above 200 mm until the final range of 355 – 355.6 mm which captured full bore releases of the largest equipment. This gave a total of 181 hole size ranges. The results were collated to produce a correlation between hole size and frequency of leaks exceeding this value. A graph depicting the result is given in Figure 1. It can be seen that there are some apparent discontinuities in the shape of the graph, most noticeably at around 200 mm and 250 mm. These correspond with the frequencies associated with the full bore rupture of 8" and 10" equipment.

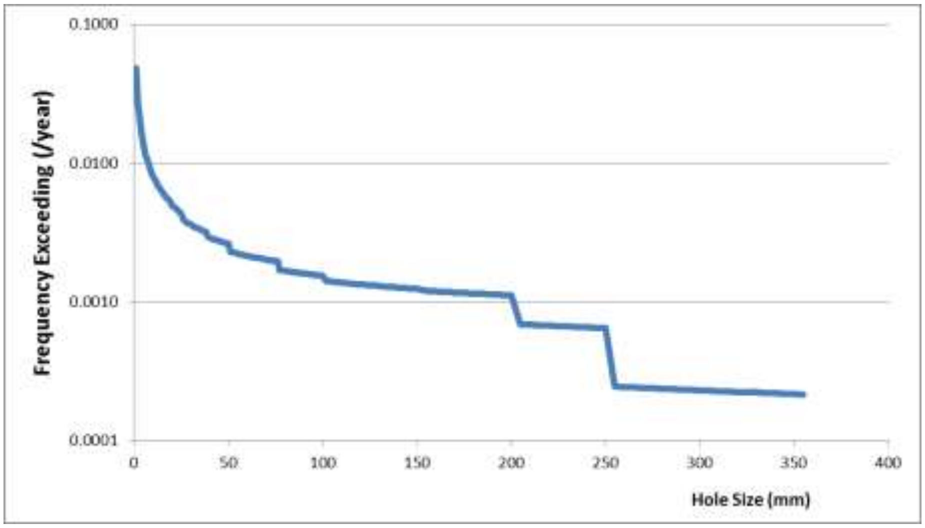

Figure 1 : Exceedance Leak Frequency Curve for Example Study

The equipment is assumed to be filled with methane at a pressure of 50 bara and temperature of 20 ˚C. It discharges into a large process area measuring 60 m x 40 m (2400 m^2) and with a height of 10 m (giving a volume of 24000 m^3) and which is populated by 10 workers. The majority of fatalities from hydrocarbon releases are generally found to occur in the early stages from the combined effects of explosion and fire. Although later fatalities may occur if the event escalates, impairs muster areas and forces evacuation, these effects are neglected here in order to simplify the analysis. This also means that the modelling of time varying discharges affected by isolation and blowdown are not included in this simplified example, although they would be in a real analysis.

In the basecase analysis, the consequences for each of the 181 hole size ranges is evaluated for a representative hole size diameter which is calculated to produce a mean area for that range. For example the 1 mm – 2 mm range is represented by a hole of 1.581 mm.

The initial mass release rate is calculated using a standard equation for gas release in choked conditions.

$$Q = C_d\left(\frac{\pi d^2}{4}\right)P_o\sqrt{\frac{M\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (1)$$

Where
Q is the mass release rate,
C_d is the coefficient of discharge
d is the equivalent hole diameter
P_o is the process system pressure
T_o is the process system temperature
M is the molecular weight of the discharging gas
R is the universal gas constant, and
γ is the ratio of specific heats

It is assumed that there are no fatalities if the release does not ignite. The probability of ignition was determined using the look-up correlation for a process gas release in a large module as given in the report for the UKOOA Ignition Model (Energy Institute, 2006). This is depicted in Figure 2.

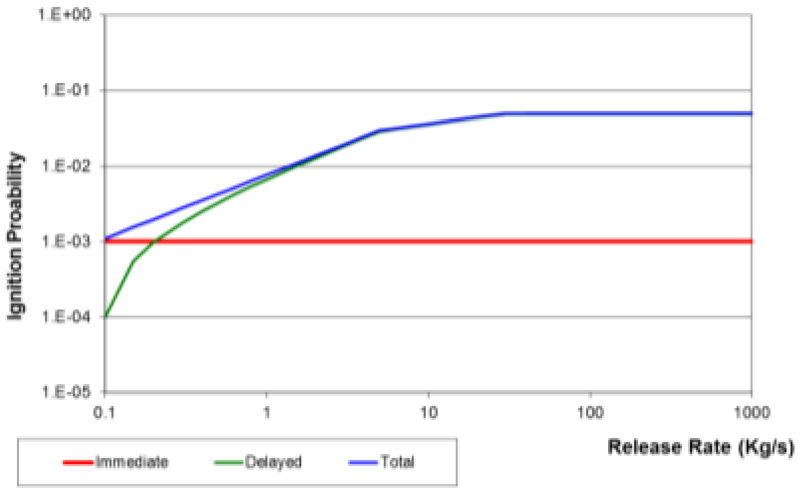

Figure 2 : Ignition Probability Correlation Use in the Example Case

A jet fire will result from any ignition, immediate or delayed, and its length is given by the equation

