USE OF THE EXCEEDANCE CURVE APPROACH IN OCCUPIED BUILDING RISK ASSESSMENT

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The exceedance curve approach was developed following the issue of the 2003 version of the CIA guidance and is widely used for determining the appropriate blast overpressure for Occupied Building Risk Assessment (OBRA). Reference 1 provides a description of this approach.

The exceedance curve approach is primarily used for OBRAs on larger continuous process units where release frequencies are estimated using generic leak data for each individual item of process equipment. It may not necessarily be appropriate for smaller plants, batch operations and other process units where releases due to operational related events (e.g. routine making and breaking of containment) may dominate.

One of the strengths of the exceedance curve approach is that it displays the range of potential scenarios, rather than a single event. There are, however, limitations on the uses of the exceedance curve approach. These limitations are described in the appendices of revised (2010) version of the CIA guidelines.

This paper will describe the construction of an exceedance curve, limitations of the exceedance curve approach and give recommendations on how their effects may be mitigated.

KEYWORDS: Building, Explosion, Risk Assessment

INTRODUCTION

An exceedance curve is a mathematical technique which plots a given parameter against cumulative frequency

- The parameter most often plotted in the context of occupied buildings risk assessment is the free-field overpressure, however other parameters (such as thermal flux, occupant vulnerability etc) may also be displayed on an exceedance curve
- Cumulative frequency is the sum of the frequencies of events leading to a specified value of the parameter, or greater.

CONSTRUCTION OF AN EXCEEDANCE CURVE

Table 1 lists a number of hypothetical vapour cloud explosion (VCE) scenarios for a facility that contains two process units (Unit A and Unit B). For each VCE scenario the predicted free field overpressure and frequency at a given point (e.g. a building location) is given. The number of scenarios in an actual study will depend on the complexity of the study. In general, including more variables in the study will increase the number of scenarios developed. These variables may include but are not limited to:

- number of release locations,
- number of release sizes considered,
- number of inventories with differing properties (i.e. material, process operating conditions),
- number of ignition locations considered,
- weather conditions on release.

The treatment of these data to construct an exceedance curve is illustrated in Table 2. The data is sorted so that the values of free field overpressure are in descending order. The cumulative frequency for each row is the sum of the frequency for that row and the cumulative frequency for the row above.

The exceedance curve plotted using the values in Table 2 is shown in Figure 1. Note that the frequency values (y axis) represent the cumulative frequency of overpressures equal to, or in excess of, the corresponding overpressure levels (x values). For example the highest frequency value 1.2E-2/yr represents the frequency of explosion events giving rise to overpressures equal to or in excess of the lowest overpressure scenario (60 mbars).

WHY IS A CUMULATIVE FREQUENCY EXCEEDANCE CURVE APPROACH USED?

Cumulative frequency is used because the risk based approach requires identification of a hazard level which will not be exceeded at a given frequency. This is different from identifying a discrete hazard level which occurs at a particular frequency.

The approach is illustrated as follows;

It is required to determine the overpressure that would not be exceeded at a frequency say 1.0E-4/yr. Figure 2 plots the points from Table 1 as discrete overpressure levels at their given frequency.

- Examination of Figure 2 shows that overpressures of 190 mbar and 250 mbar occur at frequencies of 1E-4/yr.
- 250 mbars is therefore the maximum level of overpressure with a frequency of 1E-4/yr
- However, the frequency of an event with an overpressure of 250 mbars (or greater) must exceed 1.0E-4/yr because there are eight calculated events with

