EXPRESS: A Rapid Risk Based Software to Assess the Effects of Vapor Cloud Explosions in Occupied Building Siting

Naser Badri\textsuperscript{a}, Mohammad Saber\textsuperscript{a}, Farshad Nourai\textsuperscript{a}, Davood Rashtchian\textsuperscript{a,*} and Alireza Narimannejad\textsuperscript{b}

\textsuperscript{a} Center for Process, Safety and Loss Prevention, Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran

\textsuperscript{b} National Petrochemical Company, Tehran, Iran.

Abstract

This paper introduces a software package, EXPRESS, developed to evaluate the risk associated with vapor cloud explosions (VCE) that can damage building occupants in process installations. The characteristic of EXPRESS is to be simple enough but at the same time adequate to match with quantitative risk assessment (QRA) as required by API RP 752. The application of EXPRESS is appropriate to find safe locations for different types of occupied buildings in process installations; it is also applicable to prescribe the required type of occupied buildings in fixed locations. The models and correlations implemented in the software are relevant to VCE modeling and risk estimation and integration. TNT method and proper vulnerability models are used to predict destructive consequences of VCEs generated by all independent VCE sources on building occupants. These consequences are subsequently combined with respective VCE frequencies and building occupancy fractions in order to present receiving risk by building occupants in the form of individual risk. The limited input data required and straight calculations minimize both the time needed for the building siting and the possibility of errors. Finally, EXPRESS is able to compare the results with those criteria that are internationally recognized.

Keywords: Vapor Cloud Explosion, Quantitative Risk Assessment, Siting, Occupied Building

1. Introduction

Building siting studies are generally carried out to determine incidents with considerable impacts on buildings and their occupants within process installations. Although building protection is achievable by proper building design (ASCE, 1997), there is a great tendency to identify safe locations for buildings in earlier steps (AIChE/CCPS, 1999).

Regarding to more vulnerability of building and their occupants from VCE comparing fire and toxic hazards, it is the dominant hazard scenario for this kind of studies (Melton, et al., 2008). A survey has been carried out of 147 published VCEs occurring in on-shore chemical industries between the beginning of the 1950 up to 2005 (Melton, et al., 2008). The obtained results show a significant increase in the frequency of VCEs up to 1970. This trend is also

\textsuperscript{*}Corresponding author: Tel.: +982166165480; Fax.: +982166022740
E-mail address: rashtchian@sharif.edu (D.Rashtchian).
true for those have been caused fatalities. Since the 1970s, when several devastating VCEs occurred, a considerable degree of attention and research effort has been focused on this subject (Melton, et al., 2008). Therefore, it is necessary to perform VCE hazard analysis as a basis for finding a proper distance from surrounding hazardous equipment to near buildings on a given land.

This recent problem is typically answered by heuristic rules for building locating (AIChE/CCPS, 2003). Plenty of recommendations for building locations have been given by engineering judgment approach usually as spectrum of minimum distances from hazardous equipment (Lees, 1996). By Analyzing similar credible codes and standards, a wide range of proposed distances in the range of 15 to 100 m has been revealed (AIChE/CCPS, 1999) and this difference may cause serious inconsistencies while building siting studies. Another approach for determination of proper distances is to use hazard models. These models propose distances at which receiving overpressure or risk from potential VCE sources is an acceptable level (AIChE/CCPS, 1999). Recent methods are more specific and capable to reduce the deficiency of conventional empirical ones. To fulfill these requirements, numerous publications namely API RP 752 (API, 1995) recommend a risk analysis procedure for identifying hazards and related risk management. The present developed software (EXPRESS) follows this risk analysis guideline to find safe locations for different types of building in which the receiving individual risk generated by all VCE sources meets the criteria. Nevertheless the consequence and risk-based methods have some uncertainties particularly for estimation the amount of flammable mass, degree of congestion and confinement (Raman, et al., 2005) and frequency of occurrence (API, 1995), these methods have earned great credit among researchers because of considering more effective parameters comparing to conventional methods (AIChE/CCPS, 1999).

2. The Effects of VCE on Building and Their Occupants (Historical Analysis)

Analyzing the history of 120 major accidents in on-shore chemical industries for the period 1972-2008 (Marsh, 2010) is illustrated in Figure 1 by property losses proportion in US dollar. Among the loss producing incidents, explosions and fires are the most frequently reported process accidents and VCEs account for the largest proportion
of losses by 30.0%. This high proportion presents large VCEs as unavoidable risk in some hazardous industries such as oil refineries, gas processing plants, petrochemicals, and hydrocarbon distribution terminals.

