

A RISK BASED APPROACH TO HUMAN VULNERABILITY MODELLING AND OCCUPIED BUILDING ANALYSIS

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Recent accidents like Buncefield and Texas City have put risk to people from explosion high on the agenda, particularly with respect to risks to those in buildings. Regulatory regimes for land use planning and occupied buildings are becoming more demanding and the need for accuracy and transparency has increased. For example, regulatory guidelines like API RP752 and RP753 provide guidance on the design and location of permanent and portable buildings to minimise risks to occupants. This paper focuses on advances in software models for assessing risks to people in buildings from releases of hazardous materials, particularly those which are flammable and may result in VCE's creating large overpressures.

When deciding on the location and construction of occupied buildings in the vicinity of hazardous installations, a number of factors must be considered during the design and operational phases. Key to the process of deciding where to locate buildings and what level of protection they should offer their occupants are the level of risk to which it is acceptable to expose those occupants. Traditional QRA tends to use "generic" vulnerability for people indoors where their probability of death when particular levels of different types of hazardous effects are exceeded, such as explosion overpressure, radiation from fires, flame impingement or toxicity, is treated as being independent of the type of building within which they reside. This is obviously a significant limitation to using the results of traditional QRA in selecting appropriate building types in different situations or to locate buildings in the safest place from the standpoint of risk to occupants. Risk to individuals within buildings is a function of both building location and construction. In order to minimise risk to personnel in the most cost effective way, plant designers and safety managers need to be able to compare and assess different options with ease.

This paper describes recent advances to the vulnerability modelling capabilities of the Phast Risk QRA tool. These new features enable individual definition of building types and associated occupant vulnerability. In addition, GIS facilities allowing analysts to locate buildings of a particular type in various locations help ensure overall risks can be minimised, or location specific risks for particular buildings can be assessed. A case study and some hypothetical explosion risk scenarios using the Multi Energy explosion model (Cavanagh et al., 2009; Cavanagh, 2010) illustrate the application of the new vulnerability modelling to selecting suitable building types, and locating them in the most appropriate position to minimise the fatality risks to occupants. In addition, techniques are described for using these tools and methods to help locate and design buildings to withstand the possible explosion and radiation loads they may be subjected to.

INTRODUCTION AND BACKGROUND

Through the history of the process industry there have been a significant number of incidents where accidental releases of flammable material have lead to fires and/or explosions resulting in multiple fatalities, both on-site and off-site. At Flixborough in 1974, a cloud of cyclohexane more than 100m in diameter exploded destroying the plant, damaging around 1,800 buildings up to a mile from the site and resulting in 28 fatalities, 18 in the control room, 36 injuries and a further 53 reported injuries off-site. Had this explosion occurred on a weekday, it has been estimated that more than 500 employees would have been killed. This was Britain's biggest ever peacetime explosion until the Buncefield Depot explosion in 2005.

Other incidents where explosions have resulted in significant fatalities and property damage include the Enschede firework explosion in The Netherlands (May 2000) with 22 fatalities and 947 injuries, the explosion at Phillips Petroleum's Houston Chemical Complex in Pasadena, Texas (March 2000) resulting in one fatality and 71 injuries, the Total Petrochemicals plant explosion in Toulouse, France (September 2001), resulting in 29 fatalities, 2,500 serious injuries and 8,000 light casualties and the Fluxys natural gas pipeline explosion near Brussels in Belgium (July 2004) resulting in at least 15 fatalities and 122 injuries. More recently a major explosion at BP's Texas City oil refinery resulted in 15 fatalities and more than 170 injuries.

Just as Flixborough was the catalyst for guidelines issued by the CIA, for example, on the siting and design of control rooms, Texas City became a key driver in the assessment of the validity of API RP 752 for the management of hazards associated with location of process plant buildings, and the subsequent development of API RP 753 for the management of hazards associated with the location of process plant portable buildings, which had been left largely to the discretion of the individual operators under

API RP 752. Although it resulted in no fatalities, the Buncefield Depot explosions, which occurred in the early hours of Sunday 11th December 2005, resulted in more than 40 people being injured. At least one of the initial explosions was of massive proportions, the largest peace time explosion in the UK as mentioned above. This was followed by a large fire, which engulfed a high proportion of the site and burned for several days, destroying most of the site and releasing large clouds of black smoke into the atmosphere. It was fortunate that this occurred early on a Sunday morning when there were few people around the site; otherwise there could have been tens or hundreds of fatalities. However, it has been suggested that all the factors leading to the particular outcome may not have remained unchanged had it occurred at a busy time in normal working hours (e.g. The odour from overflowing gasoline may not have gone unnoticed for three hours in the adjacent car park on a busy work day).