Table 1. Example scenario list

Scenario ID	UNIT NAME	Free field overpressure at specified point (mbar)	Frequency (/yr)
1	A	500	4.0E-05
2	A	400	3.0E-05
3	A	300	3.0E-05
4	A	450	4.0E-05
5	A	400	3.0E-05
6	A	350	3.0E-05
7	A	150	3.0E-04
8	A	250	1.0E-04
9	A	100	1.0E-03
10	A	150	3.0E-04
11	A	75	3.0E-03
12	A	100	1.0E-03
13	B	375	4.0E-05
14	B	300	3.0E-05
15	B	225	3.0E-05
16	B	340	4.0E-05
17	B	300	3.0E-05
18	B	260	3.0E-05
19	B	115	3.0E-04
20	B	190	1.0E-04
21	B	75	1.0E-03
22	B	110	3.0E-04
23	B	60	3.0E-03
24	B	75	1.0E-03

Table 2. Exceedance curve data

Scenario ID	UNIT NAME	Free field overpressure at specified point (mbar)	Frequency (/yr)	Cumulative Frequency (/yr)
1	A	500	4.0E-05	4.0E-05
4	A	450	4.0E-05	8.0E-05
2	A	400	3.0E-05	1.1E-04
5	A	400	3.0E-05	1.4E-04
13	B	375	4.0E-05	1.8E-04
6	A	350	3.0E-05	2.1E-04
16	B	340	4.0E-05	2.5E-04
3	A	300	3.0E-05	2.8E-04
14	B	300	3.0E-05	3.1E-04
17	B	300	3.0E-05	3.4E-04
18	B	260	3.0E-05	3.7E-04
8	A	250	1.0E-04	4.7E-04
15	B	225	3.0E-05	5.0E-04
20	B	190	1.0E-04	6.0E-04
7	A	150	3.0E-04	9.0E-04
10	A	150	3.0E-04	1.2E-03
19	B	115	3.0E-04	1.5E-03
22	B	110	3.0E-04	1.8E-03
9	A	100	1.0E-03	2.8E-03
12	A	100	1.0E-03	3.8E-03
11	A	75	3.0E-03	6.8E-03
21	B	75	1.0E-03	7.8E-03
24	B	75	1.0E-03	8.8E-03
23	B	60	3.0E-03	1.2E-02

overpressures greater than 250 mbar shown on Figure 2 at a frequency of 3E-5/yr or greater.

- In order to find the overpressure which can only occur at a frequency of 1.0E-4/yr it is necessary to add the frequencies of the events starting from the highest overpressure until the sum of their frequencies reaches 1.0E-4/yr. From Figure 1 (or Table 2), this overpressure is just over 400 mbars.

EXCEEDANCE CURVE METHOD AND DEMONSTRATION OF ALARP

An ALARP demonstration for an OBRA needs to consider factors such as the number of building occupants, and inherently safer options. These factors are not addressed in the exceedance curve criteria or calculations. In addition the risk to building occupants can be very sensitive to input assumptions on frequency, overpressure modelling and building response/occupant vulnerability. The output from the exceedance curve approach should, therefore, be treated as an input to decision making and subjected to a sensitivity analysis before it is used to develop design criteria for new buildings or to make decisions regarding existing buildings. A sensitivity analysis process is described. For example application see Examples A-D.

CRITERIA FOR THE EXCEEDANCE CURVE METHOD

The 2003 edition of the CIA guidance (Ref 2) presented a 1.0E-4/yr event frequency design criterion for explosion, fire and toxics. This criterion was developed on the basis that occupant vulnerability under the 1.0E-4/yr design scenario is potentially of the order of 1% and, therefore, a level of individual risk (IR) of 1.0E-6/yr (1.0E-4/yr*0.01 = 1.0E-6/yr) or lower (i.e. within the broadly acceptable region) is achieved. However, there are instances where use of this approach and criterion requires a deeper analysis to confirm the IR criterion is met:

a) If there are points on the exceedance curve with higher levels of hazard than the 1.0E-4/yr scenario at frequencies close to 1.0E-4/yr, then IR of lower than 1.0E-6/yr may not be achieved. This is because the vulnerability of building occupants to these higher levels may exceed 1%. (e.g. if occupant vulnerability is 100% to a 5.0E-5/yr event IR would be 5.0E-5/yr which is 50 times greater than the IR criterion of 1.0E-6/yr). Note that where a site has adopted IR of 1.0E-6/yr as its risk criterion, and uses a 1.0E-6/yr event frequency there is no sensitivity to vulnerability assumptions.

