ASSESSING THE ACCEPTABILITY OF RISK AND DECISION MAKING IN RELATION TO RISK REDUCTION

Mr Vimal K. Patel and Dr Jerry R. Mullins
AEA Technology Consulting, Safety Management Group, Warrington, WA3 6AT, UK

The CIA guidance on assessing risks to occupied buildings provides a means of demonstrating the acceptability of major accident hazard risks to on-site personnel. Additional guidance provided by the HSE plus the revised Tolerability of Risk Document provides guidance on the methodologies to be used to assess the withstand capabilities of occupied buildings against design basis events and on criteria to enable cost-benefit analysis to be carried out in relation to decision making on risk reduction measures. This paper will describe the key aspects of the above documentation and provide a demonstration of the application of QRA and cost-benefit analysis in decision making by means of a case study involving a UK major hazard installation.

Quantified Risk Assessment (QRA), Occupied Buildings, Cost-Benefit Analysis, Risk Reduction Measures

BACKGROUND TO CIA GUIDANCE

Since the Flixborough accident in 1974, there has been an increased awareness of the need to consider the location and design of occupied buildings. In response, the Chemical Industries Association (CIA) produced guidance on the location and design of chemical plant control rooms. This guidance suffered from a number of weaknesses; it was descriptive and missed several important factors that would be considered in a modern risk assessment. The new CIA guidance for the "Location and Design of Occupied Buildings at Chemical Manufacturing Sites" (1) has addressed these points and has been extended to cover all occupied buildings. It can also be adapted to technical progress in the assessment of hazardous chemical installations.

The guidance assesses the risk of fire, explosion or toxic gas release to building occupants on chemical manufacturing sites in new and existing occupied buildings. The aim is to assess the risk to people inside buildings. In the case of a major accident, building occupants should be protected to a risk level as low as reasonably practicable. In addition, staff involved in emergency response, such as control rooms should be protected to the extent required to carry out their functions.

The Chemical Hazardous Installation Division (CHID) within the Health and Safety Executive (HSE) has been working to make industry aware of, and apply the guidance in the CIA document. To this end, additional guidance on interpreting the CIA document has been produced(2).

INTRODUCTION

This paper will describe the key aspects of the CIA document(1) and provide a demonstration of the application of quantified risk assessment (QRA) and cost-benefit analysis in decision making by means of a case study involving a UK major hazard installation.

The purpose of the case study was to undertake an assessment of the risk of fatality to personnel in buildings on site in order to assess the acceptability of the risk and make decisions on additional risk reduction measures. An additional aim was to establish the withstand capability of the buildings against design basis events and again identify, where necessary, additional protection measures.

RISK ASSESSMENT METHODOLOGY

The basis for the CIA guidance is the use of risk assessment. The guidance uses risk assessment for both the design and location of new buildings, and to assess the adequacy of existing buildings and subsequently for any improvements.

The risk assessment considers the likelihood and consequence for a range of accident scenarios. The methodology for risk assessment must be structured and systematic in approach. The approach taken is as follows:

- Identification of possible hazard scenarios that might lead to an adverse effect.
- Estimation of event frequency.

The result of the above steps is the production of a list of failure "scenarios" together with the predicted frequencies at which they are likely to occur. The following steps of the risk assessment enable the consequences of the scenarios to be determined.

There are various types of hazard that might be calculated in the QRA. These include Vapour Cloud Explosion (VCE), Boiling Liquid Expanding Vapour Explosion (BLEVE), Pressure Burst, Exothermic Reaction, Toxic Gas release, Fire, Pool Fire, Jet Fire, Flash Fire and Fire Balls. The choice of hazards will depend upon the individual scenarios.

The risk is defined as the likelihood of a specified undesired event occurring within a specified period or in specified circumstances. The risk to people in an occupied building on site is calculated as the product of the risk of fatality from a given level of hazard, the frequency of the event and the occupancy of persons in the building.

The final step of the risk assessment involves comparison of the calculated risks with some standard. For the CIA guidance, the risk values in Figure 1 have been adopted. These values are based on HSE Tolerability of Risk criteria[3].