As a result of these and similar accidents, and the need to continuously improve safety performance and reduce risk, the location and design of occupied buildings on or around hazardous facilities has been a recurring theme. As regulation has evolved, focus has increased on the accuracy with which the effects of explosions on people, whether in buildings of a particular type or in the open-air, can be estimated.

As mentioned previously, in essence, the prediction of such effects has three distinct steps as follows:

Step 1 – Predict the extent and movement of the Vapour Cloud and its interaction with areas of congestion
Step 2 – Predict the overpressures generated if the cloud is ignited whilst moving through a congested region
Step 3 – Predict the effects of the overpressure and impulse on people in the vicinity of the explosion, both indoors and outdoors.

Many models are available, like Phast for example, to predict the behaviour of dispersing gas clouds, and Step 1 is well understood and documented. Cavanagh et al., 2010, described the implementation of two models for quantifying step 2 (the Multi Energy Method and the Baker Strehlow Tang Model) in the standard Phast Risk process QRA software model (Cavanagh, 2001; Witlox and Worthington, 2002).

But, of equivalent relative importance to the overall calculation of fatality risk is the vulnerability of individuals to effects such as radiation, explosion overpressure and toxicity. If you have accurate prediction of Steps 1 and 2, but inaccuracy in assessing the impact of these effects on people, then your assessment of risks to people will also be inaccurate and of less value to designers and risk analysts in making decisions. Converting harmful effects into rates of fatality and injury is commonly referred to as "vulnerability modelling". This paper focuses on the importance of human vulnerability modelling to calculating risks and how this has been facilitated in a "transparent" way in the most recent release of the Phast Risk QRA package.

OCCUPIED BUILDINGS AND VULNERABILITY MODELLING

Once the behaviour of a release of flammable material has been predicted in terms of initial discharge from storage, subsequent dispersion into the atmosphere and possible consequences of the resulting cloud, in this case from explosions and fires, one then needs to assess the effects on the population. Converting harmful effects into rates of fatality and injury is commonly referred to as "vulnerability modelling" and there are a number of published vulnerability models for toxic, flammable and explosion effects (see, for example Bevi Reference Manual, 2009). In the case of VCE's we are mainly interested in the effects of the damaging overpressures, flames and radiation, as described above, on people. The vulnerability models described here are used to calculate probability of death based on the results of the explosion models discussed earlier and standard models available in Phast for a range of fire types including jet-fires, pool-fires, flash-fires and fireballs. A number of methods from published literature are described all of which, in principle, can be used in conjunction with any explosion or fire model.

EXPLOSION EFFECTS

Individuals are vulnerable to explosions through a number of damage mechanisms. Causes of death or injury may include impact from flying debris, building collapse, translation impact, burns and irreversible lung damage, for example. Some of these affect individuals outside, some affect individuals in buildings and some affect individuals indoors and outdoors. There has been significant research into explosions for the obvious reasons but also with particular reference to the domain of safety management in the process industry. Both the Green Book (CPR16E, 1992) and a number of HSE sponsored reports (Jeffries et al., 1997(1), Jeffries et al., 1997(2) and Galbraith, 1998) provide information on the possible mechanisms through which people and buildings can be harmed by explosions.

Of particular interest when performing hazard analysis or QRA is estimation of the probability of death from information about explosion strength. Guidance on this topic is provided by a number of sources including, CCPS (1994), CIA (1998), API (2003) and BEVI (2009). Each of these provides guidance on how to calculate probability of death from overpressure and/or impulse results from explosion models such as those described above. Such methods are referred to generically as vulnerability models.

One of the simplest models for modelling vulnerability when calculating measures of risk, and that used up to now in the Phast Risk QRA model, is the Purple Book method (CPR18E, 1999), where discrete overpressure levels of 0.1 and 0.3 barg represent a given probability of death for individuals indoors or outdoors. This is summarised in Figure 1, reproduced from Figure 2 in The Purple Book, where P_E is the probability of death and $F_{E,in}$ and $F_{E,out}$ represent the indoor and outdoor lethality from overpressure effects.