![Bar chart showing distribution of 120 large property losses (inflated to January 2010 values) in chemical industries by type of incident. The chart displays the percentage of losses due to explosion, fire, VCE, and others.](image)

Figure 1 - Distribution of 120 large property losses (inflated to January 2010 values) in chemical industries by type of incident.

If the VCE generates destructive levels of overpressure, the possibility of human casualty and structure damage becomes a concern. The concern for human injury or death is most often addressed in the form of siting study mainly for occupant buildings in which plenty of personnel are present, because people are somewhat less likely to be injured or killed by the effects of a VCE when outside, as compared to when inside a building (Melton, et al., 2008).

Several historical VCE incidents such as Flixborough UK (1974) involved control room destruction because of improper building siting (Kletz, 1999), some of similar VCEs which have caused serious building destruction and likely indoor fatalities are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>All Fatalities</th>
<th>In Building Fatalities</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>December, 1961</td>
<td>Freeport, Texas, USA*</td>
<td>1</td>
<td>Unknown</td>
<td>(Lenoir, et al., 1993)</td>
</tr>
<tr>
<td>January, 1966</td>
<td>Raunheim, Germany</td>
<td>3</td>
<td>Unknown</td>
<td>(Lenoir, et al., 1993)</td>
</tr>
<tr>
<td>October, 1966</td>
<td>Montreal, Quebec</td>
<td>9</td>
<td>9</td>
<td>(AIChE/CCPS, 1999)</td>
</tr>
<tr>
<td>February, 1971</td>
<td>Longview, Texas, USA</td>
<td>1</td>
<td>Unknown</td>
<td>(Lenoir, et al., 1993)</td>
</tr>
<tr>
<td>June, 1974</td>
<td>Flixborough, UK</td>
<td>28</td>
<td>18</td>
<td>(AIChE/CCPS, 1999)</td>
</tr>
<tr>
<td>November, 1975</td>
<td>Beek, The Netherlands*</td>
<td>14</td>
<td>6</td>
<td>(AIChE/CCPS, 1999)</td>
</tr>
<tr>
<td>February, 1978</td>
<td>Poblado Tres, Mexico</td>
<td>40</td>
<td>Unknown</td>
<td>(Lenoir, et al., 1993)</td>
</tr>
<tr>
<td>October, 1980</td>
<td>New Castle, Delaware, UK*</td>
<td>5</td>
<td>Unknown</td>
<td>(Lenoir, et al., 1993)</td>
</tr>
</tbody>
</table>
Based on above incident statistics, it is therefore necessary to perform a VCE hazard analysis as a basis for the implementation of appropriate mitigation measures to protect personnel in occupied buildings mainly by proper siting.

3. Quantitative Risk Assessment for Occupied Building Siting

Quantitative Risk Assessment (QRA) provides advanced building evaluation tools for VCE hazards. This method adds the elements of VCE frequency and building occupancy to the consequence analysis in order to calculate the risk to an individual within the building (AIChE/CCPS, 1999).

3.1. Vapor Cloud Explosion (VCE)

VCEs are likely to occur while releasing a large quantity of flammable vaporizing liquid or gas from process equipment. Not all of these releases will necessarily lead to a VCE unless meeting some conditions. Firstly, vapor cloud with sufficient flammable region must be formed prior to ignition and secondly, be trapped in a congested enough space. The first condition is required to provide adequate flammable mass and the later to intensify flame propagation in order to generate damaging overpressure (TNO, 2005). Each congested space should be treated separately as an independent VCE source in the case of having relatively large separation distances. Otherwise, all the individual congested spaces should be aggregated as a single VCE source. Although this buffer distance depends on the size of the equipment creating the turbulence in congested space (AIChE/CCPS, 2003), a wide range of general separation distances have been published. TNO reported 25 m as the separation distance (TNO, 2005). Furthermore, smaller distances at 5 m and even 3 m (AIChE/CCPS, 2003) have been proposed. In present approach, 25 m is considered to distinguish VCE sources conservatively, because greater distances may lead to have bigger...
VCE sources and eventually much worse consequences. Following this role, distinct process units within plant area are usually selected as VCE sources.

