CHEMICAL ENGINEERING TRANSACTIONS

VOL. 26, 2012

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; ISSN 1974-9791

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1226026

Explosion Load Calculation for Building Design: Risk-Based versus Consequence-Based Approach

Stefania Benucci*[a], Marco Pontiggia[a], Giovanni Uguccioni[a]

[a] D'Appolonia S.p.A - Via Martiri di Cefalonia, 2, 20097 San Donato Milanese (MI)
stefania.benucci@dappolonia.it

As a consequence of the ignition of a flammable cloud restrained in a confined and/or congested region, an explosion could occur. Explosion studies are carried out in order to identify, for a specific plant, all the credible accidental events that could lead to flammable gas dispersion able to reach congested areas where ignition sources could be present. The frequencies, the consequences and the risk ranking of the explosion scenarios are then assessed for each identified congested area, in order to select credible explosions able to affect buildings or critical equipment.
The definition of the building blast requirements and/or the need of layout modifications can be performed adopting a Consequence-Based Approach, that takes into account the worst credible event, or a Risk-Based Approach, that considers both the consequence and the frequency values. However, sometimes Peak Overpressures derived from the Consequence-Based Approach can be far too large to be accommodated by the plant structures. The worst case scenario is however usually associated to very low probabilities, and this can result in overdesigning the structures, unless the probability of events is "implicitly" considered in the analysis by selecting a worst case according to some 'credibility' criterion. The Risk-Based method, on the contrary, considers the probability of occurrence of all the possible scenarios and allows designing the plant against an explicitly declared risk criterion.
The most common Risk-Based methods include Overpressure Probability Contours and Overpressure Exceedance Curves. The former shows the spatial location of the probability of being exposed to a specified overpressure value and it is useful when a specific target overpressure threshold value for the buildings is provided. Overpressure Exceedance Curves represent the probability of exceeding any overpressure value for a given location.
In this paper, both the Risk-Based and the Consequence-Based approaches will be applied to a realistic case study, in order to highlight the benefits and the disadvantages related to each methodological choice.

1. Introduction

One of the main aims of the explosion studies is to provide information on blast requirements of the buildings or on the need of layout modification. According to current practice, e.g. API RP 752 (2009), plant owner may choose a Consequence-Based approach or a Risk-Based approach as building siting evaluation method. Consequence-Based approach takes into account, for each building, only the impact of the Maximum Credible Event (MCE), irrespective of its frequency. Risk-Based approach considers both the consequences and the frequencies of all the potential explosion scenarios able to impact on a specific building. The worst credible event (Consequence-Based) approach can easily lead to blast loads far too large to be accommodated by the structures to be protected. Risk-Based

Please cite this article as: Benucci S., Pontiggia M. and Uguccioni G., 2012, Explosion load calculation for building design: risk-based versus consequence-based approach, Chemical Engineering Transactions, 26, 153-158 DOI: 10.3303/CET1226026

Approach allows designing the structures in order to resist to reasonable lower overpressure values, accepting explicitly a certain residual risk of exceeding the overpressure design value
In this paper both approaches will be applied to a realistic case study, represented by an existing oil plant and a new neighbouring expansion, in order to highlight the potentialities of the most common Risk-Based method, i.e. the Overpressure Exceedance Curves.

2. Methodology and Assumptions

In this chapter the methodology and the main assumptions of the explosion study will be described. The issues related to the definition of the design blast adopting both a Consequence-Based and a Risk-Based Approach will also be discussed.

2.1 Explosion Study

The first step of the explosion study is to identify the credible accidental events that could lead to flammable gas dispersion and explosion scenarios. An explosion event may result as a consequence of the late ignition, in a confined or congested region, of a flammable cloud generated by a release of a large quantity of gas or evaporating liquid. Explosion studies are performed identifying the potential accidental events able to originate explosion scenarios, evaluating the frequencies of occurrence of these explosions, assessing the consequences of the identified credible explosion scenarios and carrying out a risk ranking in order to recognize explosion scenarios that shall be considered during the definition of the blast loads of the buildings. In the following four paragraphs these steps will be illustrated.

