A SIMPLE METHODOLOGY TO ASSESS ENVIRONMENTAL RISK FROM OFFSHORE OPERATIONS

Matthew Celnik and Brian Bain
Det Norske Veritas Limited, UK

The events of 2010 in the Gulf of Mexico have reinvigorated interest in characterising the environmental aspects of offshore risk assessments. This is often overlooked as effort is concentrated on potential loss of life and asset damage. A method is proposed for constructing a "F-E curve" to give the exceedance frequency of a certain environmental impact, described by the quantity of hydrocarbon released. The SINTEF blowout database provides an excellent resource of historic blowout and well release data. By combining this data with results of a quantitative risk analysis for the hydrocarbon release from risers/pipelines and offshore process equipment, the environmental consequence can be estimated. It is envisaged that this method could be combined with other methods to model oil slicks, to give further resolution to the potential impact on coastlines and wildlife, as well as at sea.

INTRODUCTION

The events surrounding the Macondo well and the Deep Water Horizon in the Gulf of Mexico in 2010 have once again highlighted the catastrophic environmental impact of large-scale oil spills. The subsequent clean-up and legal action costs to BP have been significant; $14 billion USD by December 2011 on response activities [1]. Typically, offshore quantitative risk assessments (QRAs) focus on the consideration of risk to life on the platform due to operation. In some cases they are extended to an assessment of property damage and costs due to lack of production. However, risks to the environment are often overlooked. This is justified in most cases as the predicted frequency of large-scale hydrocarbon release is very low, even though the consequences are high, therefore the total "risk" is low. Usually environment risks are just excluded from the scope of QRAs as there is no legal requirement. Increasingly the potential risks to life, property and the environment are being considered by the oil and gas industry. As the oil and gas industry re-assesses the acceptable risk levels of environmental incidents, there is a need to quantify the risks, and implement mitigation measures where necessary.

Offshore hydrocarbon releases can range in volume from small process leaks to large blowout events. Typically only blowouts and tanker collisions are of sufficient scale to cause environmental distress. In-transit events, such as tanker collisions, are generally beyond the scope of a QRA for a particular installation, therefore this paper concentrates on blowout and well-release events, but in addition considers the risk contribution from process and riser releases, in order to obtain the overall assessment of leaks associated with an offshore installation. It is assumed, usually, that small-scale hydrocarbon releases are sufficiently small that they do not have a significant environmental impact: they are generally dispersed quickly by the natural action of sea currents and tides. However, all unintentional hydrocarbon releases in UK waters must still be reported to the Health and Safety Executive [2, 3]. SINTEF publish a worldwide list of blowouts and well-releases, recorded by operators on an annual basis [4]. This historical record lists such events back to 1955, and though it may not be comprehensive, it is still a useful resource. In addition, Scandpower annually publish blowout and well-release statistics, based on the SINTEF data, specifically applicable to installations operating to North Sea standards [5]. It is these statistics that DNV currently incorporate into offshore QRAs for North Sea installations. For other installations worldwide reference to the main SINTEF data is used.

As offshore QRAs focus on risk to life, there is little merit in considering continuation of events beyond the time it takes to evacuate the installation. This is usually taken as the temporary refuge (TR) endurance time, as this is the length of time over which fatalities are expected to occur. This approach is in accordance with UK Safety Case Regulations [6]. TR endurance time is typically taken to be one hour [7]. As the Macondo event illustrated, the duration of blowouts can be 3–4 orders of magnitude longer, therefore the standard offshore QRA methodology must be extended to consider environmental risk, or the environmental risk considered in a separate study.

In the past, work has focussed on the environmental consequences of large-scale environmental disasters, rather than the probability of occurrence. This paper details a method to include the frequency of such events into an offshore QRA as well as giving an estimate of the expected consequence.