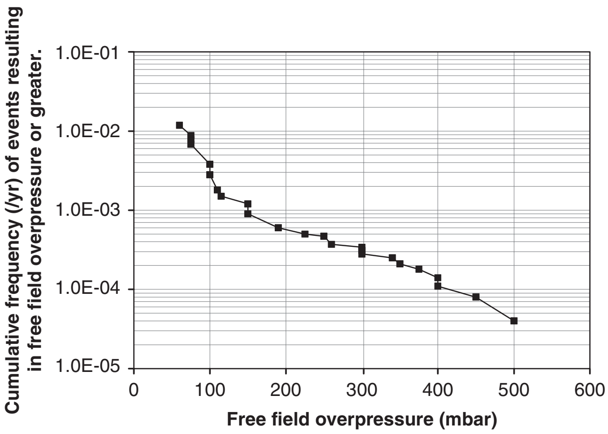

Figure 1. Example Exceedance Curve

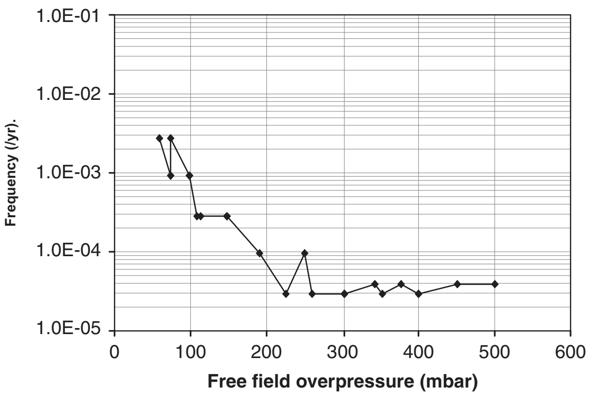

Figure 2. Discrete overpressure levels

b) The exceedance curve approach treats each contributor (explosion, fire and toxics) discretely; however, the sum of the contributors could exceed the 1.0E-6/yr IR value.

The exceedance curve methodology as often applied does not require explicit calculation of Individual Risk or Societal Risk so it is not possible to readily determine if the criteria for Individual Risk or Societal Risk are met.

SENSITIVITY OF BUILDING STRUCTURAL RESPONSE AND OCCUPANT VULNERABILITY TO OVERPRESSURE

The methodologies for structural design against overpressure do not use the traditional factors of safety used in design against normal dead and imposed loading. This allows structural and non-structural elements to undergo significant plastic deformation. A small increment in overpressure beyond the design value could lead to significant damage and potential injury to occupants. This is a concern for all forms of construction but is particularly marked for brittle construction (brickwork, block etc).

SENSITIVITY ANALYSIS PROCESS

The following sensitivity checks should be carried out on the output from an exceedance curve methodology before making decisions regarding new or existing buildings:

Check 1 - Does the exceedance curve match with historical data given the number of and type of process units with the potential for explosion?

- Various references (Refs. 2,3,4) suggest that the frequency of a VCE is of the order of 1.0E-3 to 1.0E-4/process unit-year for a typical refinery or light ends unit.

Check 2 - Is the achievement of 1.0E-6/yr IR for building occupants sensitive to frequency or vulnerability assumptions?

- Where the hazard level (e.g. overpressure) selected for design/analysis is significantly less than the maximum level, achievement of the risk criterion is sensitive to frequency and vulnerability assumptions.

Examples A-D illustrate application of sensitivity checks for a variety of situations. These examples assume that a 1.0E-4/yr event frequency criterion is used as an initial starting point.