3.2. Individual Risk Formulation

In order to simplify calculations, it is assumed that the individual risk of any VCE source \((i)\) at any point \((x,y)\), \(\text{IR}_{\text{VCE},i}(x,y)\), can be stated by combining single representative consequence and frequency as follow (AIChE/CCPS, 2004):

\[
\text{IR}_{\text{VCE},i}(x,y) = C_{\text{VCE},i}(x,y) F_{\text{VCE},i}
\]

where \(C_{\text{VCE},i}(x,y)\) is the VCE consequence (indoor probability of fatality) at point \((x,y)\) and \(F_{\text{VCE},i}\) is the VCE frequency (VCE occurrence per year). Subsequently, \(\text{IR}(x,y)\), the overall individual risk at each point \((x,y)\) is calculated by summation of all receiving individual risks on each point \((x,y)\).

\[
\text{IR}(x,y) = \sum_{i=1}^{N} \text{IR}_{\text{VCE},i}(x,y)
\]

where \(N\) is the number of all distinguished VCE sources.

Finally, the individual risk receiving by occupants of a building located in point \((x,y)\), \(\text{IR}_B(x,y)\), is estimated using following equation:

\[
\text{IR}_B(x,y) = Oc \cdot \text{IR}(x,y)
\]

where \(Oc\) is the fraction of working time that the most exposed occupant attends in the building.

3.3. VCE Consequence on Building Occupants

VCE consequence on building occupants is normally presented in the term of indoor probability of fatality.

Considering the type of building, each receiving overpressure generates different consequences. Generally, typical
figures called vulnerability charts are used to state consequence vs. receiving overpressure for different type of buildings (API, 1995). In order to simplify subsequent mathematical operations, published data on consequence vs. receiving overpressure are correlated in the form of following linear equation:

\[ C = a \cdot Op + b \]  \hspace{1cm} (4)

where \( a \) and \( b \) are constants dependent on building type. These constant values for different types of buildings are summarized in Table 2 in accordance with different receiving overpressure ranges.

Table 2- Vulnerability model parameters

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Building Description</th>
<th>Pressure Range</th>
<th>Pressure Range</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Wood frame trailer or shack</td>
<td>( 6.8 \leq Op \text{ (kPa)} &lt; 14 )</td>
<td>( 14 \leq Op \text{ (kPa)} &lt; 34 )</td>
<td>0.0441</td>
<td>-0.200</td>
</tr>
<tr>
<td>B2</td>
<td>Steel-frame/metal siding or pre-engineered building</td>
<td>( 6.8 \leq Op \text{ (kPa)} &lt; 14 )</td>
<td>( 14 \leq Op \text{ (kPa)} &lt; 34 )</td>
<td>0.0441</td>
<td>-0.200</td>
</tr>
<tr>
<td>B3</td>
<td>Unreinforced masonry hearing wall building</td>
<td>( 6.8 \leq Op \text{ (kPa)} &lt; 10 )</td>
<td>( 10 \leq Op \text{ (kPa)} &lt; 20 )</td>
<td>0.1470</td>
<td>-0.900</td>
</tr>
<tr>
<td>B4</td>
<td>Steel or concrete framed reinforced masonry infill or cladding</td>
<td>( 6.8 \leq Op \text{ (kPa)} &lt; 14 )</td>
<td>( 14 \leq Op \text{ (kPa)} &lt; 34 )</td>
<td>0.0441</td>
<td>-0.200</td>
</tr>
<tr>
<td>B5</td>
<td>Reinforced concrete or masonry shear wall building</td>
<td>( 27 \leq Op \text{ (kPa)} &lt; 41 )</td>
<td>( 41 \leq Op \text{ (kPa)} &lt; 82 )</td>
<td>0.0220</td>
<td>-0.500</td>
</tr>
</tbody>
</table>

In order to finalize vulnerability studies, TNT equivalency model (Casal, 2008) is used to predict generated overpressure on buildings by each VCE source as follow:

\[ Op = \frac{1}{D} + \frac{4}{D^2} + \frac{12}{D^3} \]  \hspace{1cm} (5)

where \( Op \) is the receiving overpressure (bar) and \( D \) is scaled distance (m.kg\(^{-1/3}\)) which is defined by following equation:

\[ D = \frac{d}{W^{1/3}} \]  \hspace{1cm} (6)
where \( d \) is the distance from the centre of the VCE source to the building (m), and \( W_{TNT} \) (kg) is the equivalent mass of TNT that is calculated using the following equation:

\[
W_{TNT} = \eta \frac{M}{E_{TNT}}
\]  

(7)

where \( E_c \) is the heat of combustion of gas (kJ\,kg\(^{-1}\)), \( E_{TNT} \) is the heat of combustion of TNT (4,680 kJ\,kg\(^{-1}\)), \( \eta \) is an empirical explosion efficiency and \( M \) is the amount of flammable mass in the cloud (kg).