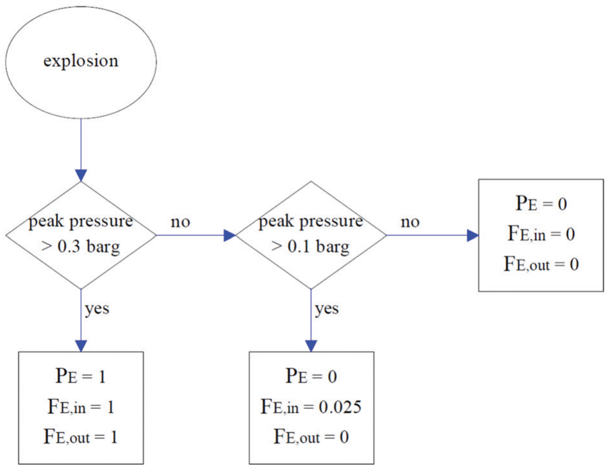

Figure 1. Discrete overpressure vulnerability levels from CPR18E (1999)

In the Phast Risk model, until recently indoor and outdoor risk was calculated globally giving separate indoor and outdoor risk measures. This allowed the modelling of buildings of one type at a time but it was difficult to combine effects for different types of building (for instance portable and reinforced buildings). However, the recent extensions to the model described above allow individual buildings to be defined with specific vulnerability data providing a much more accurate picture of the risks to which those within occupied buildings are exposed. A continuing limitation of adopting the generic discrete overpressure approach described above is that all buildings are treated as offering the same levels of protection to their occupants. However, in practice this will not be the case since one would expect a brick structure, for example, to offer greater protection to its occupants than an equivalent dimensioned timber structure.

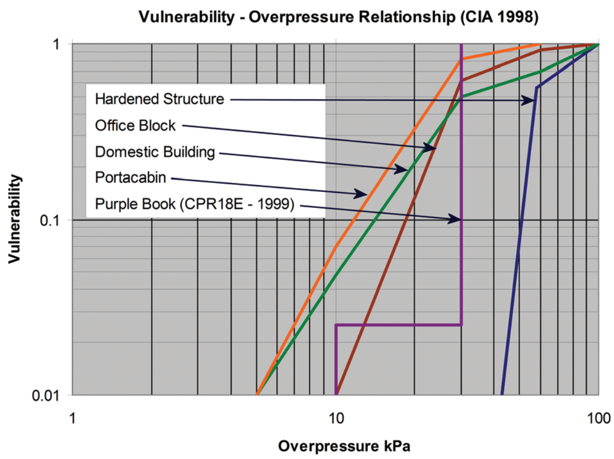

Figure 2. Vulnerability at various overpressure levels for a range of building types (CIA, 1998)

The model has therefore been extended to take account of buildings offering specific levels of protection at given levels of blast overpressure. For example, the CIA (1998) guidelines specify the vulnerability characteristics for four different building types, as follows:

Building Type	Description
Type 1 – Hardened structure	Special blast proof construction – no windows
Type 2 – Typical office block	Four storey, concrete frame and roof, brick block wall panels
Type 3 – Typical domestic building	Two storey, brick walls, timber floors
Type 4 – Portacabin	Single storey, timber construction

For each building type there is a correlation between overpressure and vulnerability, as illustrated in Figure 2. In common with the "discrete" method from the Purple Book, this method is based on peak side-on overpressure alone but the provision for different building types each with its own vulnerability (conditional probability of death) as a continuous function of overpressure provides a far more rigorous analysis. In fact, since this has been implemented in a generic fashion whereby any pressure-vulnerability relationship can be associated with a user defined building type, this methodology will also support other guidelines on the design and location of occupied building subject to explosion hazards such as API RP 752 (API 2003) for process plant buildings and API RP 753 (API 2007) for process plant portable buildings. However, it is worth noting that this is only true if the underlying data on which the continuous function is based is sound and covers the range over which the continuous function will be used. As always, accuracy of results will be critically dependant on the quality of the background data on which these are founded.

The methods described above consider overpressure criteria only, whilst it is apparent from the literature that both overpressure and impulse are important in assessing the response of buildings to blast waves. Vulnerability can be expressed as a function of both overpressure and impulse, whereby, for a given overpressure, vulnerability increases with impulse or, for a given impulse, vulnerability increases with overpressure. In this case vulnerability is a function of two variables, impulse and over pressure. Typical pressure-impulse curves can be found in The Green Book (CPR16E, 1992) and CCPS guidelines for assessing the effects of VCE's (CCPS, 1994) for particular building types (e.g. brick-built house for instance) or curves can be specifically derived for a particular building in consultation with structural engineers. To apply the overpressure and impulse relationship in this model we provide two methods; the software allows the user to define discretised curves and these provide the basis for interpolation to calculate lethality; there is also another method that takes advantage of the common shape of these curves to define the vulnerability relationship:

$$\log_{10} I_i = \log_{10} I_{0,i} + A_i/(\log_{10} P - \log_{10} P_{0,i})$$

Where I_i is the impulse for a given vulnerability level, i and overpressure level P
$I_{0,i}$ is threshold level of impulse for vulnerability level i
P is the overpressure level
$P_{0,i}$ is the threshold level of overpressure for vulnerability level i
and A_i is a constant used to scale curve shape for vulnerability level i

As many curves as necessary may be defined to reflect the desired number of vulnerability levels, provided use of these can be justified by the quality of the underlying data. The model requires the definition of three points on each curve, typically $P_{0,I}$, $I_{0,I}$ and one other point, and can then be used to estimate vulnerability for a given pressure-impulse either by interpolation or by discrete stepping between given vulnerability levels.