PROPOSED MODEL

The aim of an integrated offshore QRA is to quantify risk to life, property or the environment due to offshore operations. This allows the calculated risks to be compared with a set of acceptance criteria. If the risk is deemed too high, mitigation measures can then be defined. A common risk reporting tool is the F-N curve, which displays the frequency of exceeding a given number of fatalities due to all possible events. Introduced here is an "F-E" curve, which similarly presents the frequency of exceeding a given environmental consequence due to all relevant events. The analysis of environmental risk of offshore operations is ultimately an analysis of the volumetric release of hydrocarbons, predominantly liquids (oil), therefore this is the variable plotted on the F-E curve.

BLOWOUTS AND WELL RELEASES

For this model, blowouts are characterised by the failure of isolation by installed mechanical means, and are therefore an uncontrolled release. The frequency of blowouts f_B can be calculated using the information in the SINTEF report [4] and the associated Scandpower report for the North Sea [5]. These sources give the frequency of gas and oil blowouts (at surface and subsea) for different operations. The frequencies are quoted on a basis of either per wells drilled per year, per well, per well-year or per operation. The industry must supply the number of wells/operations of interest in order to determine the frequencies.

The total volume released from the blowout can be calculated from the average flow rate and the release duration. If the flow rate is assumed to be constant over time, then the volume released is calculated by:

$$V = Q \cdot \Delta t \tag{1}$$

where V is the volume (Nm^3), Q is the volumetric flow rate (Nm^3/day) and Δt is the duration (days). Typically the duration would be reported in days, or parts thereof. The average blowout flow rate should be defined in a QRA, and will usually be estimated as some multiple of the production flow. Standard flow rate models are often specified in guidelines and recommended practice documents, although they could be supplied on a case-by-case basis, depending on the local conditions. The assumption of constant flow rate could also be relaxed, though for this analysis it will be held.

For blowouts and well-releases, if isolation is not achieved within the first few hours, it becomes very difficult to define discrete scenarios to describe the event totally. The duration becomes a complex function of intervention method and prevailing conditions. It is proposed here to use the historical data in the SINTEF database to determine a distribution of blowout durations. An analysis of the SINTEF database for this purpose is provided in a subsequent section. The distribution of blowout durations could be described in a number of ways, but for this analysis it is assumed to be described by a continuous, monotonic probability distribution function (PDF) with two parameters; mean μ and standard deviation σ. No assumption is made on the form of the PDF at this stage. The cumulative probability distribution, describing the probability that the duration is less than or equal to a certain value is then described by:

$$P(\Delta t \leq t) = F(\mu, \sigma, t) \tag{2}$$

The volumetric release is therefore also described in a similar manner, as Q is constant, according to (1) and (2), by

$$P(V \leq Qt) = P(\Delta t \leq t) \tag{3}$$

The probability of exceeding a given volumetric release[1] is given by the complement

$$P(V > Qt) = 1 - P(\Delta t \leq t) \tag{4}$$

This is referred to here as the *exceedance probability*. The exceedance probability is conditional on a blowout event having occurred, the frequency of which is calculated from the SINTEF results as described above. Therefore, the frequency of exceeding a given volumetric release is given by

$$f(V > Qt) = f_B \cdot [1 - P(\Delta t \leq t)] \tag{5}$$

This is referred to here as the *exceedance frequency*.

OTHER HC RELEASE EVENTS

Hydrocarbons can be released in smaller quantities offshore through topside process leaks or riser failures. These events shall be referred to as “process events” here. These differ from blowouts in that they are usually controlled events; that is the safety systems installed should limit the leak potential, and terminate the leak after a (relatively) short time. Small-scale events are more frequent than blowouts.

The leak frequency of process events can be calculated using a database of equipment failure/leak frequencies, using a software tool such as DNV LEAK [8], and a survey of the number of each equipment type in an isolatable section. Equipment could be pipework, valves and flanges, for example. This parts count procedure is time-consuming, but it is normally already performed to determine the risk to life from fire or explosion, as part of an offshore QRA.