$Lf = 11.14\ Q0.447$ (2)

Where L_f is the length of the flame in metres, and

Q is the release rate in kg/s

The case study assumes that workers will become fatalities if they are subjected to more than 37.5 kW/m^2. The probability of this is given by comparing the area of the module with the area inside the 37.5 kW/m^2 radiation contour. A relationship between flame length and the dimensions of a contour for a given radiation level was found from carrying out analysis using PHAST software (DNV GL Software, 2014). This gave the following relationship

$A37.5 = 0.6786\ Lf2$(3)

And hence the fatality rate due to fire radiation is

$FRfire = A37.5/Amod,$ $A\ 37.5 < Amod$ (4)

$FRfire = 1,$ $A\ 37.5,$ $>= Amod$

Where FR_{fire} is the fatality rate for workers in the module due to fire

$A_{37.5}$ is the area within the 37.5 kW/m^2 radiation contour

and A_{mod} is the area of the module

The probability of fatalities from explosions is calculated using a series of correlations which are similar to those derived for a study of a real process module. These are:

- a correlation between release rate and maximum cloud volume (Figure 3)
- a correlation between cloud size and maximum overpressure (Figure 4), and
- the probability of exceeding a ratio of the maximum overpressure (Figure 5). This correlation is to take account of the fact that clouds may ignite before they reach their maximum size and that both cloud and ignition locations may be other than worst case.

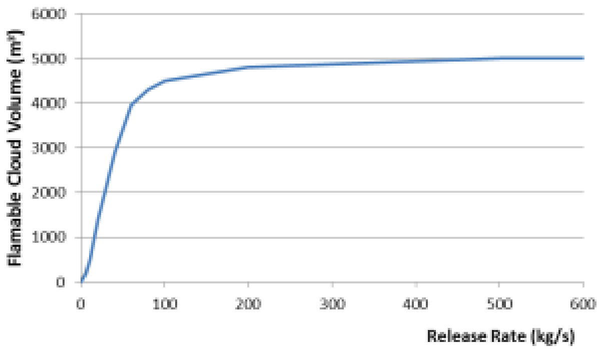

Figure 3 : Relationship Between Release Rate and Maximum Flammable Cloud Volume

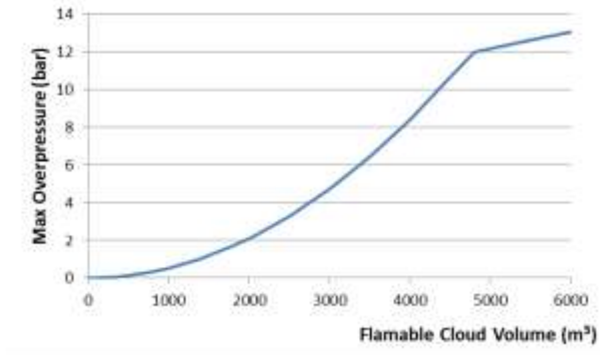

Figure 4 : Relationship Between Maximum Flammable Cloud Volume and maximum Overpressure

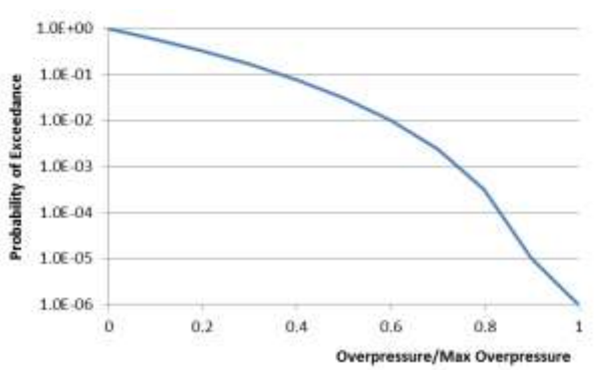

Figure 5 : Relationship Between Ratio of Overpressure to Maximum Overpressure and Probability of Exceeding This Value

A value of 0.3 bar has been assumed in the study as the overpressure above which fatalities would occur, i.e. there are no fatalities below this value but 100% fatality rate above this value.