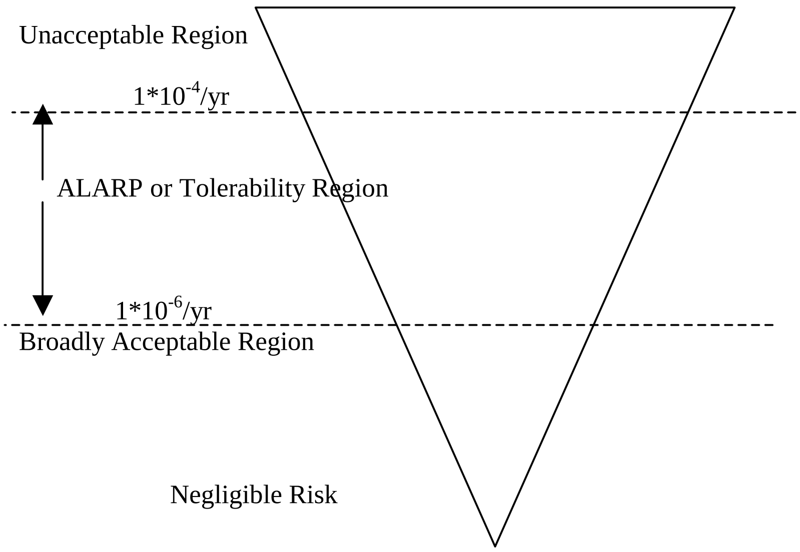

Figure 1: Levels of Risk and ALARP

The calculated risk for the occupied buildings on a chemical-manufacturing site must be compared with Figure 1. If the calculated risk is above the upper intolerable limit, then further risk reduction measures should be applied without regard to reasonable practicability. If the risk is below the broadly acceptable limit, then no further formal assessment of risk reduction measures is required. If the calculated risk is between these two limits, then there is a requirement to reduce risks to a level as low as is reasonably practicable (ALARP). This will require the application of some form of cost-benefit analysis.

ASSESSMENT OF NEW BUILDINGS

The CIA guidance states that "..people inside buildings should not be placed at greater risk by virtue of their occupancy of the buildings. They should be protected to a risk as low as reasonably practicable." It also states that "buildings should be designed to protect their occupancy against the hazards which might occur with a maximum return period of 10,000 years."

In order to meet the requirement of the CIA guidance, a design load on new buildings must be calculated. This will require a risk assessment to be undertaken. The procedure is that described in the Risk Assessment Methodology section of this paper. The hazard level at the proposed location need only be calculated. The output from the risk assessment is a list of scenarios of predicated frequencies each having a calculated consequence/hazard level at the proposed location. These are combined in a cumulative frequency/hazard relationship, from which the hazard level corresponding to 1 in 10,000 years can be obtained. This hazard level becomes the engineering basis for the building, which must protect its occupants against that hazard.

ASSESSMENT OF EXISITING BUILDINGS

The CIA guidance provides two approaches to determine the extent of any remedial measures to existing buildings - "hazard-based approach" or "risk-based approach".

The hazard-based approach requires specifying the design of a new building against specific hazard effects at that location and comparing this against the existing building. If the comparison determines that the existing building is inadequate for the hazards then remedial measures should be detailed and costed. The remedial measures should be implemented if determined to be reasonably practicable.

The risk-based approach requires a full QRA as described in the Risk Assessment Methodology section of this paper. Possible improvement measures should be identified along with their cost of implementation. A cost-benefit analysis can then be applied.

COST-BENEFIT ANALYSIS

Performing a cost-benefit analysis requires the adoption of a "value of a statistical life". The monetary value of life taken from the draft R2P2 document (4) is £900,000. The principle of cost-benefit analysis is that if the cost of implementation and benefit of an improvement in terms of monetary value of statistical lives saved are roughly in balance then the improvement should be implemented. The improvement only becomes unjustified when the improvement costs are grossly disproportionate to the benefit. A further element, which should be considered, is the application of a gross disproportion factor. This is a multiplier which should be applied to the value of a statistical life to take account of aversion to high risk. HSE guidance suggests a factor of up to 3. Individual companies may also wish to assess monetary values for other types of risks, such as, lesser human injuries, business/environmental disruption, environmental clean up etc..