For QRA purposes, HC events are usually represented by a set of discrete scenarios at different characteristic hole sizes and isolation conditions. Effects of blowdown can also be incorporated, if such a system is installed. Each scenario has an associated frequency, release rate and duration, hence the total volumetric release can be calculated as per equation (1). The frequency-volume (f_i, v_i) points from each scenario can be compiled, then sorted by volume, and the frequencies summed to give the exceedance frequency:

$$f_{pro,j}(V > v_j) = \sum_i f_i \quad \forall\, v_i > v_j \tag{6}$$

In this way a discretized exceedance frequency curve can be constructed with the points ($f_{pro,j}$, v_j). In principle, as the number of scenarios increases, the exceedance frequency curve should become smoother.

COMBINING DATASETS: BLOWOUT AND PROCESS EVENTS

In order to combine the F-E data from blowouts (continuous) and process events (discrete), it is necessary to either

[1]The analysis could also be performed for mass release, which may be more relevant for compressible fluids, such as natural gas.

discretize the blowout data or fit a continuous function to the process event data. It is simpler to discretize the blowout data, so that is the recommended approach. Indeed, assuming that there are sufficient scenarios describing the process events, a ready-made discretization grid exists: the process event points. The discretization procedure for blowout data is then

For each process exceedance point ($f_{pro,j}$, v_j):

1. Calculate the blowout duration $t_j = \frac{v_j}{Q}$ using the constant blowout release rate Q.
2. Calculate the exceedance probability P_j for each blowout duration using equation (4).
3. Calculate the exceedance frequency from the exceedance probability and the blowout frequency using equation (5): $f_{blow,j} = f_B \cdot P_j$.

We now have blowout points ($f_{blow,j}$, v_j) and process event points ($f_{pro,j}$, v_j) with the same volume coordinates. Therefore, the total frequencies are merely the sum; the frequency of exceeding a volumetric release v_j from *any* event is

$$f_{total,j} = f_{blow,j} + f_{pro,j} \tag{7}$$

SINTEF DATABASE ANALYSIS

A distribution of blowout durations can be determined by analysing the SINTEF database. The database lists 395 blowouts with recorded durations. In addition to the duration, the database holds a comprehensive number of data fields on each blowout, including geographic location, vessel type, fluid and blowout control method. It is believed that the most important parameters affecting blowout duration are the geographic location of the well and the control method used to stem the flow.

BLOWOUT CONTROL METHOD DISTRIBUTION

Figure 1 shows the distribution of blowout durations, split by the control method used. Note, often a blowout entry will list multiple control methods. The data plotted in Figure 1 counts all times a particular control method was used, whether or not it was effective, used in conjunction with another method, or was the ultimate method by which the blowout was stopped.

The sub-figures show a histogram of the data, split into 20 bins on a log-scale, and a smooth PDF generated using a standard-normal kernel density estimator (KDE) on the *natural logarithm* of the durations. They also show a standard, uni-modal log-normal curve fit to the data. The KDE and normal distribution fitting methods in the "statistics" part of the SciPy [9] module of Python [10] was used in this analysis. The full dataset, as presented in Figure 1(a) has been normalised. For ease of comparison, each sub-dataset is scaled to the entire dataset, so that the *y*-axis scales are consistent, hence the area under the curves (b)–(f) are not normalised to one. For a quantitative analysis of a particular control method, the data should be normalised before use.

Figure 1(a) shows the combined data for all blowouts. There is a definite bimodal shape to the distribution, with a peak at about 5 minutes duration, and another at around 5 days. It is expected that most of the durations listed in the database are estimates, so it is likely that 5 minutes was a reasonable "best guess" by the operator. The "peak" at 5 days could be interpreted as an approximately uniform distribution between 2 and 20 days; the number of data points is not high enough to draw a particular conclusion. Never-the-less, these data are still instructive. The shape of the histogram suggests that a log-normal fit is reasonable approximation for both peaks, while clearly the unimodal distribution fit does not capture the shape correctly.