Using the above correlations a probability of fatality for a given delayed explosion, FR_{exp}, can be calculated. The overall Fatality Rate, FR_{total}, can be calculated by combining the fatality rates for fires and explosions, noting that the fatality rate from explosions will always be zero for immediate ignitions.

$$FRtotal = FRfire + FRexp(1- FRfire) \quad (6)$$

The PLL contribution for a given hole size range will be the product of the frequency for that range and the number of fatalities which result, hence

$$PLL = N\ F\ (Pign,imm\ FRfire + Pign,del\ FRtot) \quad (7)$$

Where N is the number of workers exposed to the risk

The overall PLL is then obtained by summing all the contributions from the different hole sizes together.

Basecase Results

The PLL per year calculated for the basecase on a hole size basis was 1.22×10^{-3}. Given the resolution of hole size ranges used, it was also practical to produce a PLL Exceedance plot which presents the distribution with hole size. This is shown in Figure 6. This indicates that a relatively small proportion of the risk comes from the smaller hole sizes. In this particular example only 10% of the risk is attributable to hole sizes smaller than 50 mm even though these account for approximately 95% of the leak frequency. This is a rather smaller proportion than would normally be expected and is partly due to the large size of the process module being considered and partly due to the omission of impairments and escalations which could result in later fatalities. Nevertheless, it gives a reasonable basis for investigating how the choice of release size ranges can affect the accuracy of the results.

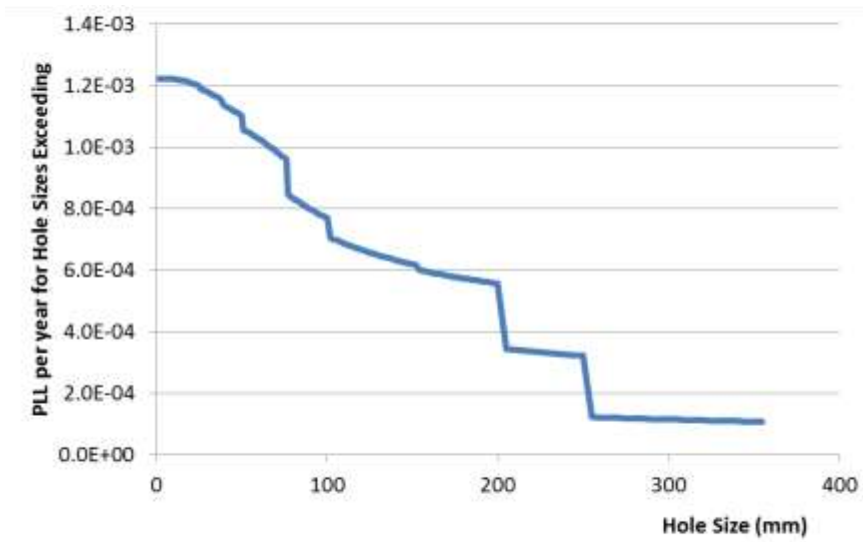

Figure 6 : PLL for Hole Sizes Exceeding a Given Value

A second analysis was carried out using a modified model in which the release size ranges were expressed in terms of the initial release rates. Again, 181 ranges were used; small ranges of 0.01 kg/s for very small release which increased in size, up to 20 kg/s, when considering larger releases. The exceptions to these were the first range, where the lower bound is set equal to the release rate corresponding to 1 mm, and the upper bound of the last range where the where the release rate is set equal to that from a 14” full bore rupture. For each range, the representative initial release rate on which the consequences were calculated was the average of the lower and upper bounds.

The frequency of each range was determined by first calculating the hole sizes which would match the lower and upper bounds for the initial release rates. This is achieved by rearranging equation (1) to give

$$d = \sqrt{\frac{4Q}{\pi C_d P_o \sqrt{\frac{M\gamma}{RT_o}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}} \qquad (8)$$

The PLL per year calculated for the basecase on the “initial release rate” basis was 1.22×10^{-3}, i.e. effectively the same result as obtained by the “hole-size” basis. The PLL calculated by the two approaches actually differed by only 0.05% due to the differences in ranges selected. This demonstrates that either basis may be used for comparison with results obtained using fewer ranges.