2.2 Hazards Identification.

The accidental events able to cause release of explosive material are process deviations (indentified in the HAZOP analysis) or Loss of Containment Events (i.e., events occurring as a consequence of unexpected ruptures or releases from piping and equipment, under normal operating conditions). In this study, only Loss of Containment Events have been considered for simplicity. Inclusion of process deviation events does not modify the concepts discussed in the paper.
The selection of Loss of Containment Events is based on isolatable sections identified from Process Flow Diagrams (PFDs) and Piping and Instrumentation Diagrams (P&IDs); the characterization of the isolatable sections in terms of transported fluid, working conditions and inventories is done as per Heat and Material Balances (H&MBs) and Equipment Datasheets.
On the basis of the Plot Plans and of the results of the flammable gas dispersion analysis, congested areas where flammable gas cloud could remain entrapped and where ignition sources could be present are defined.
In a typical analysis multiple release locations (different isolatable sections), multiple release cases (e.g. two cases for each isolatable section: significant rupture – simulated by a 25 mm leak size, and major rupture – simulated by a 100 mm leak size), multiple Potential Explosion Sites (PES, congested areas where gas can be confined and ignition sources could be present), multiple atmospheric stabilities (Pasquill categories and wind speeds, typically F and D associated with 2 m/s and 6 m/s) and finally multiple wind directions have to be taken into account in order to identify all the potential accidental explosion scenarios.

2.3 Frequencies Evaluation

The frequencies of the Loss of Containment Events are evaluated by “Parts Counts” for each identified isolatable section, and the frequency of rupture that characterizes each item and equipment, inferred from historical failure data (in this example the API RP 581 (API, 2000) data have been adopted).
Starting from the frequencies of the Loss of Containment Events, the frequencies of the explosion scenarios are calculated by Event Tree (ET) Analysis, adopting values from international literature for the probability of immediate ignition, late ignition and explosion (given the late ignition). Since late ignition usually occurs in the first minutes following the release, when Emergency Shutdown (ESD) System could not be yet in function, the presence of ESD System has not been taken into account in this study.
Atmospheric condition probabilities have been considered during the evaluation of the explosion frequency associated to each Congested Area: on the basis of wind rose, all the release events that

could originate flammable gas clouds able to reach a particular identified congested area in concentration higher than LFL/2 (conservative assumption) have given a contribution in terms of explosion frequency to the overall explosion frequency associated to that congested area. Distances to LFL/2 have been calculated by means of the Consequence Simulation software Phast.
As per common practice, each explosion scenario associated to a congested area is considered credible when its frequency of occurrence is higher than $1.00 \cdot 10^{-07}$ occurrence/y.

2.4 Consequences Assessment
Consequences analysis is performed first to assess the gas dispersion contours and define if the gas cloud can reach any of the congested areas identified on the plant layout, then, if the gas cloud can reach a congested area, in order to identify the overpressure values able to affect buildings and critical equipment that, in case, shall be blast protected. In order to model explosion scenarios, the Multi-Energy Method has been adopted. The Multi-Energy Method is based on the concept that deflagrative combustion generates blast only in those parts of a quiescent vapour cloud which are sufficiently obstructed or partially confined, while the remaining parts of flammable vapour-air mixture in the cloud burn out at a slower rate, without significant contribution to the blast.
Explosion modeling has been carried out through the calculation of the Confined Strength and the assessment by means of Phast Software both of the distances to the overpressure threshold levels and of the peak overpressure values (with the associated impulse duration) generated by each congested area on any structure of interest.
After this step, for each congested area the frequency of all release and dispersion scenarios that can cause a gas flammable concentration in the congested area and the overpressure values on any target of interest associated to each individual scenarios are assessed.