Figures 1(b)–(e) show the duration data only for those situations controlled by the blowout preventer, capping, cementing, and drilling a relief well respectively. Results for BOP controlled events, show the main peak around the 5 minute mark, and then a long tail of longer durations. The conclusion is that when a BOP is successful then the blowout is terminated very quickly. If the BOP is unsuccessful, then the duration depends on the control method(s) subsequently used.

The distribution for relief wells is even starker (Figure 1(e)). That distribution exhibits a significant peak at around 45 days, or approximately one and a half months. The data extends to beyond a year, with the longest blowout duration in this dataset of 500 days (which may be an operator estimate, of course). As drilling a relief well is a time-consuming and expensive operation, generally it is an option of last resort. It is therefore surmised that whenever a relief operation is undertaken, then that is what ultimately seals the blowout, although often relief well drilling is performed in parallel with other methods, which may stem the flow first.

Capping and cementing operations both show peaks around the 10 day mark, reflecting the expected time-scale of such operations. It is clear from graphs in Figure 1 that the majority of blowouts are controlled by methods other than those listed above. The sparsity of the data introduces some uncertainty in any model based upon this analysis.

GEOGRAPHICAL REGION DISTRIBUTION

Figure 2 shows the distribution of blowout durations, split by the geographic region.

Figure 2(a) shows the total blowout data, and is therefore the same as Figure 1(a). Figure 2(b) shows the distribution for the Gulf of Mexico (GoM) only. This represents the majority of the recorded data, 272 of 395 data points (69% of all data). Unsurprisingly therefore the GoM distribution closely matches the total distribution. Figure 2(c) shows the distribution for the North Sea only. This distribution is significantly flatter, exhibiting a spike in blowout around the 5 minute duration mark, which corresponds to use of blowout preventers, as illustrated in Figure 1(b). The major peak around 5 days is not so clear in the North Sea distribution, which illustrates the historical fact that long-duration