CASE STUDY EXAMPLE: UK HAZARDOUS INSTALLATION

The following case study provides an example of the application of the CIA guidance to the design and location of occupied buildings on chemical manufacturing sites.

QRA was used to calculate the risk of fatality to personnel in existing plant buildings on the site in order to assess the acceptability of the risk and make decisions on additional risk reduction measures.

The installation contains the following occupied buildings:

- Control room
- Maintenance workshop

For the assessment, the location midway between the control room and the maintenance workshop has been used.

The hazard sources and substances selected for the assessment were defined before the risk assessment was undertaken. The hazard sources were as follows:

- Process units
- Bulk tank storage

In this study the hazardous substance was taken to be naphtha.

For each of the hazard sources, the assessment identified the type of hazards that may lead to an adverse effect e.g. pool fire, BLEVE, fire ball and overpressures. The hazards were calculated on the following basis:

HAZARD ASSESSMENT: BLEVE

- Size of fireball

Much of the guidance available for calculating the size of the fireball is based on data derived for LPG(5). This work has been extended to cover flammable substances other than LPG and allows the radius of the sphere to be calculated using:

$$R = AM^{0.33}$$

Where

R = the radius of the fire ball (m)
M = mass of flammable substance involved (tonnes)
A = a substance specific parameter

In the case of naphtha, the following relationship has been used:

$$R_{\text{, naphtha fire ball}} = 30.4\,(M)^{0.33}$$

- Fireball duration

Fireball duration can be calculated using either of two expressions, depending on the fuel inventory.

$$t_{\text{, fire ball}} = \frac{4.5 \times A \times M^{0.33}}{29}$$

Where

t = the fire ball duration (seconds)
A = the substance specific parameter above
M= the mass of flammable substance involved (tonne)

Or if the mass of fuel is above 37 tonnes then

$$t,\ \text{fire ball} = \frac{8.2 \times A \times M^{0.167}}{29}$$

- Emissivity of the flame

The surface emissive power of the flame is related to the vessel burst pressure thus:

$$E = 235P^{0.39}$$

Where

E = the surface emissive power (kWm^{-2})
P = vessel burst pressure (MPa)

- Incident thermal flux

The incident thermal flux is calculated using:

$$I = E \times F \times T$$

Where
I = the incident thermal flux (kWm^{-2})
E = the surface emissive power of the fire ball (kWm^{-2})
F = the view factor representing the portion of energy received by the target determined by the geometry. A number equal to or less than 1. F is given by $N/(N^2+ 1)^{1.5}$ where N = distance to target/radius of fire ball
T = the absorptivity of the atmosphere. This varies according to the humidity and carbon dioxide content. A number less than 1 and conservatively taken as 1 is used in these calculations.

It should be noted that inventory levels within the process units were examined at normal operating level or at three other nominal fill levels: 100%, 50% and 25% of the vessel capacity.

HAZARD ASSESSMENT: POOL FIRES
A pool fire radiates heat from the flame to its immediate surroundings. The amount of heat, (the heat flux) received by a person (the target) depends on:
The size of the flame which in turn depends on:

- the area of the pool
- properties of the fuel - the heat of combustion and the rate of burning of the fuel surface
- the heat given out by the flame (the emissivity)
- the quantity of heat absorbed by the atmosphere (the transmissivity).

The potential exposure requires the determination of the flame height above a pool and then the heat received by the target. The flame height can be calculated from the diameter of the pool and the rate of heat evolution. The method follows guidance from the Society of Fire Protection Engineers(6).

The height of a flame can be found from:

$$\frac{H_{flame}}{D} = 42\left[\frac{m''}{\rho(gD)^{0.5}}\right]^{0.61}$$

Where

H_{flame} = the height of the flame (m)
m'' = the mass burning rate (kg m^{-2} s^{-1});
D = the diameter of the circle of equivalent area to the bund (m)
G = acceleration due to gravity.

The incident flux on a target is given by:

$$Q_I = \tau \phi Q_S$$

where

Q_I = the incident flux received by a target (kWm^{-2})

Q_s = the source flux (kWm^{-2}), 130 kWm^{-2} for a typical flame for a 1 m diameter pool. This is pessimistic as it drops with increasing size (56 kWm^{-2} for a pool 10 m diameter(6)). 100 kW m^{-2} has been used.