USE OF EXCEEDANCE CURVES IN SITUATIONS WHERE THERE ARE MULTIPLE SOURCES OF OVERPRESSURE

This section highlights potential pitfalls in selection of the blast loads for design of new or analysis of existing buildings where there are multiple sources of overpressure and give recommendations to ensure these are mitigated in particular when using the exceedance curve method.

STRUCTURAL RESPONSE TO BLAST LOAD

The response of a structural element or a building to a blast load may be represented by a Pressure Impulse (PI) diagram which plots overpressure v's impulse (see Figure 8, which is for illustration only). The PI diagram displays a line of iso-response (or iso-damage) for the structural element. If the structural element is exposed to PI combinations above and or to the right of the iso-response line it will fail the criteria. If the structural element is exposed to PI combinations below and or to the left of the iso-response it will meet or exceed the criteria.

BLAST WAVE INTERACTION WITH BUILDINGS – REFLECTED OVERPRESSURE

An explosion generates a blast wave which propagates from the source as a hemisphere of increasing radius and decreasing overpressure/impulse. The explosion models typically used for onshore sites calculate the parameters of the "free field" blast wave at a given distance from the explosion source. Free field as the term implies, assumes that the blast wave propagates in an open flat environment with no obstructions outside the source.

When a blast wave interacts with an obstruction such as a building, the blast wave is reflected by the surface of the building facing the source of the blast resulting in an increase in overpressure on the surface. This increase depends on the angle of incidence and the magnitude of the overpressure. Formulae and charts for determining the appropriate reflection factor are given in specialist literature (e.g. refs 5,6). Surfaces parallel to the direction of propagation (side walls and roof) and rear walls experience the free field blast wave.

SITUATIONS OF CONCERN

Examination of the PI curve in Figure 8 shows that the structural response is directly related to overpressure where the impulse is either constant, or where the impulse is increasing with increasing overpressure. Where the impulse decreases with increasing overpressure this may not be the case. Situations where the impulse may decrease with increasing overpressure include;

a) where the scenarios include a variety of explosion sources e.g.
   - A mixture of explosion types (e.g. vessel pressure bursts explosion and VCEs)
   - VCE scenarios from different sizes of congested volumes at different distances,
   - VCE from releases of different fuels (e.g. hydrogen, hydrocarbons).

b) where the scenarios include explosion sources at a variety of angles to the building.

   See examples E and F below.

CONCLUSIONS AND RECOMMENDATIONS

An ALARP demonstration for an occupied building needs to consider factors such as the number of building occupants, and inherently safer options. These factors are not addressed in the exceedance curve criteria or calculations. In addition the risk to building occupants can be very sensitive to input assumptions on frequency, overpressure modelling and building response/occupant vulnerability. The output from the exceedance curve should, therefore, be treated as an input to decision making and subjected to a sensitivity analysis before it is used to develop design criteria for new buildings or to make decisions regarding existing buildings.

Structural elements, respond to a combination of overpressure, impulse and orientation to the blast wave. In many situations the level of response will be directly proportional to the overpressure, but this may not always the case. The following recommendations apply when using the exceedance curve approach

- Limit exceedance curves to one particular type of hazardous event. For example do not include VCE explosions and vessel pressure burst explosions on the same curve.
- Consider producing an impulse exceedance curve in addition to an overpressure exceedance curve.
- Where explosion sources are from a variety of directions, consider developing an exceedance curve for each wall of the building taking into account reflection factors.

A competent structural engineer should review the detailed list of scenarios and the methodology used to select the blast load for each building to ensure that an appropriate blast load is taken for each surface (walls /roofs) of the building.

DEFINITIONS

Explosion an event which generates a pressure wave which propagates outwards from the source.

Blast wave is a diagrammatic relationship between time and pressure at a given location due to an explosion. A blast wave is typically idealised as shown in Figure 7. Note that Figure 7 shows the positive phase as a right angled triangle, however, the shape of the blast wave may vary depending on a number of factors.