FLAMMABLE EFFECTS

Similarly, should a flammable release ignite forming a jet fire, pool fire, flash fire or fireball one also needs to assess the effects on the population within occupied buildings of the radiation level and the duration over which this level is reached or exceeded. As with overpressure vulnerability, there are also a number of published vulnerability models for these various flammable effects.

PROBIT METHOD

For example, the Dutch Bevi regulation (Bevi Reference Manual, 2009) uses a combination of simple instantaneous exceedance and a probit method. For those exposed to levels above the defined exceedance level (in the case of Bevi 35 kw/m^2) the vulnerability is 1; this zone is referred to as the criteria zone where a fixed exceedance "criteria" is set above which a given vulnerability is applied.

In the Probit zone, below 35 kw/m^2, the method uses the probit approach to flammable consequences. A dose is derived based on the radiation level and duration of the exposure. Then the dose is converted to a probability of death using the probit function. Therefore, for those exposed to levels of radiation below the defined exceedance level, the probability of dying from exposure to heat radiation is given by the probit relationship:

$$\mathrm{Pr} = -36.38 + 2.56 \ln\left(\int Q^{4/3} dt\right)$$

Where Pr is the probit associated with the probability of dying, Q is heat radiation at time t and t is exposure time. P_E, probability of death, is then derived from Pr using the appropriate error function. This is referred to as the Probit zone. This approach is summarised in Figure 3, reproduced from CPR18E (1999), and the Table below, reproduced from Bevi Reference Manual, 2009. Typical vulnerability data input for this method is shown in Figure 4

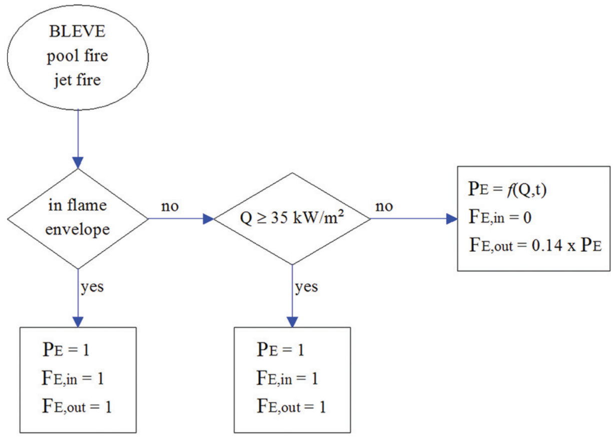

Figure 3. Probability of death, P_E for exposure to a BLEVE, pool fire and jet fire, where fractions of population dying indoors and outdoors are FE, in and FE,out respectively

Area	Location-specific Risk	Societal risk Inside	Societal risk Outside
flame zone	1	1	1
heat radiation > 35 kW/m^2	1	1	1
heat radiation < 35 kW/m^2	PE	0	0.14 × PE

The risk is calculated from the probability of death, $P_{E,}$, and the vulnerability factors (F_E) which vary by type of risk and radiation level. The logic behind this approach is that if the intensity is high enough it will cause combustion, setting clothes and buildings alight. The resulting variation of the probability of death may be viewed as a function of radiation level and exposure time as shown in Figure 5. There is a step change at 35 kW/m^2 where the lethality jumps to 1 for all exposure times. The relationship between P_E and radiation intensity is shown for exposure times of 20, 15, 10 and 5 s.

INTENSITY METHOD

This is a more straight forward method of associating vulnerability with radiation level and exposure time and is analogous with the discrete over-pressure method for explosion vulnerability. The inputs to this method are radiation intensity and exposure time, as shown in Figure 6.

Probability of Death as a Function of Radiation and Exposure Time are provided in tabular form and vulnerability must increase with radiation intensity. The minimum exposure time necessary to cause this level of harm must also be provided and this time is common to all intensity levels. When the model calculates vulnerability it uses the

