Sensitivity of Vapor Cloud Explosion Exceedance Analysis to the Ignition Probability Model for Offshore Process Systems

Maryam Mortazavi
Department of Civil Engineering, Case Western Reserve University, Cleveland, OH, 44122

YeongAe Heo*
Department of Civil Engineering, Case Western Reserve University, Cleveland, OH, 44122

Abdullahi Salman
Department of Civil & Environmental Engineering, The University of Alabama in Huntsville, Huntsville, AL 35899, USA

* Corresponding Author. Tel: 216-368-0455; E-mail: yaheo@case.edu

ABSTRACT: Probabilistic methodologies have been strictly recommended in the offshore field since the worst offshore explosion disaster in terms of lives lost in the North Sea in 1988. For today's offshore projects, essential design specifications including design loads for critical hazardous events are produced by quantitative risk analysis (QRA), which substantially governs the success of offshore projects. The offshore topside process systems are most vulnerable to hydrocarbon-relevant disasters such as vapor cloud explosion (VCE) and fire. However, it still remains extremely challenging to properly predict and mitigate the risk of such complex offshore topside systems, due to the nature of complexity in the system in addition to harsh environmental and operating conditions. Therefore, this study aims to advance the understanding of uncertainties and risk in the complex offshore systems exposed to multiple interrelated natural and man-made hazards (i.e. winds, VCEs). This study investigates the effects of uncertainties on the risk quantification focusing on VCE risk and ignition probability models, which has not been studied yet. A detailed probabilistic risk quantification of VCE is performed for a specific offshore topside system. The estimated design explosion load based on the VCE risk is compared for different ignition probability models.

1. INTRODUCTION

Historic offshore disasters such as 1988 Piper alpha (Paté-Cornell, 1993) have given rise to design paradigm shift to probabilistic risk-based approaches in the offshore engineering field. Accordingly, quantitative risk assessment (QRA) has been widely adopted to estimate design loads for critical accidental hazards induced by hydrocarbon release such as fires and explosions as well as non-hydrocarbon hazards such as dropped-object impact, collisions, etc. As vapor cloud explosion (VCE) is the most devastating hazard which can lead to catastrophic damage to human life, economy, and environments, it is essential to include in the QRA report for all offshore projects. However, existing guidelines (Norosk Standard Z-013, 2010) for vapor cloud explosion risk assessment (ERA) have been rarely examined yet.

For probabilistic risk-based structural design, it is essential to identify dominant scenario parameters for a specific hazard as these parameters determine the total number of scenarios, and design loads are determined by an exceedance curve or hazard curve generated using these scenarios. Heo (2013) describes VCE scenario parameters with respect to wind, leak, and ignition conditions to quantify the annual rate of occurrence for *ith* explosion scenario (P_E^i) as shown in Eq. (1) for ERA:

$$P_E^i = \lambda_L^i \,.\, P_H^i \,.\, P_{LL}^i .\; P_{LD}^i . \\ P_{WS}^i . P_{WD}^i . P_{IL}^i . P_{IT}^i . P_{IG}^i \qquad (1)$$

where λ_L^i is annual leak frequency and P_H^i, P_{LL}^i, P_{LD}^i, P_{WS}^i, P_{WD}^i, P_{IL}^i, P_{IT}^i, P_{IG}^i are the probability of hole size, leak location, leak direction, wind speed, wind direction, ignition time, and ignition of FPSO for the i^{th} scenario respectively. This explosion probability highly depends on numerical assumptions for these scenario parameters (e.g. probability distribution functions and the interval length of each scenario parameter). For each explosion scenario, three-dimensional computational fluids dynamic (CFD) analyses are carried out to generate a flammable gas cloud by a dispersion analysis based on the selected leak and wind conditions. Subsequently explosion analysis is performed to compute explosion responses (e.g. pressure time series, temperatures, etc.) given the flammable gas cloud volume computed by the dispersion analysis and the selected ignition conditions (i.e. the ignition time and location). The VCE exceedance curve, also known as VCE hazard curve, can then be plotted using the computed annual probability of exceedance versus the explosion pressure. The VCE design load can be finally determined by reading off the explosion pressure at the allowable annual occurrence rate or return period of 10^{-4} or 10^{-5} for accidental actions according to the international standards (ISO 19901-3, 2010). Since the design load is directly related to the explosion scenario parameters, the selection of ERA scenarios can lead to serious impact on offshore installations.