2.5 Risk Ranking
The explosion Risk Ranking allows to select, among all the credible studied cases, those to be considered in order to define the requirements for blast protection or the need of layout modifications. Protection by increasing the separation distances or by providing blast protection is mandatory for explosion scenarios classified inside the “intolerable risk” area. For scenarios in the ALARP (As Low As Reasonably Practicable) area, potential solutions are identified, and adopted only if technically and economically viable.
The Risk Ranking is performed adopting a “Risk Matrix” approach. In this study, the risk matrix shown in Table 3 has been adopted. The Frequency and Severity Classes in the Matrix are defined as shown in the following Table 1 and Table 2.

Table 1: Frequency Classes

Frequency Classes	Occurrence per year
(0) Practically Not Credible	$< 10^{-6}$
(A) Rare occurrence	10^{-6} - 10^{-4}
(B) Unlikely occurrence	10^{-4} - 10^{-3}
(C) Credible occurrence	10^{-3} - 10^{-1}
(D) Probable occurrence	10^{-1} - 1
(E) Frequent occurrence	> 1

Table 2: Severity Classes

Severity Classes	Peak Overpressure
(1) Slight damage	< 0.015 barg
(2) Minor damage	0.015 barg – 0.03 barg
(3) Local damage	0.03 barg - 0.07 barg
(4) Major damage	0.07 barg - 0.14 barg
(5) Extensive damage	> 0.14 barg

Concerning the damage to non blast-designed buildings, “Local damage” is defined as a damage not impairing the functionality of the structure (assumed possible when peak overpressures impacting on the structures are lower than 0.07 barg), Major damage is defined as a damage causing impairment of the building function (overpressure between 0.07 barg and 0.14 barg), Extensive damage is defined as a damage causing building collapse (overpressure higher than 0.14 barg).
On the basis of the classification for Frequencies and Consequences described above, for each explosion scenario (i.e. explosion occurring in any given congested area) the risk level is assessed by the intersection of the frequency column with the severity row in the risk matrix reported in the following Table 3.

Table 3: Risk Matrix

Risk Matrix	0 ($<10^{-6}$)	A (10^{-6} - 10^{-4})	B (10^{-4} - 10^{-3})	C (10^{-3} - 10^{-1})	D (10^{-1} - 1)	E (>1)
1 – Slight	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
2 – Minor	Acceptable	Acceptable	Acceptable	ALARP	ALARP	ALARP
3 – Local	Acceptable	Acceptable	ALARP	ALARP	Intolerable	Intolerable
4 – Major	Acceptable	ALARP	ALARP	Intolerable	Intolerable	Intolerable
5 – Extensive	ALARP	ALARP	Intolerable	Intolerable	Intolerable	Intolerable

2.6 Blast requirements for Building Design

The two approaches for assessing the building blast requirements are the consequence-based or the risk-based approach. They are discussed in the following.

2.7 Consequence-Based Approach

Consequence-based approach considers only the maximum credible event. The worst credible case of a stoichiometric flammable cloud engulfing the whole congested area, ignited in the worst position, however, can result in very high blast loads, associated to very low frequency of occurrence and therefore which can poorly represent the reality. When Consequence-based approach shows that potential overpressure impacts on particular building are unacceptable, analysts should turn to a Risk-based method for a complete assessment – API RP 752 (API, 2009).

2.8 Risk-Based Approach

The most common Risk-based methods include Overpressure Probability Contours and Overpressure Exceedance Curves.

Overpressure Probability Contours illustrate the spatial location of the probability of being exposed to a specified overpressure value. They are useful when the owner defines a target overpressure threshold value for the buildings. From the overpressure probability contours, the probability that each plant building is subject to the blast threshold load or higher can be easily assessed.

Overpressure Exceedance Curves represent the probability of exceeding any overpressure value for a given location and provide a substantial amount of information for specific locations that may be affected by explosion events. The use of Exceedance curves requires to set a target value not for the overpressure, but for the probability that a building is subject to a blast load higher than the design load.