τ = the transmissivity through air (between $0 \le \tau \le 1$ and assumed pessimistically as 1)

ϕ = the view factor - how the target sees the source, between $0 \le \phi \le 1$ and given by

$$\phi = \frac{A_{flame}}{\pi L^2}$$

where

A_{flame} = the cross section area of the flame viewed by the target (m^2)

L = the distance of the target from the source (m)

The view factor for the respective distances from the poolfire to the target buildings have been calculated and the incident flux at the target evaluated.

Pool fires must take into account potential overflow of flammable material from bunded areas.

HAZARD ASSESSMENT: BLAST OVERPRESSURE

The TNT equivalence method of evaluating the potential hazard from blast has been used. This equates the energy of the gas cloud to an equivalent mass of TNT. Knowing the TNT equivalence and the distance to the target, a blast overpressure can be calculated (7).

To calculate the TNT equivalence, the energy release from a given mass of naphtha on complete combustion is required and then adjusted to account for the efficiency of the explosion thus:

$$TNT_{\text{naphtha equiv}} = \frac{\text{mass of naphtha} \times 0.04 \times \text{heat of combustion}_{\text{naphtha}}}{\text{heat of combustion}_{\text{TNT}}}$$

Work by British Gas and others indicate that in order to evaluate the energy release from a VCE, only that part of the gas cloud which is surrounded by confining structures should be used.

This TNT equivalent needs to be related to the potential overpressures and this is achieved by scaling. The scaling is referred to as a scaled distance and takes account of the actual distance from the gas cloud centre and the cube root of the TNT equivalent.

$$\text{Scaled distance} = \frac{\text{distance from centre of gas cloud}}{(TNT_{\text{equivalent}})^{0.333}}$$

Using the graphs linking scaled distance to overpressure, values of the overpressure can be determined(7).

RESULTS OF ASSESSMENT

The individual risk of fatality for personnel in the occupied buildings arising from blast overpressure and thermal radiation is summarised in Table 1 and 2. The overall calculated risks are as follows:

Control Room and Maintenance Workshop - $2.4 * 10^{-5}$ / year (24 hour occupancy)

Table 1: Risk Values for Blast Overpressure

Plant	Event Frequency	Overpressure kPa	Vulnerability	Occupancy	Individual Risk
No A & No B	1.00E-04	12	0.09	0.24	2.16E-06
No A & No B	1.00E-04	12	0.09	1	9.00E-06
No C	1.00E-04	5.5	0.014	0.24	3.36E-07
No C	1.00E-04	5.5	0.014	1	1.40E-06
No D	1.00E-04	4.3	0	0.24	0.00E+00
No D	1.00E-04	4.3	0	1	0.00E+00
				24 hr Risk	1.03E-05