Overpressure is the pressure generated at a specific location. It is usually expressed as pressure relative to ambient (gauge pressure). The overpressure used to describe a particular blast load is usually the peak free field value of the positive phase.

Duration is the length of time associated with the blast wave. The duration used to describe a particular blast load is usually the positive phase duration.

Impulse is the integration of overpressure over time. For a triangular blast wave the positive phase impulse is calculated as;

$$\text{Impulse} = 0.5 \times \text{Peak free field overpressure positive phase} \times \text{Positive phase duration}$$

Blast load is the load applied to the structure or object. Blast load depends on the characteristics of the blast wave (overpressure, duration (or impulse) and shape) and the angle of incidence of the blast wave with the building.

EXAMPLES

EXAMPLE A – ADMINISTRATION BUILDING VCE

Refer to Figure 3 which shows an exceedance curve for VCE at a proposed location for a new administration building.

CHECK 1 Does the exceedance curve match with historical data?

The unit in Example A above is considerably less complex than a typical refinery unit. On an equipment count basis the frequency of release could be a factor of approximately 10 lower than a typical refinery process unit. A large explosion could therefore be predicted to occur on such a plant at a frequency of approximately 1.0E-5/process unit-yr. On this basis the exceedance curve is broadly in line with historical accident experience.

CHECK 2 Is the achievement of 1.0E-6/yr IR for building occupants sensitive to frequency or vulnerability assumptions?

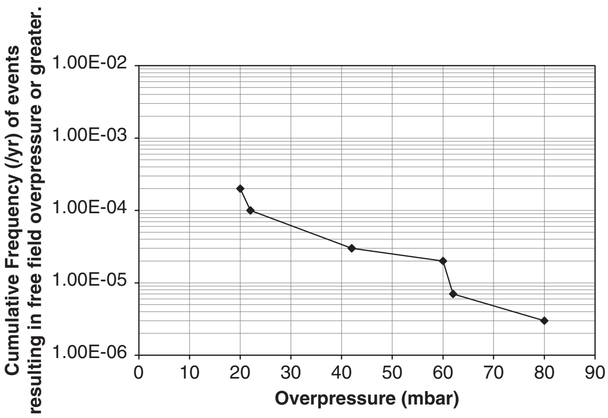

Figure 3. EXAMPLE 1

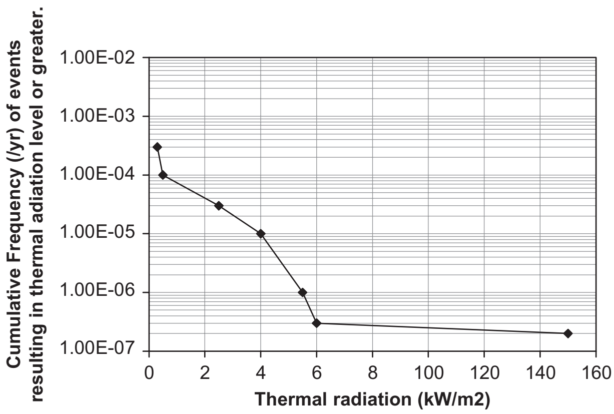

Figure 4. EXAMPLE 2

Achievement of the 10E-6/yr IR criterion is sensitive to both frequency and vulnerability assumptions. The largest overpressure is 80 mbars whereas the overpressure at 1.0E-4/yr is 20 mbars. There is a factor of 4 between the "largest event" and the 1.0E-4/yr "design overpressure". No special features are required to protect occupants from 20 mbar overpressure as this is below the limit at which glass would represent a hazard. Depending on the form of construction (e.g. brittle) serious damage and injury to occupants could occur if a building "designed" to 20 mbars were exposed to 80 mbar.

Example A recommendations
For the administration building the following options should be considered:

1. Design the building for 80 mbars overpressure due to the sensitivity to frequency.
2. Relocate the building to an area where no structural features are required (i.e. to a location where the predicted overpressure is 30 mbar or less).

In this situation, option 2 was selected as it is inherently safer and sufficient space was available.

