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Improving Accuracy of Frequency Estimation of Major Vapor Cloud Explosions for Evaluating Control Room Location through Quantitative Risk Assessment

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Frequency estimation of vapor cloud explosions (VCE) are traditionally based on sparse VCE incidents data analysis while process conditions that generate VCE's have a wide spectrum giving VCE's with different strengths. The present paper is focused on developing a systematic methodology to estimate the frequency of VCEs based on process and plant conditions in order to find optimal location of a control room using quantitative risk assessment (QRA). In the presented approach, after classification of plant areas according to variables likely to generate different release conditions, a comprehensive release study is carried out to determine individual probable leakages. Consequently, only those leakages that meet the criteria to launch a strong enough VCE are fed to an event tree in order to estimate the final VCE frequency. Compared to traditional methods, the new proposed approach has the advantages of both being supported by a more populated database of leakage frequencies not explosion incidents, and that it features a multi-variable functionality of process/plant conditions. The first advantage guarantees the accuracy and the latter lets one to use the methodology to differentiate between process units with regard to VCE frequency.

1. Introduction

Control room siting challenge is typically addressed using heuristic rules and there is little work reported in literature based on process safety analysis (CCPS, 2003e). Nevertheless, there are a large number of standards, codes of practice and other publications that propose a wide range of minimum distances between control room and hazardous equipment ranging from 15 m up to 100 m (CCPS, 1999d). To eliminate this inconsistency, QRA studies (CCPS, 2004a) have been introduced and carried out by recently (Badri et al., 2010). These recent methods are still debatable mostly because of uncertainty in VCE frequency estimation. Previous methods for estimating VCE frequencies are based on the analysis of the historical VCE incidents and are not able to consider process condition effects (API, 1995). This paper has introduced a new approach to address these deficiencies. In this way, firstly, a mathematical formulation has been presented to obtain individual risk (IR) on control room occupants by combining single consequence and frequency. And then, a comprehensive procedure

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has been developed to calculate VCE frequency based on leakage frequency and influential process conditions.

2. QRA for Control Room Siting

For a QRA study, it is firstly required to distinguish independent VCE sources. Each congested space should be treated separately as an independent VCE source if they have relatively large separation distances. Otherwise, all the individual congested spaces should be aggregated into a single VCE source. A simple mathematical formulation may be used to estimate the received IR by control room occupants from VCE sources. It is assumed that the IR created by each independent VCE source, $IR_{VCE,i}$, can be stated by combining the ultimate, single, representative consequence and frequency as follows (CCPS, 2004a):

$$IR_{VCE,i} = C_{VCE,i} \times F_{VCE,i} \tag{1}$$

Where $C_{VCE,i}$ is the representative VCE consequence (indoor probability of fatality) and $F_{VCE,i}$ is its representative VCE frequency (VCE occurrence per year). Subsequently, the overall exposed IR on control room occupants ($IR_{overall}$) is calculated by summation of all created IRs from all VCE sources.

Generally, typical figures and tables are used to state expected consequence vs. receiving overpressure for different types of buildings (API, 1995) and various models are available for predicting the overpressure of a VCE. On the other hand, although hazard estimates can be made for specific chemical processes using those of refining processes that are published by API (1995) to arrive at frequency values, generic outcome frequencies for VCE's are not available at present.

3. VCE Frequency Estimation Procedure

It is assumed that all VCEs are resulted by flammable material leakages. Therefore, the VCE frequency strongly depends on leakage frequency. The accuracy of VCE frequency estimation can be improved by taking into account the likely contributions from the influencing parameters such as isolation system performance, process conditions and degree of complexity in terms of number of equipment, piping length and fittings density. The introduced approach is briefly illustrated in Figure 1. All steps have been described in detail as follows:

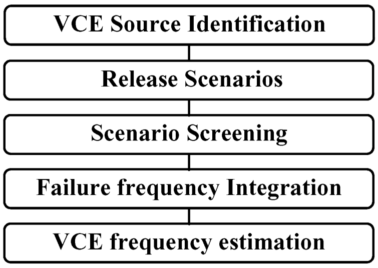

Figure 1: VCE frequency estimation approach

3.1 VCE Source Identification and Release Scenarios

Independent congested spaces separated with enough free space are considered as VCE sources. Although this buffer distance depends on the size of the equipment creating the turbulence in congested space (TNO, 2005), a wide range of general separation distances has been reported including 25 m by TNO (2005) and 3-5 m by CCPS (2003c). In the presented approach 25 m has been considered to distinguish VCE sources conservatively since it gives larger independent VCE sources.

Release scenarios are mostly distinguished by two main indicators: (1) discharge flow rate and (2) the amount of discharge. VCE source equipment is classified into similar process parts (SPP) with each part having similar release indicators. This classification is done considering the parameters that affect release conditions including material phase, material composition and pressure.