Table 2: Risk Values for Thermal Radiation

Plant	Event Frequency	Plant Item	Thermal Dose Unit	Probability of Fatality	Occupancy	Individual Risk
No A	1.00E-04	Column	1425.32	0.09	0.24	2.16E-06
No A	1.00E-04	Column	1425.32	0.09	1.00	9.00E-06
No B	1.00E-04	Column	1202.42	0.04	0.24	9.60E-07
No B	1.00E-04	Column	1202.42	0.04	1.00	4.00E-06
No B	1.00E-04	Column	825.61	0	0.24	0.00E+00
No B	1.00E-04	Column	825.61	0	1.00	0.00E+00
No D	1.00E-04	Column	891.25	0	0.24	0.00E+00
No D	1.00E-04	Column	891.25	0	1.00	0.00E+00
LPG	3.33E-05	Tank (100%)	1035.42	0.02	0.24	1.60E-07
LPG	3.33E-05	Tank (100%)	1035.42	0.02	1.00	6.66E-07
LPG	3.33E-05	Tank (50%)	525.68	0	0.24	0.00E+00
LPG	3.33E-05	Tank (50%)	525.68	0	1.00	0.00E+00
LPG	3.33E-05	Tank (25%)	253.11	0	0.24	0.00E+00
LPG	3.33E-05	Tank (25%)	253.11	0	1.00	0.00E+00
No A	1.00E-04	Reflux Drum	253.96	0	0.24	0.00E+00
No B	1.00E-04	Reflux Drum	253.96	0	1.00	0.00E+00
No B	1.00E-04	Reflux Drum	210.45	0	0.24	0.00E+00
No B	1.00E-04	Reflux Drum	210.45	0	1.00	0.00E+00
No C	1.00E-04	Reflux Drum	295.87	0	0.24	0.00E+00
No C	1.00E-04	Reflux Drum	295.87	0	1.00	0.00E+00
No D	1.00E-04	Reflux Drum	129.77	0	0.24	0.00E+00
No D	1.00E-04	Reflux Drum	129.77	0	1.00	0.00E+00
No A	1.00E-04	Bund	199.00	0	0.24	0.00E+00
No A	1.00E-04	Bund	199.00	0	1.00	0.00E+00
No B	1.00E-04	Bund	268.00	0	0.24	0.00E+00
No B	1.00E-04	Bund	268.00	0	1.00	0.00E+00
No A & No B	1.00E-04	Bund	375.00	0	0.24	0.00E+00
No A & No B	1.00E-04	Bund	375.00	0	1.00	0.00E+00
					24 hr Risk	1.37E-05

Individual risk (IR) values have been calculated on the basis of the following expression:

Individual risk = event frequency x probability of fatality x building occupancy.

The event frequencies were based on generic frequency data for major fire/explosion in non-cracker or coker processing units.

For the purposes of calculating individual risk of fatality, consequences in terms of thermal dose units $[s(kWm^{-2})^{4/3}]$ have been converted into a probability of fatality using the Eisenberg probit relationship
$Y= 2.56Ln([s(kWm^{-2})^{4/3}]) - 14.9$. The Vulnerability of personnel is dependent upon the blast overpressure and the type of building involved. For this study, the vulnerability curve in the CIA guidance has been used[1]. Commissioned by HSE, W. S. Atkins developed the vulnerability curve after assessing several buildings of the type typically located on or around chemical sites. There are some uncertainties with the use of such data and the users of the vulnerability curve should satisfy themselves that the basis assumed and the limitations of the W. S. Atkins report [8] is acceptable for the risk assessment undertaken.

For the purposes of this case study, personnel have been assumed to be in the buildings either 24 hours a day, 7 days a week, or normal working hours (building occupancy factors 1.0 and 0.24 respectively).

Tables 3 and 4 provide data on the consequences and cumulative event frequencies

Table 3: Blast Overpressure Consequences and Cumulative Frequency

Plant	Event Frequency	Consequence (Overpressure) at Location	Cumulative Frequency
No A & No B	1.00E-04	12	1.00E-04
No C	1.00E-04	5.5	2.00E-04
No D	1.00E-04	4.3	3.00E-04

Table 4: Thermal Radiation Consequences and Cumulative Frequency

Plant	Plant Item	Event Frequency	Consequence (Flux) at Location	Cumulative Frequency
No A	Column	1.00E-04	53.22	1.00E-04
No B	Column	1.00E-04	48.12	2.00E-04
No D	Column	1.00E-04	38.44	3.00E-04
No C/1	Column	1.00E-04	30.75	4.00E-04
LPG	Tank	3.33E-05	30.66	4.33E-04
No A	Reflux Drum	1.00E-04	24.65	5.33E-04
LPG	Tank	3.33E-05	21.88	5.67E-04
No B	Reflux Drum	1.00E-04	21.41	6.67E-04
No C/1	Reflux Drum	1.00E-04	21.24	7.67E-04
LPG	Tank	3.33E-05	15.02	8.00E-04
No D	Reflux Drum	1.00E-05	14.93	9.00E-04

ACCEPTABILITY OF RISK

The calculated risks associated with operations at the installation are between the upper (intolerable) and lower (acceptable) risk thresholds as defined in the CIA guidance (1×10^{-4} and 1×10^{-6} per year respectively). The risks associated with operation of the plant are therefore judged to be acceptable, provided that all reasonably practicable measures have been taken to reduce risks.