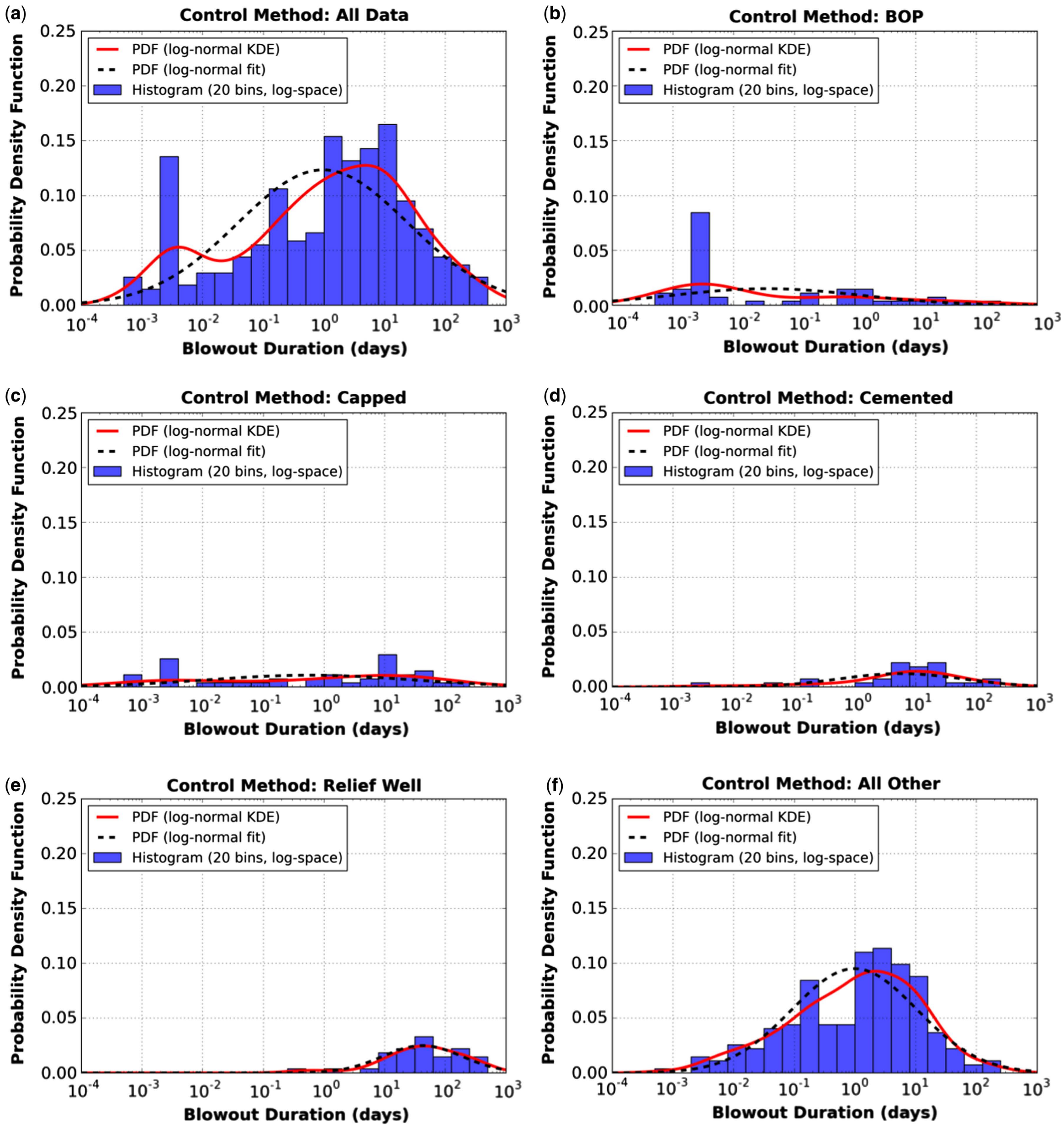

Figure 1. Probability density functions for historical blowout durations, split by control method. All curves/histograms have been weighted by the total number of points for all control methods

blowouts rarely occur in this region[2]. GoM operations have been undertaken in the decades before North Sea operations. This may also account for the larger GoM dataset, and the longer blowout durations in that region; by the time North Sea operations started technology had been developed, and hence better control methods were available, reducing the consequences of blowouts. A future analysis could investigate the change in GoM distribution over time, to determine the validity of this assumption. Figure 2(d) shows the distribution for all other blowouts worldwide. Here the peak is at a slightly longer duration around 10 days, which may suggest the operators in the North Sea and GoM are better at stopping blowouts in shorter times.

[2]Note, as this paper was being drafted an large-scale gas blowout was underway on the Elgin platform operated by Total, which was predicted to last a significant time and may require a relief well operation to stem.

EXCEEDANCE PROBABILITY

Figure 3 shows the probability of a blowout exceeding a given duration, split by control method. The importance