EXAMPLE B – ADMINISTRATION BUILDING THERMAL RADIATION
Refer to Figure 4 which shows an exceedance curve for thermal radiation at a proposed location for a new administration building.

The process unit is a gas plant and, therefore, there is a large variation in frequency of thermal impact due to hole size and orientation of the jet flame.

The 1.0E-4/yr thermal radiation event is predicted to result in 10 kW/m^2 and 1.0E-6/yr thermal radiation is predicted to result in 50 kW/m^2. Thermal radiation effects are however determined by dose (i.e. flux and time) so it is not possible to determine which event dominates the risk to occupants without knowing the duration of the events. Nevertheless thermal radiation of 50 kW/m^2 for a short period of time could potentially ignite combustible material and 10 kW/m^2 would impede escape routes in the open.

Example B recommendations
Investigate the duration of various fire scenarios and if appropriate eliminate combustible materials and windows from facades facing the fire hazard and provide sheltered escape routes.

EXAMPLE C – BUILDING AFFECTED BY TWO PROCESS UNITS
Refer to Figure 5 which shows the VCE exceedance curve taken from Ref 1 for a building which could be affected by two process units.

CHECK 1 Does the exceedance curve match with historical data?
The curve represents a building which could be affected by explosions on 2 process units. The scenarios from one of the process units (unit A) result in higher levels of overpressure at the building location. The frequency of the largest explosion is of the order of 1.0E-4/yr. On this basis the exceedance curve is broadly in line with historical accident experience.

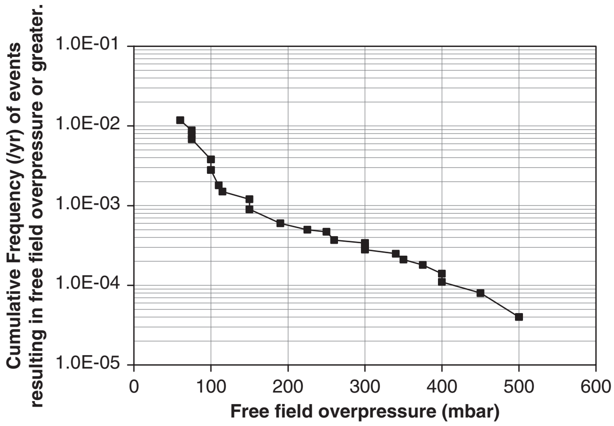

Figure 5. EXAMPLE 3

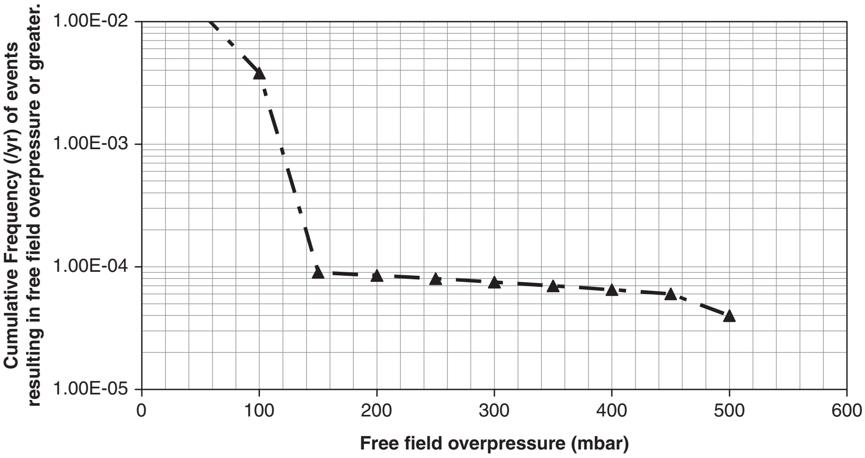

Figure 6. EXAMPLE 4

CHECK 2 Is the achievement of 1.0E-6/yr IR for building occupants sensitive to frequency or vulnerability assumptions?
The exceedance curve is not sensitive as the largest overpressure is 500 mbars whereas the overpressure at 1.0E-4/yr is 450 mbars. There is a factor of approximately 1.1 between the scenario with the greatest overpressure and the 1.0E-4/yr "design overpressure".