Heo and Lee (2017) investigated the effects of scenario selection on the ERA results and corresponding VCE design loads by different sample sizes of leak and wind variables. 5 different explosion scenario sets were selected to generate exceedance curves. It is demonstrated that different sample sizes of leak and wind variables result in a significant divergence in design load estimation for an FPSO. Explosion responses greatly vary due to the ignition parameters such as ignition time, and locations which are related to the size of flammable gas clouds and the intensity of explosion pressures. In addition, the probability that a gas cloud ignites is another vital parameter in ERA. Although there are a few existing IP models (Cox et al., 1990; CMPT, 1999; UKOOA, 2006; Scandpower, 2007; Mossemiller, 2011), it is quite challenging to develop a reliable IP model due to its complex nature, large aleatory uncertainties and limited data (e.g. ignition sources, ignition counts per source, etc.). Since a few existing IP models have been developed based on such limited data combining experts' judgment and numerical analysis, it is obvious that large epistemic uncertainties are included in the IP models. These ignition variables and its effects on the ERA results, however, have not been properly examined yet. Specifically, the IP model which is essential for the ERA is not a simple parameter, but it requires extensive resources and multidisciplinary efforts to develop. Accordingly, these models have been widely adopted for ERA with lack of understanding of the limitations and uncertainties in the model. Therefore, in this study, two IP models which are most widely used in the offshore field are selectively examined to demonstrate the sensitivity of the probabilistic estimation of VCE design loads to the IP model for a specific FPSO. A total 64 VCE scenarios is considered with combination of scenario parameters. CFD analysis is performed for dispersion and explosion analysis using FLACS software package. The exceedance VCE curve is plotted for the two IP models. The VCE design load obtained from the two IP models is compared by reading off the explosion pressure at the allowable annual occurrence rate of 10^{-4}.

2. SYSTEM DETAILS AND VCE SCENARIOS

2.1. System Details

The topside of the FPSO is functionally laid out, consisting of accommodation, process, and utility areas. The areas containing hydrocarbons such as the process area are typically equipped by safety devices such as blast and fire walls, emergency shutdown valves, firefighting systems, and various detectors and sensors to prevent escalating fires and explosions. In line with this safety context, these areas are also designed to be segmented by the emergency shutdown valves so that each sementation is isolated in case of accidental operation conditions. Hence, an inventory analysis was carried out for a testbed FPSO prior to this study to list equipment such as pipes, tanks, and pumps within each isolable section and to estimate the amount of hydrocarbons which will be trapped within the section. Two isolable sections denoted as Sections 5 and 11 are considered to determine leak variables for this study.

2.2. VCE Scenarios

2.2.1. Leak Frequencies: λ_L

The calculated annual leak frequencies at Sections 5 and 11 are 0.049 and 0.028 respectively. Equipment-wise leak incident statistics for offshore installations of the Hydrocarbon Release (HCR) Database (Hydrocarbon Release System, 1992~2012) are used to calculate the leak frequencies of the isolable sections.

2.2.2. Leak Scenario Parameters: P_{LL}, P_{LD}, P_H

The volume of a flammable gas cloud results from leak location, direction, and rate. The locations of two isolable sections are considered the leak location. For leak direction as shown in Figure 1, 0º and 180º are considered along the length of the FPSO. The leak rate is determined by the hole size given the stream properties, pressure and temperature in the isolable section as shown in the following equations (CMPT, 1999):

$$Q = Q_0 \exp[\frac{-Q_0}{m_G} t] \tag{2}$$

$$Q_0 = C_D\, A\, P_0\, Z \tag{3}$$

$$Z = \sqrt{\frac{M\gamma}{RT_0} (\frac{2}{\gamma+1})^{\frac{\gamma+1}{\gamma-1}}} \tag{4}$$

where Q is the reduced release rate after isolation (kg/s), Q_0 is the initial release rate (kg/s), m_G is the mass of gas, C_D is a discharge coefficient, A is the hole area (m^2), P_0 is the initial pressure of gas (N/m^2), M is the molecular weight of gas, γ is ratio of specific heat, R is the universal gas constant, and T_0 is the initial temperature of gas. 150mm of the hole size is used to calculate initial leak rates for the two sections as shown in Table 1.