Generally, three different categories for the reactivity of flammable materials are considered and their respective explosion efficiencies are shown in Table 3.

<table>
<thead>
<tr>
<th>Reactivity Category</th>
<th>Involved Material</th>
<th>Explosion Efficiency (( \eta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Methane and Carbon Monoxide</td>
<td>5%</td>
</tr>
<tr>
<td>High</td>
<td>Hydrogen, Ethylene, Ethylene Oxide and Propylene Oxide</td>
<td>15%</td>
</tr>
<tr>
<td>Medium</td>
<td>all other flammable gases and vapors</td>
<td>10%</td>
</tr>
</tbody>
</table>

It is assumed that only those parts of a flammable vapor cloud that are congested or partially confined contribute to the build-up of overpressure. Therefore, the volume of the cloud within the VCE source (V) is converted into a homogeneous mixture of flammable gas and air at the stoichiometric concentration of lower flammable limit (LFL). This assumption is generally applicable considering major VCE cases (Tufano, et al., 1998). In order to estimate the amount of \( M \) following equation is used:

\[
M = V \cdot LFL \cdot \rho_{gas}
\]  

(8)

where \( \rho_{gas} \) is the flammable gas density (kg\,m\(^3\)) at atmospheric condition and \( V \) is the volume of VCE source, which is approximated by a rectangular volume. This volume is characterized by an area (A) tangent to most remote exterior equipment borders and an average equipment height measured from ground level (\( h_{avg} \)).
Following equation is used for estimating the volume of VCE source ($V$):

$$V = h_{avg}A$$

(9)

where $h_{avg}$ is calculated as below:

$$h_{avg} = \frac{\sum^n_i h_i}{n}$$

(10)

where $h_i$ is the respective equipment height from ground level and $n$ in the total number of major equipment located in VCE source.

VCE analysis is performed only if the quantity of flammable gas in the cloud is greater than 100 kg (Casal, 2008), where damaging overpressure is expected. Otherwise, only the flash fire phenomenon is more likely.

3.4. VCE Frequency

VCE frequency is estimated based on historical data of VCE incidents for different types of process units. Each company should develop a historical record of all major VCEs and an estimate of the number of plant years operation to arrive at estimated frequencies of VCEs for generic process units. Such most referred information is shown in Table 4 for specific process units (API, 1995).

<table>
<thead>
<tr>
<th>Process Unit Type</th>
<th>VCE Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Number of VCEs/Years of Operation)</td>
</tr>
<tr>
<td>Alkylation</td>
<td>5.1e-4</td>
</tr>
<tr>
<td>Cat Cracking</td>
<td>6.5e-4</td>
</tr>
<tr>
<td>Cat Reforming</td>
<td>2.6e-4</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>4.9e-4</td>
</tr>
<tr>
<td>Hydrotreating</td>
<td>2.0e-4</td>
</tr>
<tr>
<td>Hydrocracking</td>
<td>5.6e-4</td>
</tr>
<tr>
<td>Other Units</td>
<td>4.3e-4</td>
</tr>
</tbody>
</table>

3.5. Individual Risk Criteria
When considering individual risk screening criteria, there is an upper bound of risk above which mitigation action must be considered. There is also a lower bound below which it is impractical to continue spending resources on reducing risk (API, 1995). In between these two bounds, there is an area of uncertainty, where the decision-making process on risk reduction will be less clear and may require further analysis. Health and Safety Executive (HSE) in the United Kingdom suggests fatality risks of $1.0 \times 10^{-3} \text{ yr}^{-1}$ and $1.0 \times 10^{-5} \text{ yr}^{-1}$ as an upper and lower bounds respectively.