DESIGN BASIS EVENTS

The CIA[(1)] and HSE[(2)] guidance require that an assessment be made of the withstand capability of the buildings against a 1:10000 year return event. Tables 3 and 4 present the QRA data in terms of consequences and cumulative frequency for blast overpressure and thermal radiation respectively.

The 1:10000 year return events for the control room and maintenance workshop are approximately 12 kPa and 53.22 kWm^{-2} for blast overpressure and thermal radiation respectively.

RISK REDUCTION MEASURES

The following risk reduction measures have been identified to reduce the risk of fatality for on-site personnel in the occupied buildings. These are detailed below with the approximate cost of implementation.

- No A & B column size reduction (£66k)
- Fire proof columns and reflux drums (£44k)
- Refuges at rear of office and side of control room (£90k)
- Blast proof control room (£170k)
- Replace window frames & install laminated safety glass on both buildings (£123 k)
- Install gas detection and automatic boiler shutdown system plus water spray barrier (69 k)
- Blast proof film applied to all windows (£7100)
- Install heat proof glass on both buildings (ca £123k)

A cost-benefit analysis has been carried out using the following data:

Monetary value of life = £900,000 (Taken from draft R2P2 document[(3)].
Gross disproportion factor = 2
Life of plant = 50 years

Number of staff (full time equivalent) in control room = 5
Number of staff (full time equivalent) in maintenance workshop = 4

For the purposes of initial screening, it has been assumed that all potential mitigation measures would produce maximum benefit i.e. reduce the risk to zero. On this basis, the justifiable spend for each building is as follows:

Control room = £22500
Maintenance workshop = £16900

On the basis of this initial assessment, the only additional protection measures not screened out are as follows: blast proof film applied to all windows and provision of heat proof glass to affected windows

In the case of the maintenance workshop, it is proposed that the only additional risk reduction measure which should be applied is the provision of blast proof film to all building windows. This is in keeping with best practice on installations subject to explosion hazards and is intended to maintain the integrity of the windows in the event of overpressure and hence assist safe escape. It is considered that other protection measures related to protection from thermal radiation are not justified on the basis that the building complies with the appropriate fire safety regulations, thereby aiding safe escape.

It is considered that additional risk reduction measures do need to be undertaken in the case of the control room because this facility is required to manage any post accident situation. Risk reduction in terms of ensuring that the control room will withstand design basis events is considered below:

The assessment indicates that the existing control room will not withstand design basis events in terms of 1:10000 year return thermal fluxes and blast overpressure. Since the control room is needed for post accident management, it is proposed that adequate protection be provided to enable such operations to be carried out. With the plant as is, the control room would need to withstand a thermal radiation flux of 53.22 kWm^{-2} and a blast overpressure of 12 kPa. The current construction, comprising a timber portacabin with standard glass, does not provide the required protection.

In order to provide the required control room withstand capability in terms of thermal radiation, it is proposed that suitable heat resistant glass be fitted with the additional provision that the windows be made non-opening. In order to provide the required blast protection, the recommendation is to install plant flammable gas detection plus automatic shutdown of the boiler house and installation of a protective water spray barrier. This will remove the only strong ignition source from the site and lower the design basis blast loading on the control room to 3 kPa. The building will survive this loading.

In the event that the above combination of measures is impracticable, then an alternative solution would be to provide a blast proof control room. Such a construction would also provide the necessary protection from thermal radiation.

The above cost-benefit analysis process can also be applied to other types of risks, such as, lesser human injuries, business/ environmental disruption, environmental clean up etc.

CONCLUSIONS

This paper provides an example of the application of the CIA guidance for the location and design of occupied buildings on chemical manufacturing sites(1).

The guidance assesses the risk of fire, explosion or toxic gas release to building occupants on chemical manufacturing sites in both new and existing occupied buildings. The aim is to assess the risk to people inside buildings and ensure that risks are as low as is reasonably practicable. In addition, personnel in buildings required to carry out emergency response actions should be adequately protected from design basis events in order to carry out their functions. A case study is presented which shows how to carry out a QRA and design basis assessment and also demonstrates the techniques to be used in considering additional building protection.

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