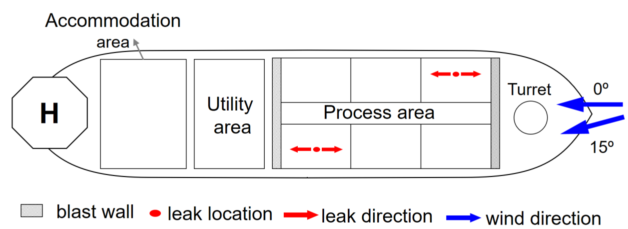

Figure 1: Process area with schematic scenario parameters for leak location, direction and wind direction.

Table 1: Initial leak rates for the sections

	Section 5	Section 11
Initial release rate (kg/s)	39.7	400.9

2.2.3. Wind Scenario Parameters: P_{WS}, P_{WD}

The wind plays a critical role to mix the released hydrocarbons with the air and disperse the gas mixture with various gas concentration ratio. Two wind directions, 0º and 15º and two wind velocities of 2.5m/s and 7.5 m/s are considered. According to the heading analysis and metocean analysis for the FPSO, the wind direction of 15 º is the largest deviation of the wind during the weather vanning while 2.5m/s and 7.5m/s are classified as low and medium wind speeds respectively.

2.2.4. Ignition Scenario Parameters: P_{IL}, P_{IT}, P_{IG}

Not only leak variables, but also ignition time is another factor to determine the volume of a flammable gas cloud as it explodes as soon as ignition occurs no matter how much the total inventory volume of an isolable section is to be released out. Besides, explosion responses considerably vary for different ignition location within a flammable gas cloud due to the various gas concentration ratio. 60% and 100% of the maximum flammable gas cloud volumes are considered which represent two different ignition times. Also, the upper and lower flammable limit zones are considered for two different ignition locations at each gas cloud. Combination of these selected samples of each random variable result in the total number of 64 VCE scenarios. Table 2 shows the values of scenario parameter.

Table 2: Sample values for the scenario parameters

Scenario parameter	Sample values	
Leak location	Section 5	Section 11
Leak direction	0º	180º
Leak hole size	150mm	
Wind direction	0	180
Wind speed	2.5m/s	7.5m/s
Ignition time	at 60% of V_{FLAM}^{max} *	at 100% of V_{FLAM}^{max} *
Ignition location	UFL	LFL

* maximum flammable gas cloud volumes

3. IGNITION PROBABILITY MODELS

One of the major uncertainties in QRA of offshore installations is the probability of ignition. Sources of uncertainties in ignition probabilities originate from both methodology and data. Over the years, several ignition probability models have been proposed. The IP models range from simple models based on a few key factors such as release rate to more complex models that attempt to consider as many relevant factors as possible.

Ignition can be categorized into immediate or delayed ignition. Immediate ignition occurs at or near the point of release and it is quick enough to prevent the formation of a vapor cloud. It can occur as a result of released material being above its auto-ignition temperature or where the source of the leak and ignition are the same. On the other hand, delayed ignition occurs after the formation of a vapor cloud. Immediate ignition of gases usually results in jet fires while delayed ignition can result in either an explosion or a vapor cloud fire. Figure 2 demonstrates the possible outcomes of ignition using an event tree. Despite the importance of immediate and delayed ignition in possible outcomes, only a few of the available IP models distinguish between them.

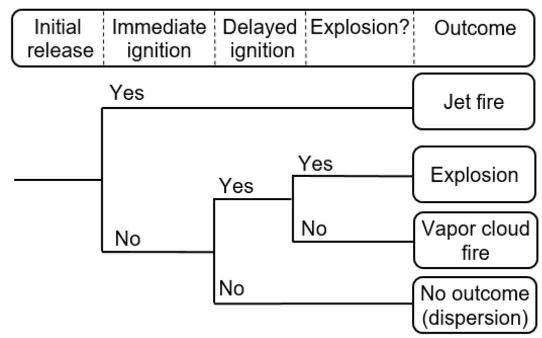

Figure 2: Event tree for possible outcomes of ignition

Among several existing IP models, two commonly used IP models are adopted in this study to evaluate the effect of ignition models on the overall risk.