Subsequently, it is required to estimate the total mass that can be discharged through different leak sizes (d) from each SPP. Considering that discharges often impinge on nearby surfaces such as the ground, a wall, a tank, or piping, it is assumed that all discharged mass is trapped in a VCE source until the maximum available congested space (V_c) is full of gas at lower flammable limit (LFL) concentration. This volume of gas is normally used as the worst scenario condition to predict VCE consequences (TOTAL, 2005). In order to calculate V_c it has been assumed that each VCE source is a box with a height equal to the average equipment height in the SPP. The total discharged mass (TDM) is calculated as follows:

$$\mathrm{TDM} = \mathrm{Q_d} \times \mathrm{T_i} + \mathrm{M_0} \tag{2}$$

Where Q_d is the discharge flow rate (kg/sec), T_i is the required time (sec) to isolate the involved equipment by closing emergency shutdown valves (ESDVs) considered at 120 sec in order to cover all lag times in detection and isolation actions and M_0 is the initial material inventory stored in equipment located in the relevant isolated part.

One should note that in most cases, sufficient amount of flammable gas is available for occupying the congested volumes even with small leak sizes within a few seconds after a release. Therefore, depressurization systems, which are typically designed to deplete the gas in 15 min, do not have a considerable effect on the required flammable mass.

3.2 Scenario Screening and Frequency Integration

Different leak sizes in each SPP provide different TDMs because of different discharge rates. Therefore, it is required to calculate TDMs from all possible leak sizes ranging from pin holes (1 mm) to full bore ruptures of the maximum line diameter. It is assumed that pipes, fittings and equipment are the most likely sources of leakage. Any leak size capable of providing enough TDM to fill the VCE source volume at LFL concentration will be screened to continue the study. Otherwise, it is assumed that there is not enough flammable mass to launch a strong enough VCE. Selected leak sizes ranging from d_{min} (minimum leak size capable of filling V_c) to d_{max} (maximum pipe diameter in SPP) are then used to calculate leak frequency for each SPP by using generic leak frequency data. The used leak frequencies for the main process equipment items are based on a methodology described by DNV (2006), in which the leak size distribution is correlated by an analytical frequency function that introduces non-zero leak frequencies for all leak sizes between 1mm and the diameter of the inlet pipe in the form of following equation:

$$F(d) = C(1 + aD^{n})d^{m} \tag{3}$$

Where F is the frequency of leaks exceeding size d (for example, per meter year for pipes), d is leak size, D is the maximum connecting pipe diameter, and C, a, n and m are constants. Then, the frequency (F_{SPP}) of all leaks that are capable of launching major VCEs for each SPP is calculated by the following equation:

$$F_{SPP} = \sum_{i=1}^{n} L_{i} \times F_{p,i} + \sum_{i=1}^{n} N_{F,i} \times F_{F,i} + \sum_{j=1}^{m} N_{Eq,j} \times F_{Eq,j} \tag{4}$$

Where, $F_{p,i}$ and $F_{F,i}$ are the frequencies of leaks exceeding size d_{min} from pipes and fittings, respectively for size category i, $F_{Eq,j}$ is the frequency of leaks exceeding size d_{min} for equipment j, L_i is pipe length of category size i, $N_{F,i}$ is the number of fittings of size category i and $N_{Eq,j}$ is the number of equipment type j.

Finally, the leak frequency of each VCE source (F_{Leak}) is calculated by aggregating all N involved SPP leak frequencies.

$$F_{Leak} = \sum_{i=1}^{N} F_{SPP,i} \tag{5}$$

3.3 VCE frequency estimation

In order to estimate the frequency of VCE that can be generated by each VCE source an event tree is used (Figure 2). Values for probabilities of immediate and delayed ignition and probability of enough congestion have been considered as 0.25, 0.9 and 0.5, respectively (CCPS, 2004a). Detailed studies should be undertaken to extract the values of ignition probabilities case by case because these values are a function of material reactivity and flammable gas presence time in exposed area.

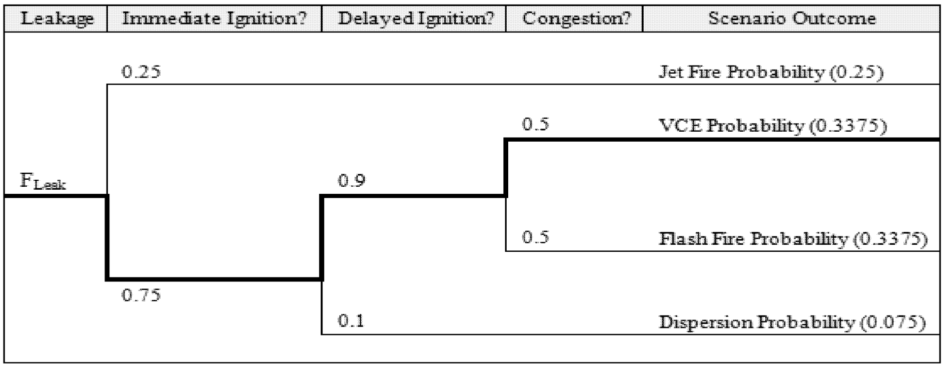

Figure 2: event tree analysis to determine VCE probability

The presence of depressurization systems will decrease the time of flammable gas exposure in the process area and consequently the probability of delayed ignition. Thus, VCE frequency is smaller if depressurization system is activated.