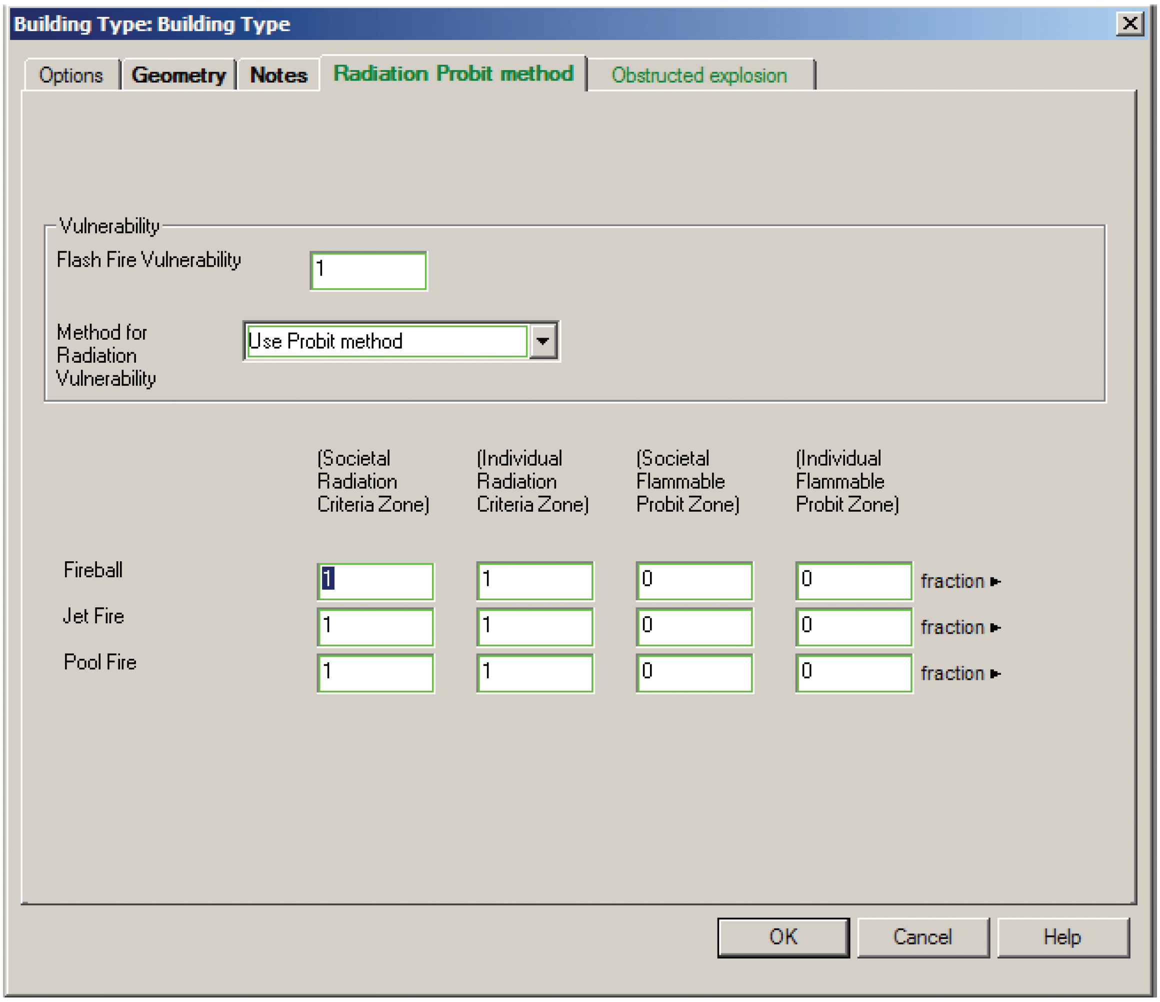

Figure 4. Typical building vulnerability data input when using flammable probit method

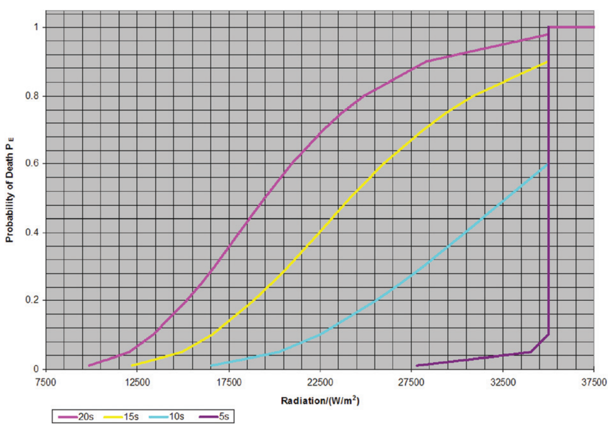

Figure 5. Probability of Death as a Function of Radiation Intensity and Exposure Time using Purple Book probit constants ($a = -36.38$, $b = 2.56$, $n = 4/3$)

observed radiation level and exposure time to assess the vulnerability according to the table. There is no interpolation so the model behaves as a step function. For example, based on Figure 7, radiation levels in the range 4 kW >= Intensity <12.5 kW will have a vulnerability of 0.1 according to the table shown. Below the lowest intensity level in the table the vulnerability is zero and if the exposure time for which a given radiation level persists is less than the required exposure time, again the occupant vulnerability is zero. More detailed information on these methods is provided in the software theory manuals provided with Phast Risk (Worthington, 2010).