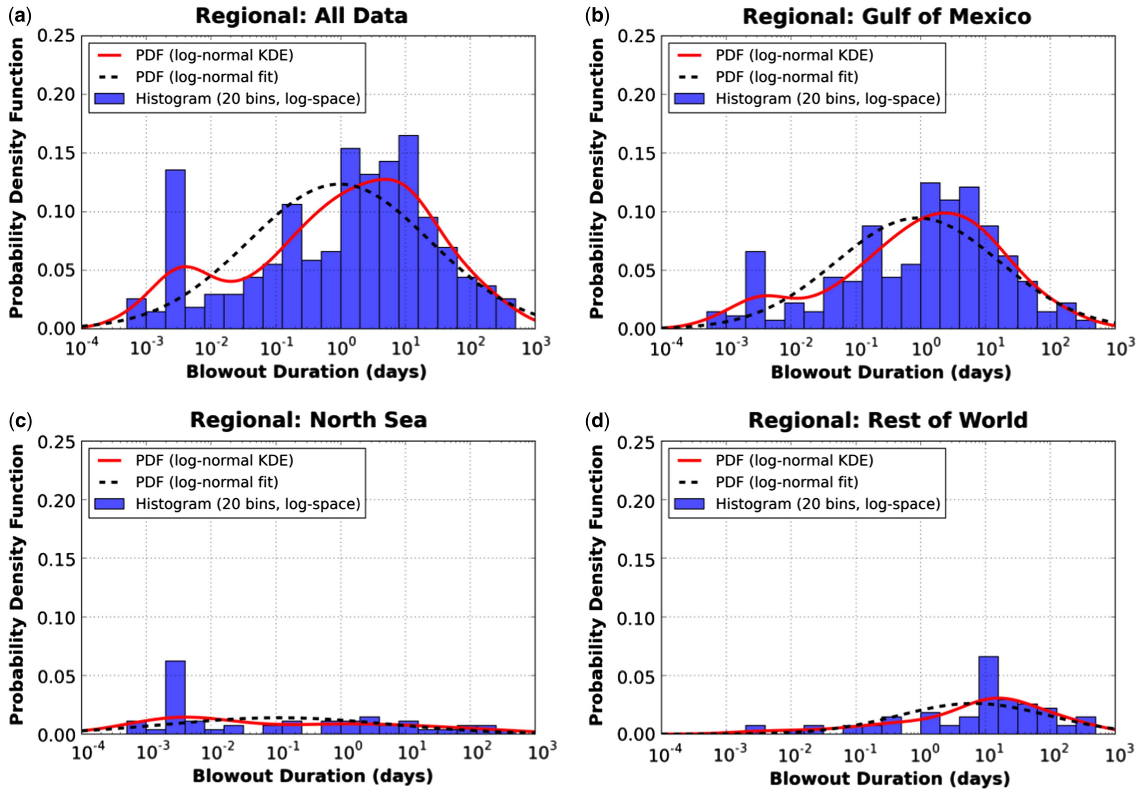

Figure 2. Probability density functions for historical blowout durations, split by geographic region. All curves/histograms has been weighted by the total number of points for all geographic regions

of the presence of a BOP is quite clear from this figure. Selected blowout durations at given exceedance probabilities are listed in Table 1.

There is over an order of magnitude difference between the expected blowout durations when a BOP is used compared to a relief well at 10% probability. This difference is greater at more likely probabilities. This clearly shows that the use of blowout preventers has had a significant impact on blowout release durations.

Figure 4 shows the probability of a blowout exceeding a given duration, split by geographic region. This figure shows that the North Sea data exhibits a lower exceedance probability for any given duration than the Gulf of Mexico and the rest of the world. The Gulf of Mexico shows a lower exceedance probability for any given duration than the rest of the world also. This reflects the historical fact that the North Sea has not suffered as many large-scale blowouts as elsewhere.

EXAMPLE CALCULATION

Here an example calculation is presented to combine process event exceedance frequencies with the blowout model described above. The datasets are combined using the method outlined earlier.

Tables 2 and 3 give the model input data; the process event mass releases and frequencies, and the blowout frequencies and release rates. Seven process events and four blowouts have been presented here, but note that it a typical QRA there will be thousands of process and blowout events, to cover all possible scenarios. The process and blowout event data here are fictional, but are approximately representative of values that may be expected in an actual quantitative risk assessment. Table 2 also gives the cumulative frequency of the process events, summing from the largest mass to the smallest.

Table 4 shows the cumulative blowout frequencies for the four individual blowout events and the total, calculated at the mass released points of the process events in Table 2. These values have been calculated using the model described above.

In order to calculate the total environmental consequence of all events (process and blowout), the cumulative frequencies are summed for each mass point, as described earlier. Figure 5 shows the exceedance curve points calculated for process events and blowout events, and then the total for all events, using the example data presented here.