Effect of Number of Ranges

In practice only a relatively small number of release size ranges will be used in a QRA – most commonly in the range of two to four – depending on the study scope or limitations of the tool. There are, however, probabilistic explosion procedures that require up to 9 different ranges e.g. NORSOK Z013 where it has been recognised that a greater number of ranges are required at least in the field of explosion analysis. This may also be true for other parts of the analysis yet QRAs have seldom used more than 5 ranges, 3 ranges are generally considered a reasonable compromise of accuracy versus modelling effort and 2 ranges are still used in some situations. Limiting the number of ranges obviously has a detrimental effect on the accuracy of the result. In order to gain some insight into the magnitude of this deviation, the analysis was carried out using various numbers of release size ranges; 20, 10, 5, 3, 2 and 1 and the resulting calculated PLL values compared with the basecase. This was done using both hole size and initial release rate basis. Tables 2 and 3 show the ranges used. These were selected purely on the basis of judgement of what might seem reasonable rather than some more detailed consideration. The representative release size in each band in the range was based on either the average hole size area, or the average release rate. The calculated values for PLL and their deviation from the basecase are given in Table 4, where the deviation is relative to the base case which used 181 bands of release size.

20 Ranges		10 Ranges		5 Ranges		3 Ranges		2 Ranges		1 Ranges	
Lower Bound (mm)	Upper Bound (mm)	Lower Bound (mm)	Upper Bound (mm)	Lower Bound (mm)	Upper Bound (mm)	Lower Bound (mm)	Upper Bound (mm)	Lower Bound (mm)	Upper Bound (mm)	Lower Bound (mm)	Upper Bound (mm)
1	2	1	2.5	1	5	1	10	1	25	1	355.6
2	3	2.5	7	5	12	10	50	25	355.6		
3	5	7	10	12	25	50	355.6				
5	7	10	17	25	100						
7	10	17	25	100	355.6						
10	13	25	35								
13	17	35	50								
17	20	50	100								
20	25	100	200								
25	30	200	355.6								
30	35										
35	40										
40	50										
50	60										
60	80										
80	100										
100	150										
150	200										
200	280										
280	355.6										

Table 2 : Selected Ranges : Hole Size Basis

20 Ranges		10 Ranges		5 Ranges		3 Ranges		2 Ranges		1 Range	
Lower Bound (kg/s)	Upper Bound (kg/s)	Lower Bound (kg/s)	Upper Bound (kg/s)	Lower Bound (kg/s)	Upper Bound (kg/s)	Lower Bound (kg/s)	Upper Bound (kg/s)	Lower Bound (kg/s)	Upper Bound (kg/s)	Lower Bound (kg/s)	Upper Bound (kg/s)
0.0054	0.1	0.0054	0.2	0.0054	0.5	0.0054	1	0.0054	10	0.0054	680
0.1	0.2	0.2	0.5	0.5	2	1	10	10	680		
0.2	0.35	0.5	1	2	10	10	680				
0.35	0.5	1	2	10	25						
0.5	0.75	2	5	25	680						
0.75	1	5	10								
1	1.5	10	20								
1.5	2	20	50								
2	3.5	50	100								
3.5	5	100	680								
5	7.5										
7.5	10										
10	15										
15	20										
20	35										
35	50										
50	75										
75	100										
100	200										
200	680										

Table 3 : Selected Ranges : Initial Release Rate Basis

Hole Size Basis		
No. of Ranges	PLL	Deviation
181 (Basecase)	1.222E-03	N/A
20	1.232E-03	0.83%
10	1.405E-03	15.0%
5	1.964E-03	60.7%
3	1.673E-03	36.9%
2	2.454E-03	101%
1	2.407E-02	1870%

Initial Release Rate Basis		
No. of Ranges	PLL	Deviation
181 (Basecase)	1.221E-03	N/A
20	1.219E-03	-0.27%
10	1.263E-03	3.32%
5	1.331E-03	8.88%
3	1.617E-03	32.3%
2	3.412E-03	179%
1	2.396E-02	1861%

Table 4 : Deviation in the Calculation of Risk For Different Number of Ranges

It can be seen that significant deviations can be introduced by using only a few ranges to conduct the analysis. In this case the use of three hole size ranges gives a PLL value that is 30% higher than the basecase while using only two gives a PLL value which is more than

100% higher. Inspection of the deviation-columns in Tables 4a and 4b show that the deviations increase as the number of ranges decrease. This finding is intuitively obvious, but it is notable that most of the deviations are positive, i.e. the calculations of PLL are tending to overestimate the relatively accurate basecase result. The reason for this is that the representative hole size or initial release rate used generally results in an overestimate of the actual average consequences for that release size range. It will always be possible to obtain an exact match if the correct representative value is used. For example, in the case considered above, it was found that the same PLL value as in the basecase (1.222×10^{-3}) could be achieved using representative hole sizes of 4.441 mm, 24.84 mm and 73.30 mm instead of the "average area" diameters of 7.11 mm, 36.06 mm and 253.92 mm for the ranges of 1 mm – 10 mm, 10 mm – 100 mm and 100 mm – 335.6 mm respectively.