CASE STUDIES

A simple QRA case study has been created to illustrate the importance of radiation and explosion vulnerability associated with occupants of different types of building in different locations. Some typical results are presented to illustrate how a range of individual and societal risk metrics can be

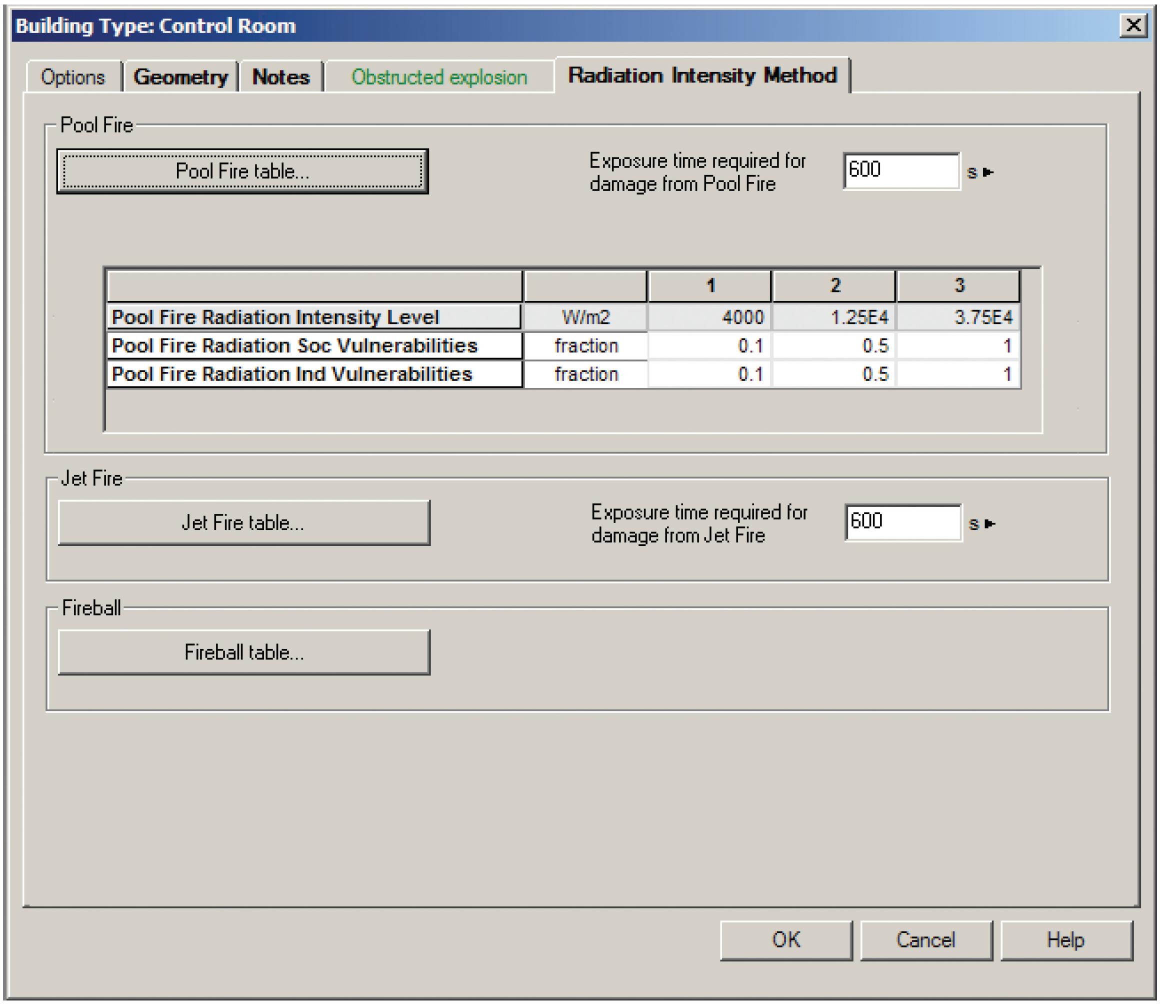

Figure 6. Typical building vulnerability data input when using radiation intensity method

used in deciding on appropriate building design and location, based on minimising risk to occupants – a risk based approach to human vulnerability modelling and occupied building analysis.

The basic case study is illustrated in Figure 8. This represents a simple hydrocarbon processing facility with some areas of congestion which represent explosion hazards and a number of vessels, pipes and other process equipment which represent possible sources of releases of flammable vapour and liquid, thus posing the full range of possible flammable hazards.