CONCLUSIONS

A methodology for describing the environmental risk of offshore operations in a manner similar to standard QRA reporting has been presented. An analysis of the SINTEF blowout database has been performed, which revealed that

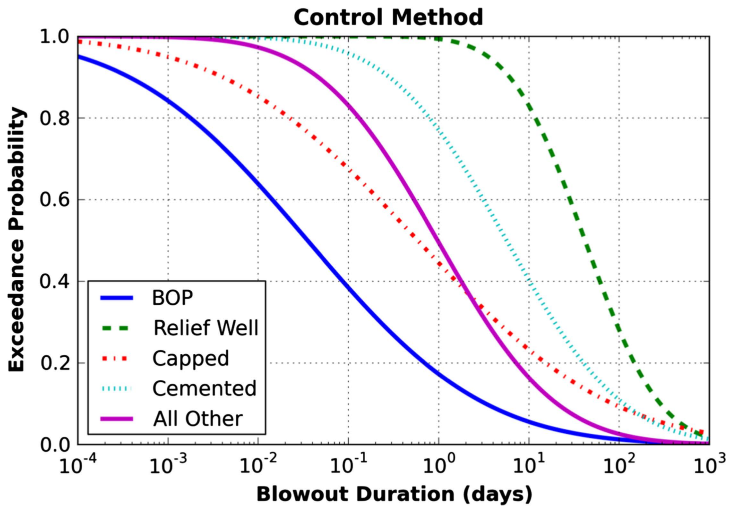

Figure 3. Exceedance probability of blowout duration, split by control method

Table 1. Predicted blowout durations at given exceedance probabilities of 0.1, 0.5 and 0.9 for different control methods

	Predicted Blowout Duration (days) at exceedance probability (%) of		
Control Method	10	50	90
BOP	13	1.2×10^{-2}	5.0×10^{-4}
Relief Well	316	47	5.7
Capping	105	1.2	1.2×10^{-3}
Cementing	102	8.3	0.2
All Other (Combined)	20	1.2	3.0×10^{-2}

the distribution of blowout durations is bimodal, which each peak approximately represented by a log-normal distribution. The duration distribution was split by blowout control method used, which demonstrated the effectiveness of blowout preventers in limiting the consequences of a blowout. Drilling relief wells was shown to have historically taken significantly longer, by orders of magnitude, than other control methods.

RECOMMENDATIONS

Knowledge of the volume of hydrocarbon released is a first step to determine the follow-on consequences of such events. In this model the consequences of a hydrocarbon

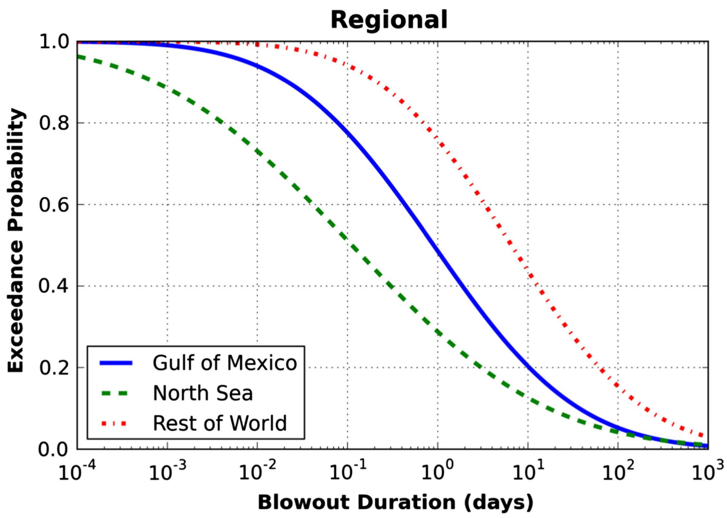

Figure 4. Exceedance probability of blowout duration, split by geographic region

Table 2. Example set of process events; masses released and event frequency

Process Event ID	Mass Released (kg)	Frequency (per year)	Cumulative Frequency (per year)
1	18	1.34×10^{-2}	$1.78645201 \times 10^{-2}$
2	618	3.94×10^{-3}	4.464201×10^{-3}
3	3002	6.95×10^{-5}	5.24201×10^{-4}
4	4.62×10^{4}	4.54×10^{-5}	4.54701×10^{-4}
5	3.96×10^{5}	3.90×10^{-7}	4.01×10^{-7}
6	1.00×10^{7}	1.00×10^{-8}	1.10×10^{-8}
7	1.00×10^{9}	1.00×10^{-9}	1.00×10^{-9}