3.1. IP model 1: CMPT Model (1999)

The model was developed based on historical data and expert judgment by Spouge (1999) in the Centre for Marine and Petroleum Technology (CMPT) within a contract by Det Norske Veritas (DNV) Technica for offshore installations. It provides a generic ignition probability based on the release type (gas or oil) and release rate (kg/s). The model does not differentiate between immediate and delayed ignition, but it provides judgmental values for ignition delay probabilities at different time intervals. It is reported that the delayed probabilities agree reasonably well with historical blowout data but are not consistent with process leak data (Spouge, 1999). Therefore, the ignition delay probabilities should be further investigated. Table 3 and Table 4 show the ignition probabilities of the CMPT model (Spouge, 1999).

Table 3: Generic ignition probability

Leak rate category	Release rate (kg/s)	Probability of ignition	
		Gas	Oil
Tiny	< 0.5	0.005	0.03
Small	0.5 – 5	0.04	0.04
Medium	5 – 25	0.10	0.06
Large	25 – 200	0.30	0.08
Massive	> 200	0.50	0.10

Table 4: Ignition delay probabilities

Time interval (mins)	Probability of ignition in interval	Probability of ignition by end of interval
0 (immediate)	0.10	0.10
0 – 5	0.20	0.30
5 – 20	0.37	0.67
20 – 60	0.29	0.96
> 60	0.04	1.00

To calculate the probability of ignition for each VCE scenario, the values of generic ignition probabilities in Table 3 are used based on the leak rate categories. The delayed ignition probabilities are not used in this study due to inconsistency with process data leak data, which is the scope of this study.

3.2. IP model 2: UKOOA Look-Up Correlation Model (2006)

The UKOOA look-up correlation model was developed by Energy Institute (EI, 2006) and is the most widely used model in recent years applicable to both offshore and onshore installations. In Phase 1 of the EI study, a full model was developed that considers types of plants, released material properties, process conditions, ignition source characteristics, and ignition characteristics of immediate and adjacent plant areas. The UKOOA full model is cumbersome for QRA. Therefore, a simple look-up correlation model for application in QRA was developed. The look-up correlation model was developed by selecting suitable best-fit lines to results obtained by running the full UKOOA model. Hence, the look-up model is more versatile compared to other simpler and more general models. The look-up tables are based on three parameters: release type (gas, LPG, liquid), release rate, and type of installation. There are totally 27 scenarios, which take a variety of offshore and onshore facilities into account. The UKOOA look-up model provides overall ignition probability and does not explicitly differentiate immediate and delayed ignition.

In this study, the look-up correlation tables will be used for the QRA. The look-up correlations consist of up to three gradients with the form given by Eq. (5):

$$\log_{10}(y) = m \cdot \log_{10}(x) + c \qquad (5)$$

where y is the ignition probability, x is the mass release rate (kg/s), m is the 'gradient' of the correlation, and c is the y-axis 'offset' of the correlation. The look-up tables provide the maximum and minimum ignition probabilities, gradient (m) and offset (c) for all ignition scenarios considered. For an offshore FPSO (Gas), scenario no. 24 can be used to satisfy the release type and installation type. The look-up correlation characteristics of scenario no. 24 are shown in Table 5 (EI, 2006). The minimum and maximum ignition probabilities for this scenario are 0.001 and 0.15.

Table 5: Look-up correlation characteristics of offshore FPSO (gas)

Points	Leak rate	grad	offset
a	0.1	0.073	-2.89
b	1	1.214	-2.89
c	50	NA	NA

Note: NA means "Not applicable".

To calculate the ignition probabilities, the release rate of VCE scenarios are required in the UKOOA IP model. Figure 3 shows the ignition probabilities proposed by the two IP models versus leak rate. As shown in the figure, the CMPT model proposes higher ignition probability values.