It could be argued that the results above are very specific to the parameters used and that a different set of parameters would produce different results. This is correct and in order to test the level of variation that could be obtained the analysis was run with different combinations of alternate values for system pressure, molecular weight and module area;

- System Pressure : 5 bar, 10 bar, 20 bar, 50 bar, 100 bar and 200 bar.
- Molecular Weight : 16, 20, 25, 30, 37 and 44.
- Module Area : 300 m^2, 600 m^2, 1200 m^2, 1800 m^2, 2400 m^2 and 3000 m^2

i.e. 216 combinations.

The percentage deviations relative to the calculated basecase values were collated and sorted to provide plots of level of inaccuracy against the proportion of results that exceed this value. These are shown below for both the "Hole Size Basis" and "Initial Release Rate Basis" in Figures 7 and 8. It can be seen that, as would be expected, the fewer ranges which are used, the greater the likely deviation. Note that the results for the "1 range" case are so inaccurate that the curve representing the results is outside the scale of the graphs. It can also be seen that using an initial release rate basis appears to produce a smaller deviation from the basecase. This is due to the selection of the ranges and indicates that a more fortuitous selection was made in this case. In any event there appears to be no evidence to support a contention that the initial release rate basis is less accurate.

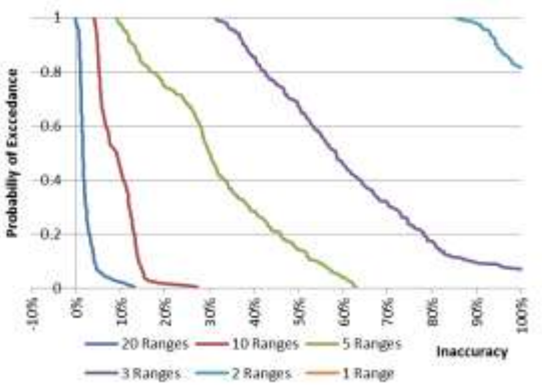

Figure 7 : Graph of Inaccuracy Against Probability of Exceedance – Hole Size Basis

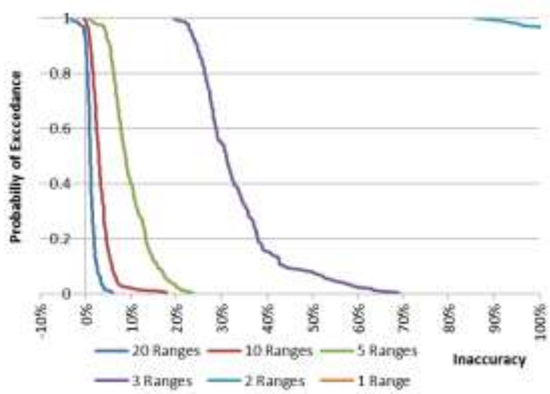

Figure 8 : Graph of Inaccuracy Against Probability of Exceedance – Initial Release Rate Basis

Alternative Methods of Selection of Representative Value

The results presented in Table 4 indicate that the representative values used for the calculation of consequences are larger than they should be and that this leads to an over estimate in the calculated results, i.e. the representative value should be lower in range than is typically used. To examine this further, a series of analyses were made in which the method of selecting the representative value was changed.

The method used in the forgoing sets of analyses can be described using the following equations:

$$d_{rep} = \left(\frac{d_{min}^2 + d_{max}^2}{2}\right)^{\frac{1}{2}}, \text{ for diameters} \quad \text{or} \quad Q_{rep} = \left(\frac{Q_{min} + Q_{max}}{2}\right) \quad \text{for initial release rates} \qquad (9a)\ (9b)$$

Where the subscripts min and max denote the lower and upper bounds of the range and "rep" to the representative value.

These can be generalised to

$$X_{rep} = \left(\frac{X_{min}^{n}+X_{max}^{n}}{2}\right)^{\frac{1}{n}} \qquad (10)$$

The value of the index, n, for use with the initial release rate basis will be half that used for hole diameters in order to achieve the same effect.