2.9 Selection of Target Exceedance Frequency

If the Overpressure Exceedance Curves method is chosen, in order to define the buildings blast requirements (i.e. peak overpressure and impulse duration to be considered during the design), the target Exceedance Frequency shall be selected on the basis of the risk acceptability criteria defined for the project.

The Chemical Industries Association Guidance (1998) requires buildings to be designed to resist overpressure scenarios characterized by a frequency of 10^{-4} occ/y and suggests that less frequent events need not to be considered. UKOOA Fire and Explosion Guidance (UKOOA, 2003) states that a frequency between 10^{-4} and 10^{-5} exceedance per year can be considered a reasonable target frequency. For the present study the acceptable values for blast load exceedance frequencies adopted are 10^{-5} occ/y for Unmanned Buildings and 10^{-6} occ/y for Manned Buildings.

3. Results and Discussion

The main findings of application of the methodologies described above, applied to a realistic case, are presented and discussed in this chapter.

3.1 Overpressure Probability Contours

An immediate representation of the Risk-based Approach is given in Figure 1, where the frequency map of Domino Effects on Buildings, assumed to resist at most to Explosion Overpressures equal to 0.14 barg, are shown.

From the overpressure contours we can infer that the unmanned building, could be interested by overpressure values higher than or equal to 0.14 barg with a frequency lower than 10^{-5} occ/y; since this frequency of occurrence is lower than the target exceedance frequency, the building is considered acceptable, in a risk-based approach.
Adopting a Consequence-based approach the same building should be designed to withstand a blast load of 0.320 barg that would be a technically and economically not viable option.
In Table 4, the comparison of the result of the Consequence Based (Worst Case) approach and the Risk Based approach for this building and for other locations in the same layout are shown. As could be expected, the design overpressure resulting from the Consequence Based approach is much higher, and only in few cases similar, to the overpressure value obtained with the Risk Based approach.

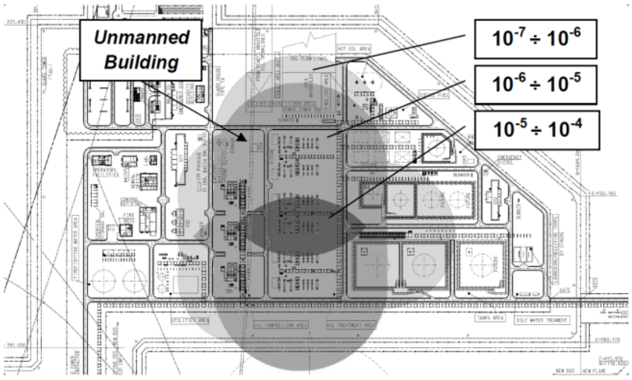

Figure 1: Frequency Map of Overpressure Effects on Buildings due to Explosion OverP of 0.14 barg

3.2 Overpressure Exceedance Curves
In Figure 2 the exceedance curve assessed for the same Unmanned Building (Figure 1) is shown. The peak overpressure corresponding to an exceedance frequency of 10^{-5} occ/y (return time of 100,000 y), target value for unmanned building, is equal to 0.10 barg. In case a Consequence-based approach is adopted, the peak overpressure for the same shelter should be 0.32 barg (see Table 4). As shown in the exceedance curve, this maximum overpressure value is associated to a very low frequency, corresponding to a return time higher than 1,400,000 y. To design the building for this overpressure value would therefore mean investing resources for a reduction of the risk to values so low to be in practice not significant.

3.3 Consequence-Based versus Risk-Based Approach
In Table 4 the results of the application of the Consequence-Based and Risk-Based approaches to various buildings in the plant under study are shown.
Significant differences can be noted in applying the Worst Case and the Risk Based approach.