Example C recommendations
The following options should be considered:

1. Set the design overpressure to 450 mbar and check that the structure can resist 500 mbars without significant increase in vulnerability to the occupants.
2. Estimate the cost of designing to resist 500 mbars and if this not significantly different to design for 450 mbars set the design criterion to 500 mbars.

EXAMPLE D – CHEMICAL PLANT CONTROL ROOM
Refer to Figure 6 which shows the VCE exceedance curve for a local control room on a chemical plant.

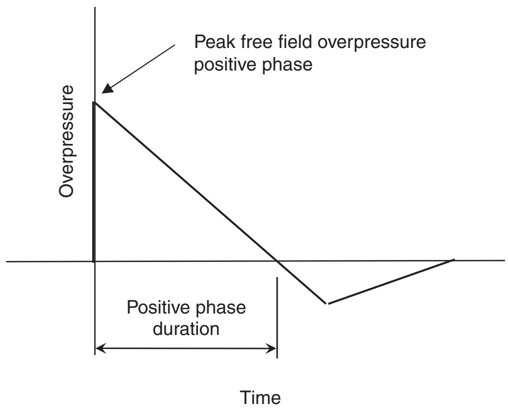

Figure 7. Typical Time Pressure profile for blast wave in free air

CHECK 1 Does the exceedance curve match with historical data?
The curve represents a local control building which could be affected by explosions on a single chemical plant process unit. On this basis the exceedance curve is broadly in line with historical accident experience.

CHECK 2 Is the achievement of 1.0E-6/yr IR for building occupants sensitive to frequency or vulnerability assumptions?
The exceedance curve is very sensitive as the largest overpressure is 500 mbars whereas the overpressure at 1.0E-4/yr is 145 mbars. There is a factor of 3.6 between the scenario with the greatest overpressure and the 1.0E-4/yr "design overpressure". This situation is sensitive to the frequency calculation.

Example D recommendations
For the chemical plant control room the following options should be considered:

- Move personnel to a blast-protected central control building and use this local control building as a normally unattended equipment room.

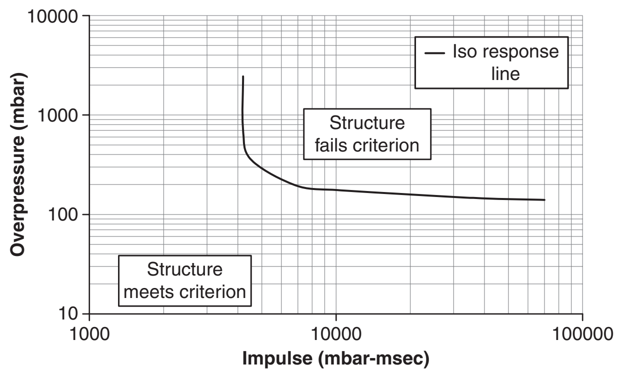

Figure 8. Pressure Impulse diagram

Table 3. Explosion scenarios

Scenario	Overpressure (mbar)	Duration (msec)	Impulse (mbar-msec)
Vessel Burst	500	10	2500
VCE in small congested volume close to location	300	30	4500
VCE in large congested volume far from location	200	200	20000

- Set the design overpressure at 145 mbar and check that the structure can resist 500 mbars without significant increase in vulnerability to the occupants. (This is unlikely to be the case given the large difference.)
- Estimate the cost of designing to resist 500 mbars and if this not significantly different to design for 145 mbars set the design criterion to 500 mbars. (The cost increment could be significant.) (NB. The building may be readily upgradeable to an intermediate overpressure, whereas achieving the final design criterion might not be without disproportionate cost, entailing new build etc. The assessment would then entail a balance of residual risk and cost).
- Set the design overpressure to 500 mbars as the frequency of 500 mbar case is close to 1.0E-4/yr

In this situation option 1 was selected. Personnel were relocated as this was the inherently safer option.