The analyses looked at different values of n in order to gain some insight into what more appropriate alternatives might be. As would be expected, the smaller the index value used, the more the spectrum of possible inaccuracies moves towards underestimating the result instead of overestimating. Perhaps surprisingly, the most appropriate values in this study are close to zero. Small negative values also give better values than using a value of 2 for hole size basis and unity for initial release rate basis. .

Figures 9 and 10 show the results for n=0.001, this value was used because n=0 causes a division by zero error in the analysis. Tables 5 and 6 show the median deviation for different numbers of ranges and index values.

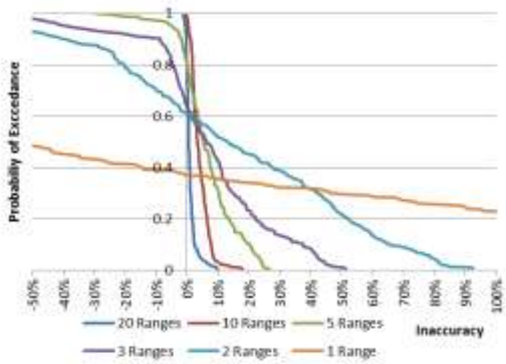

Figure 9 : Graph of Inaccuracy Against Probability of Exceedance – Hole Size Basis, Index = 0.001

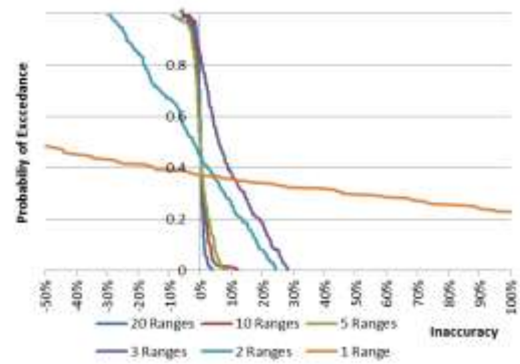

Figure 10 : Graph of Inaccuracy Against Probability of Exceedance – Initial Release Rate Basis, Index = 0.0005

	Index				
No. of Ranges	-2	-1	0	1	2
20	-0.24%	0.19%	0.65%	1.08%	1.59%
10	-0.77%	1.03%	3.48%	6.33%	9.09%
5	-18.37%	-6.52%	5.31%	19.76%	29.90%
3	-30.99%	-19.71%	6.35%	39.17%	58.38%
2	-71.24%	-39.64%	12.89%	99.32%	147.93%
1	-99.96%	-99.93%	-53.24%	1662.03%	1668.83%

Table 5 : Median Inaccuracies by Number of Ranges and Index – Hole Size Basis

	Index				
No. of Ranges	-1	-0.5	0	0.5	1
20	-0.76%	-0.33%	0.11%	0.58%	1.05%
10	-2.69%	-1.25%	-0.01%	1.41%	2.91%
5	-7.29%	-3.65%	-0.10%	4.61%	8.81%
3	-26.65%	-6.46%	6.01%	20.81%	30.98%
2	-35.21%	-11.93%	-2.38%	91.79%	286.16%
1	-99.96%	-99.93%	-53.45%	1654.15%	1660.91%

Table 6 : Median Inaccuracies by Number of Ranges and Index – Initial Release Rate Basis

A further approach which has been used in the LEAK Software (DNV GL Software, 2014) has been to use the following equations;

Representative hole size; $$d_{rep} = \left[\frac{m}{m+A} \cdot \frac{d_{max}^{m+A} - d_{min}^{m+A}}{d_{max}^{m} - d_{min}^{m}}\right]^{\frac{1}{A}} \quad (11)$$

Representative release rate; $$Q_{rep} = \frac{m}{m+2} \cdot \frac{Q_{max}^{\left(\frac{m}{2}+1\right)} - Q_{min}^{\left(\frac{m}{2}+1\right)}}{Q_{max}^{\left(\frac{m}{2}\right)} - Q_{min}^{\left(\frac{m}{2}\right)}} \quad (12)$$

Where, m is a gradient parameter used in the exceedance frequency correlation for an individual piece of equipment,

and A is a constant which is normally taken as 2

This calculation is carried out for each piece of equipment in the group which relates to the release case being considered. The overall representative value is obtained by a weighted average using the magnitude of the frequencies themselves:

$d_{rep}^{*} = \sum_i d_{rep\,i}\ f_i / \sum_i f_i$ and $Q_{rep}^{*} = \sum_i dQ_{rep\,i}\ f_i / \sum_i f_i$ (13a) (13b)

Where d_{rep}^{*} is the overall (weighted average) representative diameter

Q_{rep}^{*} is the overall (weighted average) representative diameter and f_i are the frequencies for the range for individual pieces of equipment

The intent is to weight the calculated value towards the lower end of the range to account for the fact that for any given range the frequency distribution is skewed towards that end.