Calculations have been made for the "base" case QRA to give overall levels of individual and societal risk. A number of further calculations have then been made to assess the effects on the overall risks of adding control rooms at two different locations. Figure 9 shows the base case FN Curves which are in the ALARP region, and FN curves after the addition of Control Room 1, built to withstand gradually increasing levels of overpressure and considering only the effects of explosion overpressure on this

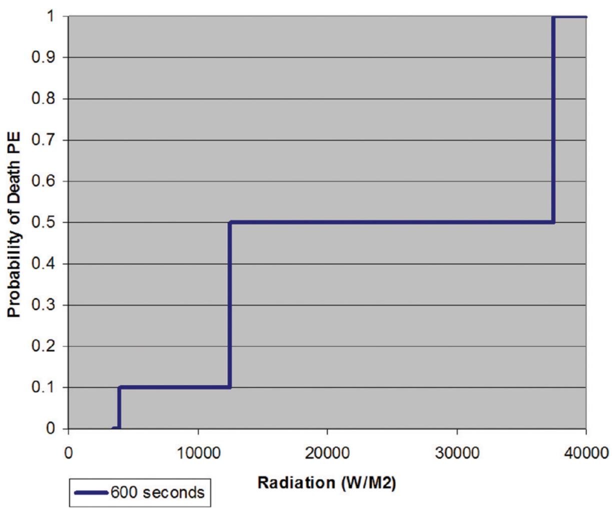

Figure 7. Probability of Death as a Function of Radiation Intensity for Exposure Time of 600s using intensity method

Figure 8. Example storage facility with two possible control room locations

building and its occupants. As can be seen from Figure 9, if the control room is built to withstand an overpressure of less than 0.5 bar, then the level of societal risk moves into the unacceptable region. Therefore, in order to place Control Room 1 as shown it must provide at least this level of blast protection. Furthermore, in order to maintain the level of societal risk close to its existing level, the building should provide protection to 1 bar. Otherwise the operator must show that all reasonable measures have been taken to ensure risks are "As Low As Reasonably Practicable". Figure 10 shows the same results but for Control Room 2 which is further away from the sources of congestion contributing to explosions as illustrated in Figure 8. From this Figure it can be seen that by moving the control room further away, the control room need only have blast resistance to 0.2 bar to maintain levels of societal risk within the ALARP region shown.

It is worth noting at this point that, when using societal risk criteria in this way, these criteria are being used make judgements about the risks to a small fraction of those present at a single establishment from a particular hazard. That said, they still provide a useful tool for assessing the impact on overall risks to particular groups of personnel at individual facilities based on how well they might be protected from the specific hazard.

Considering Individual Risk criteria, Figure 11 shows Individual Risk Contours for a risk level of 1×10^{-6} per year – so-called overpressure exceedance contours. Contours are included based on 1×10^{-6} per year frequency of exceeding overpressure levels of 0.1, 0.2, 0.3, 0.5, 1 and 2 bar. Using these contours, designers can place their control rooms and other buildings based on the combination of acceptable risk to occupants and level of blast protection offered by each building type.

Moving on to consider risks from pool and jet fires from radiation effects, Figure 12 shows the base case QRA results along with results after adding Control Room 1 and considering societal risks to occupants from radiation levels of 4 kW/m^2 and 12.5 kW/m^2 for both pool and jet fires. As can be seen from this figure, societal risks remain within the ALARP region provided that Control Room 1 is constructed to withstand a radiation level of greater than 4 kW/m^2 for more than 600 seconds. It should also be noted that, in order to maintain the levels of societal risk close to those prior to placing Control Room 1, it is preferable that this building is constructed to withstand radiation levels greater than 12.5 kW/m^2 for more than 600s. Considering Individual Risk criteria, Figure 13 shows Individual Risk Contours for a risk level of 1×10^{-6} per year of exceeding levels of radiation from jet fires and pool fires of 4 kW/m^2, 12.5 kW/m^2 and 37.5 kW/m^2 for 600 s duration. Again, based on individual risk criteria, these contours provide guidance on appropriate locations for occupied buildings based on their level of resistance to radiation from fires.