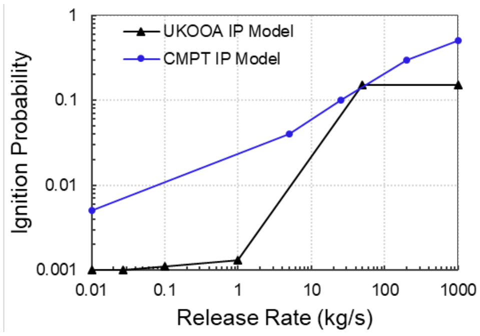

Figure 3: Comparison of IP models

4. EFFECTS ON VCE DESIGN LOAD

Regulatory guidelines such as the Norwegian Petroleum Directorate (NPD) guideline suggests a maximum annual probability of 10^{-4} for the cut-off risk criterion for design purposes. Therefore, the design load for VCE overpressure can be specified by reading off the annual exceedance probability of 10^{-4} from the exceedance curve. Figure 4 shows the overpressure exceedance curve for the two IP models. As shown in Figure 4, the obtained design overpressure is approximately 2.3 bar and 3.7 bar for the UKOOA look-up model and the CMPT model, respectively. The design overpressure using the CMPT ignition model is 61% higher than the pressure using the UKOOA look-up model. This large discrepancy clearly shows the effect of selecting an IP model in the probabilistic risk-based design of offshore structures. This discrepancy in design overpressure can change the structural design of offshore platforms dramatically, which are supposed to resist blast load.

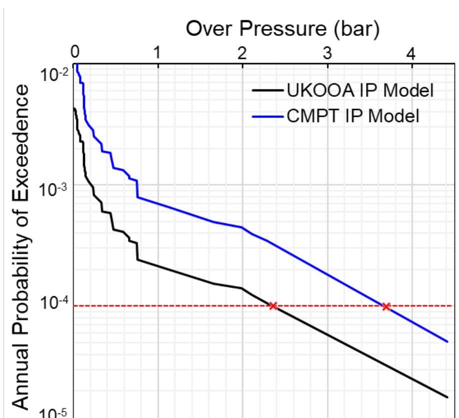

Figure 4: Overpressure exceedance curve

5. CONCLUDING REMARKS

This study demonstrates how much selecting an IP model affects estimating design explosion loads. Given the same VCE scenarios (64 scenarios in total) for a specific offshore process system, exceedance analysis results using two different IP models are compared. While both IP models developed by CMPT and UKOOA are based on hydrocarbon release rates, large discrepancies in the ignition probability of these two models are observed for small (less than 10 kg/s) and large (greater than 100 kg/s) release rates in particular as shown in Figure 3. Since the CMPT IP model is more conservative than the UKOOA IP model, the VCE design load obtained from the probabilistic exceedance analysis using the CMPT IP model is more than 60 % larger than the UKOOA IP model as shown in Figure 4. As a 1 bar increase in the VCE design load leads to tremendous construction cost rising, further investigation of existing IP models is necessary to enhance risk-based blast resistance design guidelines.

6. ACKNOWLEDGMENTS

Research reported in this paper was supported by an Early-Career Research Fellowship from the Gulf Research Program of the US National Academies of Sciences, Engineering, and Medicine. The content is solely the responsibility of the authors and does not necessarily represent the official views of the Gulf Research Program of the US National Academies of Sciences, Engineering, and Medicine.

7. REFERENCES

Cox, A. W., Lees, F. P., & Ang, M. L. (1990). Classification of hazardous locations: *IChemE.*

EI. (2006). "Ignition probability review, model development and look-up correlations" *London: Energy Institute.*

Hydrocarbon Release System. (1992~2012). Offshore Division of Health and Safety Executive. http://www.hse.gov.uk/hcr3/

Heo, Y. A. (2013). "Structural response of offshore plants to risk-based blast load" *Architectural research*, 15(3), 151-158.

Heo, Y. A., & Lee, I. (2017). "Parametric generation of explosion scenarios for quantitative risk assessment of gas explosion in offshore plants" *Process Safety Progress*, 36(2), 139-149.

ISO 19901-3. (2010). "Petroleum and Natural Gas Industries-Specific Requirements for offshore structures-Part3: Topside Structure" *International Organization for Standardization*, 128pp.

Moosemiller, M. (2011). Development of algorithms for predicting ignition probabilities and explosion frequencies. *Journal of Loss Prevention in the Process Industries, 24*(3), 259-265

Norsok Standard Z-013. (2010). "Risk and emergency preparedness assessment", Edition 3, Norwegian Oil Industry Association.

Paté-Cornell, M. E. (1993). "Learning from the piper alpha accident: A postmortem analysis of technical and organizational factors" *Risk Analysis*, 13(2), 215-232.

Scandpower. (2007). Ignition modeling in risk analysis (89.390.008/R1). Retrieved from https://www.scribd.com/document/242782907/OLF-Ignition-Modeling-in-Risk-Analysis

Spouge, J. (1999). "A guide to quantitative risk assessment for offshore installations" *CMPT Aberdeen*.