Since the LEAK programme involves no consequence modelling beyond the determination of the release rate corresponding to a given hole size, it is not able to take into account the relationships between the release size and ignition probability, explosion strength, fire size and ultimately the fatality rate.

A comparison with the values obtained using equations 9 and 10 and those from the LEAK programme indicates the closest match for values of n which are between -0.5 and 0 for both the hole size and release rate basis. Therefore, the LEAK formulation supports the conclusion that values of n in the region of zero are appropriate.

Effect of Approach on Consequence Modelling Effort

The preceding sections of this paper demonstrate that the use of initial release rate ranges, as opposed to hole size ranges does not lead to any loss of accuracy. In fact, typical ranges and representative values used in QRA will result in the initial release rate approach being more accurate if a more fortuitous set of values happens to be selected. The other consideration to be taken into account in determining the optimum approach is the relative amount of effort expended in consequence analysis.

The effects on consequences caused by different system temperatures and pressures are found to be relatively small for most parameters investigated when keeping the release rate constant. For example, standard correlations between release rate and jet flame size, such as that given in equation (2), do not take account of the system pressure driving the release since this has only a small effect. The calculated flame length for an ignited release of, say, 10 kg/s at 10 bar is the same as the length for a 10 kg/s release at 100 bar. The equivalent diameters for the two scenarios will be different but this will be taken into account in the frequency analysis where the diameters for the upper and lower bounds will be adjusted in accordance with equation (8) to take account of the pressures and calculate an appropriate frequency for that range. This has the benefit that the analyst can deal with the consequence analysis for a limited number of initial release rates, say 0.5 kg/s, 5 kg/s and 50 kg/s which will be appropriate for a wide range of system pressures and use these results many times over in determining consequences. In contrast, use of the hole size approach leads to numerous different jet fire sizes because isolatable sections with differing pressures and temperatures are being considered. These then have to be looked at independently and this will increase the effort and cost involved in carrying out the overall study.

The method used in the LEAK programme inevitably generates a different representative hole size or release rate for each collection of equipment so following it strictly would require a separate consequence assessment for each release size case. This may be marginally more accurate but utilising a common release rate is more practical given the calculation of representative hole size or release rate is itself only approximate.

CFD techniques are becoming more useful and popular especially in the calculation of Design Accidental Loads (DALs). These techniques also form part of the overall consequence modelling for gas dispersion, estimating ignition probabilities and calculating explosion overpressures. The wide variety of "external" parameters that have an influence on the gas dispersion makes it impossible to simulate all combinations of circumstances with CFD. With a modest discretization of the parameters such as 3 wind speeds, 5 release rates, 8 wind directions, 6 leak directions and 2 leak locations per isolatable section in an area this would result in the need to model a total of 1440 cases for each isolatable section within each area. As there might be several isolatable sections and areas, the computational effort for such an amount of cases would be substantial and not practical within the scope of a normal QRA. DNVGL uses response surfaces and CFD cases to calibrate the variation of possible consequences. The foundations of the response surfaces are relevant physical and geometrical effects that concern dispersion and explosion in order to reduce the number of CFD cases needed (Huser, 2000). Large computational savings are obtained by combining results by utilizing the same CFD simulations to represent several isolatable sections. When using the release rate to categorize the leak sizes as opposed to hole size, two or more isolatable sections with different pressure, temperature and fluid composition can be represented with the same consequence simulations. In this way, different release cases can be lumped together into one representative consequence assessment and the same results used to represent all segments in the same group.

There are situations where it is not possible to use the same representative consequences. The main parameter that can have a significant influence on the consequences in terms of gas cloud size is the release gas specific gravity. This is observed from running a large number of CFD based explosion risk analyses. It is not reasonable to group release cases if the specific gravities of the release cases are very different because the dispersion behaviours will be significantly different, particularly if one gas is heavier than air and the other is lighter. In such cases, separate consequence assessments are required.