Therefore, the frequency of VCE for each VCE zone can be calculated as follows:

$$F_{VCE} = 0.3375 \times F_{Leak} \tag{6}$$

4. Case Studies

The proposed methodology has been demonstrated through a case study of a process plant consisting of two gas compression stations (GCS), two natural gas liquids (NGL) recovery units and a control room (Figure 3). The control room is constructed of reinforced concrete. Because of adequate free spaces between process units, each of them was assumed as an independent VCE source. Details of respective process conditions and VCE sources dimensions are given in Table 1.

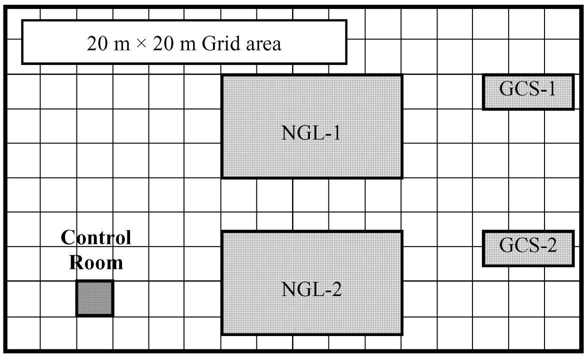

Figure 3: process units and control room layout

Table 1: process unit specifications

Process unit	Capacity (kg/hr)	Phase	Composition	P (bar)	V_c (m^3)
GCS 1 & 2	180,000	Gas	~ C_1	16-66	6,000
NGL 1 & 2	300,000	Gas/Liquid	C_1, C_2, C_3, C_4 & C_5	2-60	72,000

First, the GCS and NGL units were divided to 13 and 5 SPPs respectively based on process conditions and discharge modeling was carried out to determine the d_{min} for all SPPs. Then available pipe length and number of fittings for all size categories and number of each equipment type were gathered and the leak frequencies from d_{min} to d_{max} were integrated over them. Subsequently, the VCE frequencies were calculated as 8.05E-5 yr^{-1} for GCSs and 1.2E-4 yr^{-1} for NGL units. TNT model (CCPS, 2004a) with 10% explosion efficiency was used to predict the overpressure from all VCE sources reaching control room. Assuming the explosion center at the nearest VCE source edge, overpressures were 0.021 and 0.022 bar from GCS 1 and 2 and 0.23 and 0.55 bar from NGL 1 and 2. Using the vulnerability model of reinforced concrete buildings (API, 1995), the final value of IR for control room occupants was 7.3E-5 yr^{-1}, which is much larger than the IR criteria of 1.0e-5 yr^{-1} (CCPS, 2009b). Risk mitigation can be done by moving the control room far away from the left side of NGL 2 unit by 30m. If a VCE frequency of 4.3e-4 yr^{-1} as reported by API (1995) is used, the IR would be about 2.6E-4 yr^{-1}, which means that a 40 m replacement is required in order to have an acceptable IR.

So, the figures calculated by the two methods do not agree and in fact, there is no guarantee that one of them is always less or greater than the other.

5. Conclusion

The proposed method is capable of integrating the effects of main parameters identified theoretically and empirically as the constituting VCE frequency elements (process condition, pipe length, fitting density and unit dimensions). Therefore, the presented multi-variable function is markedly more practical and realistic than the traditional method for comparing the potential (or frequency) of different process units of launching destructive VCEs. Such comparisons were impossible previously because the generic VCE frequency data had no reference to process conditions. On the other hand, the results of the new approach are more reliable to be combined with VCE consequences in order to carry out QRA studies. This increased accuracy is mainly due to using greatly more populated and comprehensive statistical data on generic leakage frequencies rather than the sparse population of VCE incidents data. These two advantages decrease the uncertainties of QRA studies and consequently improve the reliability of siting studies for control rooms. Finally, in the new proposed method a specific VCE frequency is calculated for each process unit that can be used in QRA studies in order to find a safer location for a control room. Since the risk received by control room occupants is strictly dependent on VCE frequency, assuming the same VCE frequency for all process units will affect the final calculated exposed risk on control room occupants. This contradiction may have significant effects on control room layout and its design.

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