release are measured purely in terms of the mass released. A more appropriate assessment of the environmental damage would need to consider such parameters as wind direction, proximity to a coastline, rate of dispersion by weather and so on. Computational tools already exist to model the flow of oil slicks across open water; a more complete analysis would be obtained by linking these two approaches together. If the potential oil release risk is determined too high by the F-E analysis during an offshore QRA, it is recommended that a further analysis is performed to determine the ultimate consequences of such a release, using tools like those listed above. Such predictions could possibly influence operators to implement mitigation measures during the planning phase, and hence be better prepared for future incidents.

Table 3. Example set of blowout events; release rates and event frequencies

Blowout Event ID	Release Rate (kg/s)	Frequency (per year)
1	22.82	2.47×10^{-4}
2	68.45	1.11×10^{-4}
3	114.08	1.48×10^{-4}
4	22.82	5.47×10^{-5}

Table 4. Example exceedance frequencies for the given process event masses released

Mass Release Point (kg)	Cumulative Process Frequency (per year)	Cumulative Blowout Frequency (per year)				
		Blowout 1	Blowout 2	Blowout 3	Blowout 4	Total
18	1.79×10^{-2}	2.47×10^{-4}	1.11×10^{-4}	1.48×10^{-4}	5.47×10^{-5}	5.62×10^{-4}
618	4.46×10^{-3}	2.46×10^{-4}	1.11×10^{-4}	1.48×10^{-4}	5.45×10^{-5}	5.60×10^{-4}
3002	5.24×10^{-4}	2.39×10^{-4}	1.10×10^{-4}	1.48×10^{-4}	5.30×10^{-5}	5.51×10^{-4}
46188	4.55×10^{-4}	2.13×10^{-4}	1.01×10^{-4}	1.37×10^{-4}	4.72×10^{-5}	4.99×10^{-4}
395668	4.01×10^{-7}	1.79×10^{-4}	9.01×10^{-5}	1.24×10^{-4}	3.96×10^{-5}	4.33×10^{-4}
1×10^{7}	1.10×10^{-8}	7.56×10^{-5}	5.14×10^{-5}	7.91×10^{-5}	1.67×10^{-5}	2.23×10^{-4}
1×10^{9}	1.00×10^{-9}	1.56×10^{-6}	2.81×10^{-6}	6.16×10^{-5}	3.46×10^{-7}	1.09×10^{-5}

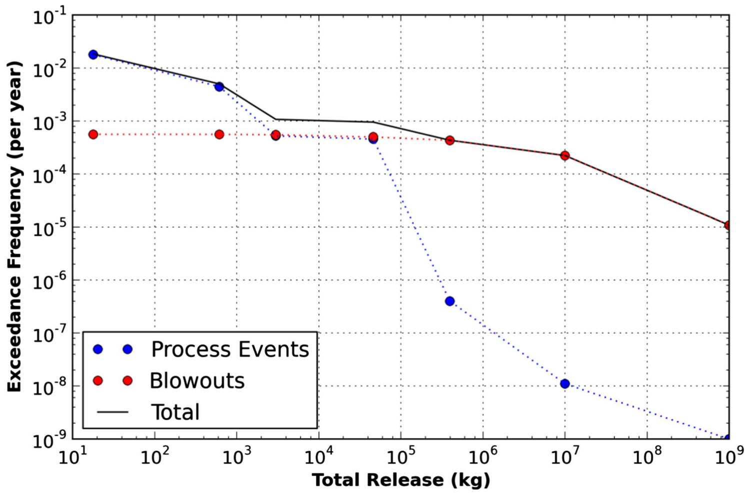

Figure 5. Example combined mass released exceedance curve for process and blowout events.

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