As an example of the benefit of the approach, a process area design can be significantly enhanced by improving the ventilation and venting properties. The operator may want to investigate the effects of different configurations of blast walls, decks (grated or plated), layout arrangements, wind walls, etc. If an area of the platform has, say, five process sections with different operating conditions, then, by using the initial release rate approach instead of the hole size approach, the computational effort can be reduced from five to one or two representative leak cases. Each of these cases needs to be considered with external parameters such as 1 - 2 leak locations, 2 - 4 release rates, 4 - 6 jet directions, 2 - 4 wind speeds, and 3 - 6 wind directions. For each such leak case, between 48 and 1152 CFD simulations should then be considered depending on the combinations of alternatives considered. When fewer CFD cases are selected, the derived response surfaces are less well tailored and produce less accurate results. As a minimum number of sensitivities one can consider 2 blast wall configurations, 2 deck configurations, 2 layout arrangements, and 2 different wind wall configurations; in total 16 design options. This amounts to 16 x 48 = 768 CFD simulations when using the minimum number of CFD runs per design option. Obviously, if one should consider all 5 release cases separately, the computational costs and time needed would increase by a factor of 2.5. If more sections are to be represented, the savings are even greater. Even with today's fast computers and parallelized codes, there is benefit in consolidating the explosion analysis. There is a fundamental dilemma in that the usefulness of looking at design options is largest in early phases of a project when less time and information is available. This prompts us to consider computational procedures that can be run in a short time and give appropriate decision support on the main design issues that can be modified at that stage. Thus the use of initial release rates instead of hole sizes is an approach that can increase efficiency and contribute more effectively to the design cycle.

When using the risk analysis for practical design improvements such as location of wind walls, layout-arrangements, blast wall design and loads, deck arrangements, etc., it is essential to model these design effects as accurately as possible. With today's CFD tools, one can obtain the physical effects of, for example, an improved layout arrangement on both the gas dispersion and explosion properties of a module. Such details cannot be modelled using simplified empirical models for gas dispersion and explosion. Unfortunately, the computational effort and time required is restricting the number of CFD cases that can be run, but this can be alleviated by the use of explosion results for more than one release case.

It could be argued that the explosion analysis part of the overall QRA could be conducted with initial release rates while the remainder of it uses the hole size approach. This is possible but the conversion from hole size to release rate and back again makes the overall process more time consuming, less transparent and more prone to error.

Selection of Minimum Release Size

It is common practice to neglect the effect of very small holes which have insufficient consequence to contribute to the risks but which have a relatively high frequency. The cut-off point is rather arbitrary but can relate to the release rate for a jet fire which could foreseeably escalate to a larger event. Common values are 1 mm for hole size basis and 0.01 kg/s or 0.1 kg/s for release rate basis. If a minimum hole size is selected then the flame length associated with it will be a function of the system pressure driving the release. The preferred approach would be to define a cut-off in terms of release rate and this is compatible with defining release size ranges in terms of release rates.

Conclusions

A number of conclusions can be drawn from this work:

1. The inaccuracy introduced into a QRA study by using a limited number of release sizes (both hole size and initial release rate) can be significant since the representative values used in the consequence modelling are more likely to deviate significantly from the optimum value.
2. Increasing the number of release size ranges to a minimum five should be considered as a means of improving accuracy of predictions.
3. The best representative release size for a given range appears, on the basis of the scenarios examined, to be considerably less than the values typically used.
4. The release size values obtained using the formulation included in the LEAK code are close to those calculated as optimal in this study
5. The use of initial release rate ranges as opposed to hole size ranges does not introduce additional inaccuracies into the calculation process.
6. The use of initial release rate ranges as opposed to hole size ranges can greatly reduce the amount of effort and cost involved in the consequence analysis.
7. It can reduce the time needed for explosion studies during the initial design phases of an installation where different design options are being considered.

Use of the initial release rate approach is therefore preferable and the most accurate solution will be arrived at by using;

- a large number of initial release rate ranges, at least five;
- selecting ranges which are well distributed; and
- using a representative value which takes account of the frequency within a given range by weighting it towards the lower bound .

Future Work

This study has used a simplified model, focussing on the immediate effects of ignited releases to give an indication of the issues surrounding the choice of release size ranges. While it is believed that the example chosen and the parameters used are representative there would be merit in investigating the issue further. In particular, the study could be broadened to consider a more detailed methodology which takes account of fatalities in other modules of an installation and later fatalities which result from impairments and escalations. The case used in this study was for a pure gas release but oil and 2-phase releases could also be considered. This work could also provide firmer advice on the selection of release size categories and the positioning of the representative release.

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