EXAMPLE E – BLAST LOAD SCENARIOS INCLUDING A MIXTURE OF EXPLOSION TYPES

Three hypothetical scenarios are shown in Table 3. The scenarios are listed by decreasing overpressure. The overpressure impulse pairs for each of these scenarios are plotted on a PI diagram (Figure 9). It can be seen that in terms of structural response the greatest response is to the scenario with the lowest overpressure.

EXAMPLE F – EXPLOSION SOURCES AT A VARIETY OF ORIENTATIONS

A site has two process units and it is proposed to locate a new building (Building A) between the units (as shown in Figure 10). The output from the analysis is to use an overpressure of 300 mbar as the design basis for the new building. Events leading to overpressures of 300 mbar at Building A are only possible from scenarios on Process Unit 1. The maximum level of overpressure at Building A from events in Process Unit 2 is 200 mbars. Table 4 presents the free field and reflected overpressures on the east and west walls. Reflection factors were calculated based on reference 27.

From Table 3 it can be seen that by choosing the Process Unit 1 scenario for 300 mbars the blast load on

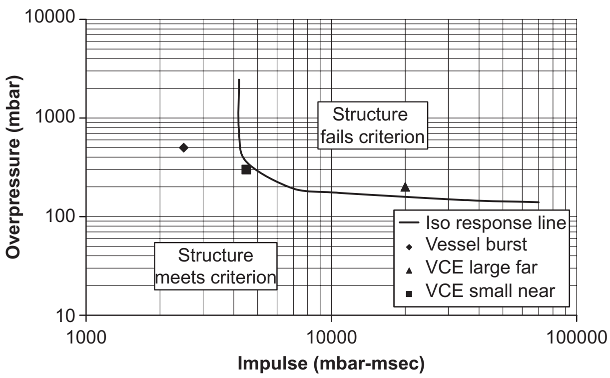

Figure 9. Pressure Impulse diagram

Figure 10. Plant layout

Table 4. Overpressure at Building A

Scenario	Free field overpressure on west wall (mbars)	Reflected overpressure on west wall (mbars)	Free field overpressure on east wall (mbars)	Reflected overpressure on east wall mbars
Process Unit 1	300	**673**	300	N/A
Process Unit 2	200	N/A	200	**433**

the east wall of building A is 300 mbar free field. There is, however, a scenario on Process Unit 2 which although it gives rise to a lower free field overpressure at the building location will result in a greater overpressure (433 mbars) on the east wall due to the reflection effect.

If the explosion on Process Unit 1 was taken solely as the design basis for the building the occupants could be vulnerable to explosions on Process Unit 2.

REFERENCES

1. *Location and Design of Occupied Buildings at Chemical Plants – Assessment Step by Step* – Martin Goose http://www.hse.gov.uk/foi/internalops/hid/spc/stepbystep.pdf
2. Guidance for the Location and Design of Occupied Buildings on Chemical Manufacturing Sites. CIA (2003).
3. Guidance for the Location and Design of Occupied Buildings on Chemical Manufacturing Sites. CIA (2010).
4. *API RP 752 - Management of Hazards Associated with Location of Process Plant Permanent Buildings* – First Edition - American Petroleum Institute (1995).
5. *Blast effects on Buildings*, 2nd edition, by D. Comrie, G. Mays, P. Smith – Published by Thomas Telford Ltd, ISBN 9780727735218.
6. "*Approved methods and algorithms for DOD explosives siting*", Department of Defense Explosives Safety Board Technical Paper No. 14, Alexandria, Virginia, November 2008, available from the Pentagon website http://www.ddesb.pentagon.mil/TP14%20November%202008.pdf