4. Conclusions

Design Buildings for Explosion Loads obtained by means of Consequence-Based Approach can in most cases lead to significant overdesign, obtaining a reduction of the risk to values that are not significant, and should be adopted only for extremely critical building (for instance, temporary refuge, control room, and so on) where a probabilistic approach is considered not to be prudent.
In the normal industrial cases, when the worst case approach result in blast loads exceeding normal industrial values, a Risk-Based Approach should be adopted to obtain a realistic value of the blast load, related to an explicitly defined value of the risk of building damage. Overpressure Exceedance Curves can be used in order to locate specific blast load requirements related to any exceedance frequency value of concern.

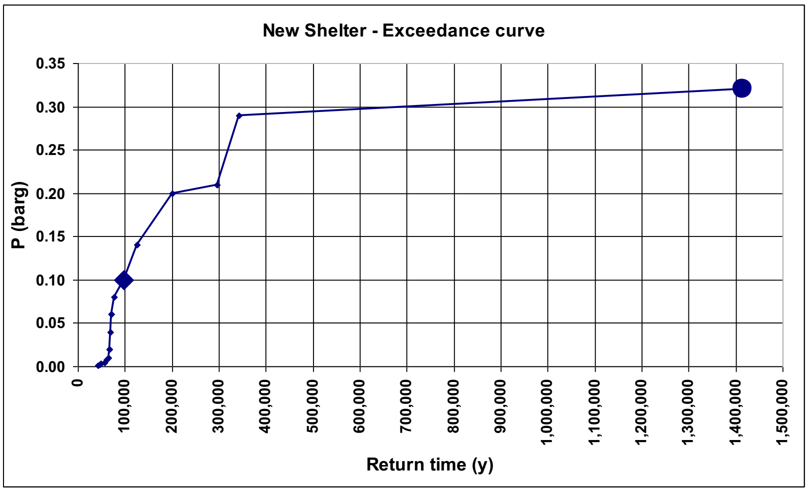

Figure 2: Exceedance curve – Peak Overpressure corresponding to a return time of 100,000 y (Risk-based Approach – Unmanned Building) in comparison with Consequence-Based Approach (maximum Peak Overpressure disregarding the associated return time, higher than 1,400,000 y)

Table 4: Comparison among the results obtained for the two approaches (the Reference building is the one shown on Figure 1)

Building	*Manned / Unmanned*	*Target Exceedance Frequency (occ/y)*	***Consequence Based*** *Design Load (barg)*	***Risk Based*** *Design Load (barg)*
Reference	U	$1.00 \cdot 10^{-05}$	0.320	0.106
A	U	$1.00 \cdot 10^{-05}$	0.140	0.082
B	U	$1.00 \cdot 10^{-05}$	0.090	0.059
C	U	$1.00 \cdot 10^{-05}$	0.140	0.095
D	M	$1.00 \cdot 10^{-06}$	0.060	0.060
E	M	$1.00 \cdot 10^{-06}$	0.080	0.080
F	U	$1.00 \cdot 10^{-05}$	0.050	0.050
G	M	$1.00 \cdot 10^{-06}$	0.050	0.050
H	U	$1.00 \cdot 10^{-05}$	0.090	0.061
I	U	$1.00 \cdot 10^{-05}$	0.080	0.059
J	M	$1.00 \cdot 10^{-06}$	0.120	0.119

References

API, 2000. API Recommended Practice 581, First Edition, May 2000, Risk-Based Inspection Base Resource Document, American Petroleum Institute, Washington, USA.

API, 2009. API Recommended Practice 752, Third Edition, December 2009, Management of Hazards Associated with Location of Process Plant Permanent Buildings, American Petroleum Institute, Washington, USA.

Chemical Industries Association, 1998. Guidance for the location and design of occupied buildings on chemical manufacturing sites, Feb 1998, Chemical Industries Association, ISBN 1 85897 077 6.

UKOOA, 2003. UK Offshore Operators Associations (UKOOA), October 2003, Fire and Explosion Guidance. Part 1: Avoidance and Mitigation of Explosions, UK Offshore Operators Associations, London, U.K.