4. EXPRESS (EXPlosion Risk Estimation for Safe Siting) Structure

The software package EXPRESS is developed to implement the models and correlations summarized in previous sections. EXPRESS runs in Windows platform and is developed under MATLAB 7.6. A flow diagram representing the structure of EXPRESS is given in Figure 2.
EXPRESS presents results of estimated individual risk throughout four steps. In the first step, plant dimensions (horizontal and vertical dimensions) and number of involved units (VCE sources) should be specified to determine a rectangular area. This area is further divided into equal sized square grids, the size of grids is adjustable and is considered at 1 m by default (Figures 3 and 4). After identification of plant borders and grid sizes, in the second step, unit site data, unit process type and congested volume are requested for each predefined process unit. Unit site data comprises unit dimensions (horizontal and vertical dimensions) and unit coordination (the coordination of left and below corner) (Figures 3 and 5). In the third step, unit process data consisting of physical properties of released material (molecular weight, heat of combustion, atmospheric density and LFL concentration) and the category of material reactivity (Figure 6) are identified for VCE consequence modeling. Once all of above data were chosen, occupancy fraction and the type of building which is supposed to be located within the plant area is selected in the forth step. This selection determines the vulnerability correlation in further calculations. Then, levels of individual risk criteria (lower and higher bounds) are chosen (Figure 7) in order to categorize the plant area by three distinct colors.

Figure 3- Plant and involved units dimensions, the coordination of units
Figure 4- EXPRESS interface; plant specifications

Figure 5- EXPRESS interface; unit specifications
5. Case Study

The proposed methodology is demonstrated through a case study (Figure 8) of a process plant (160 m × 100 m) consisting of two similar gas compression stations (40 m × 30 m). Now, there is a need to find out safe locations for a control room that is constructed of reinforced concrete (Type B5) with occupancy fraction at 0.25. Gas compression stations 1 & 2 are fed by 180,000 kg/hr natural gas at 2 bar pressure and this gas is supposed to be compressed up to
25 bar pressure through two compressors in series. Because of adequate free spaces between gas compression stations (more than 25 m); both of them are assumed as independent VCE source by almost 7,200 m³ volume (6 m average height), and considering that the amount of liquid phase is negligible it is acceptably assumed that the process only contains methane in gas phase. Physical properties of methane are shown in Table 5.

![EXPRESS output; plant area and involved units](image)

**Figure 8- EXPRESS output; plant area and involved units**

<table>
<thead>
<tr>
<th>Physical properties of methane (Casal, 2008)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight (kg/kg.mole)</td>
<td>16</td>
</tr>
<tr>
<td>Heat of combustion (kJ/kg)</td>
<td>50,000</td>
</tr>
<tr>
<td>LFL concentration (ppm)</td>
<td>44,000</td>
</tr>
<tr>
<td>Atmospheric gas density (kg/m³)</td>
<td>0.65</td>
</tr>
<tr>
<td>Material reactivity</td>
<td>Low</td>
</tr>
</tbody>
</table>

Considering 1.0e-4 yr⁻¹ and 1.0e-5 yr⁻¹ as higher and lower bounds of individual risk criteria for a arbitrary company, following results are obtained (Figure 9). It can be concluded that areas with individual risks greater 1.0e-4 yr⁻¹ and
1.0e-5 yr⁻¹ extend almost 17 and 32 m from both unit borders respectively. Therefore, control room can not be located at distances smaller than 17 m and there is no restriction for distances greater than 32 m, within this range, the problem is unclear and extra studies are required.

![Diagram showing plant area and risk distribution](image)

**Figure 9- EXPRESS output; individual risk distribution (Risk contours)**

6. Conclusion

When an analyst searches a place for locating an occupied building within a plant area, all possible locations may be considered as unsafe locations because of proximity to hazardous equipment. Therefore, there is a critical need to estimate such distances in which their related risk are not tolerable. In this paper, a software package, named EXPRESS, has been developed to find the safe locations for occupied building within process plant area. These safe locations are defined as the areas in which the receiving individual risk by building occupants meets risk criteria. To carry out risk analysis with API RP 752 requirements, firstly, plant areas are divided into equal size grids. Then, TNT method and different building vulnerability models are used to predict generated consequences of all VCE sources over all determined grids. These consequences are further combined with generic VCE frequencies to estimate the amount of individual risk. Thus, this software is capable of considering the effect of multiple VCE
Finally, results are shown in the form of contours categorizing the plant area into three colored zones representing areas with three levels of individual risk criteria. EXPRESS is quick and free of complicated equations. It also has a user-friendly graphic interface through which the user can easily enter the specifications of desired plant and see the results graphically. These recent advantages and the limited number of inputs decrease the possibility of error. The applicability of EXPRESS has been illustrated with a case study including two gas compression stations and a control room that shows this software is so useful in the case of risk based decision-making.

**References**