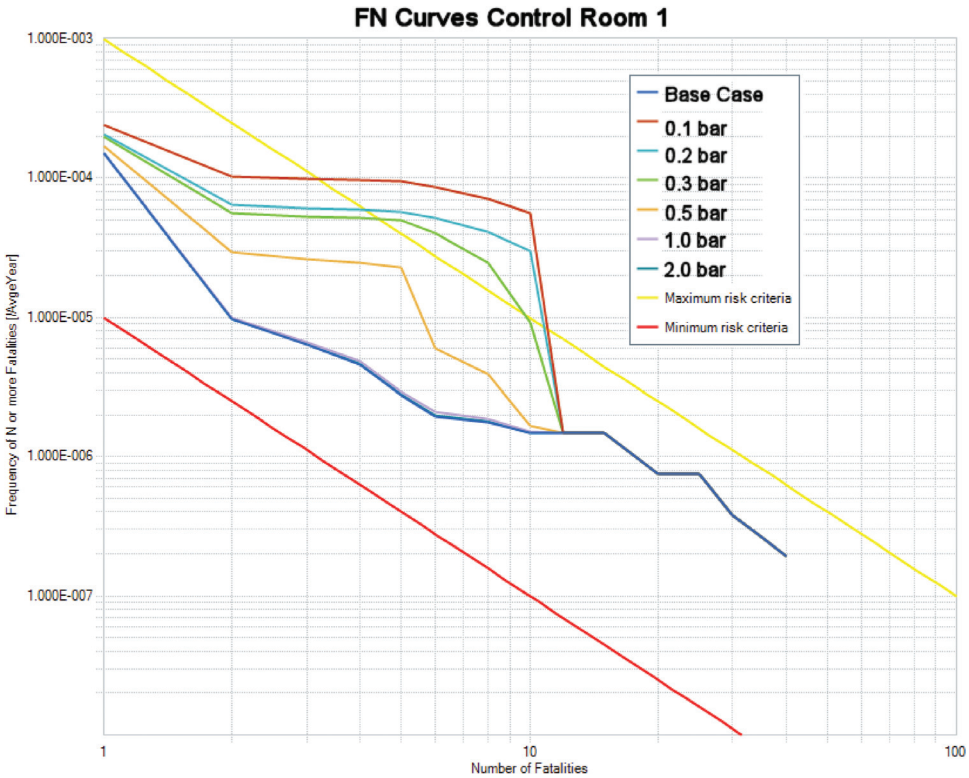

Figure 9. FN Curves for base case and Control Room 1 constructed to withstand overpressures of 0.1, 0.2, 0.3, 0.5, 1 and 2 bar

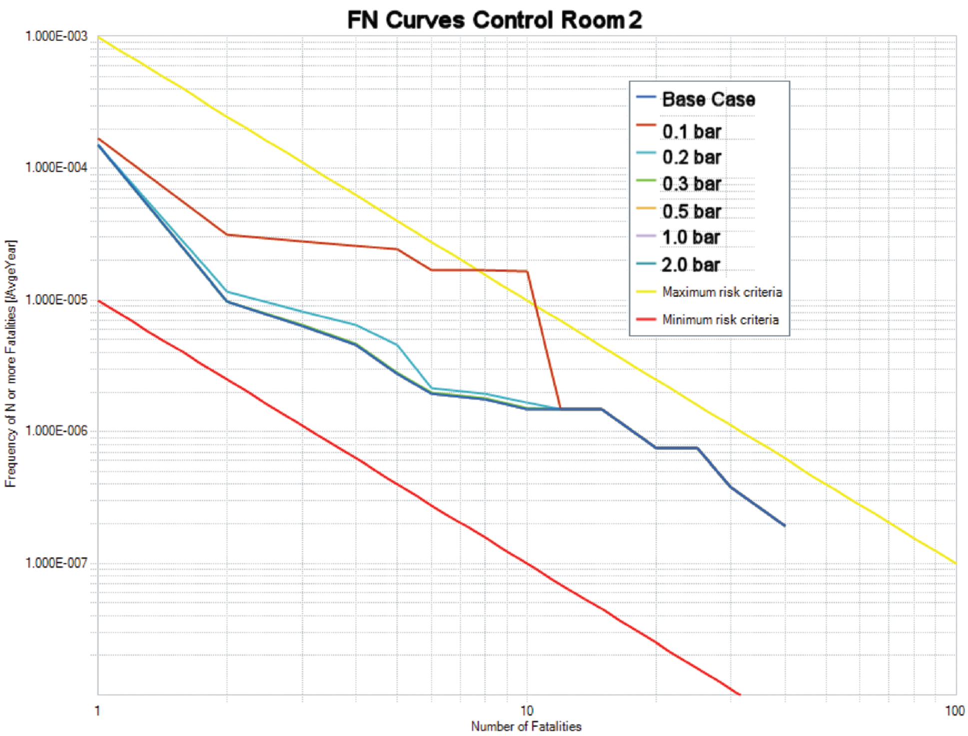

Figure 10. FN Curves for base case and Control Room 2 constructed to withstand overpressures of 0.1, 0.2, 0.3, 0.5, 1 and 2 bar

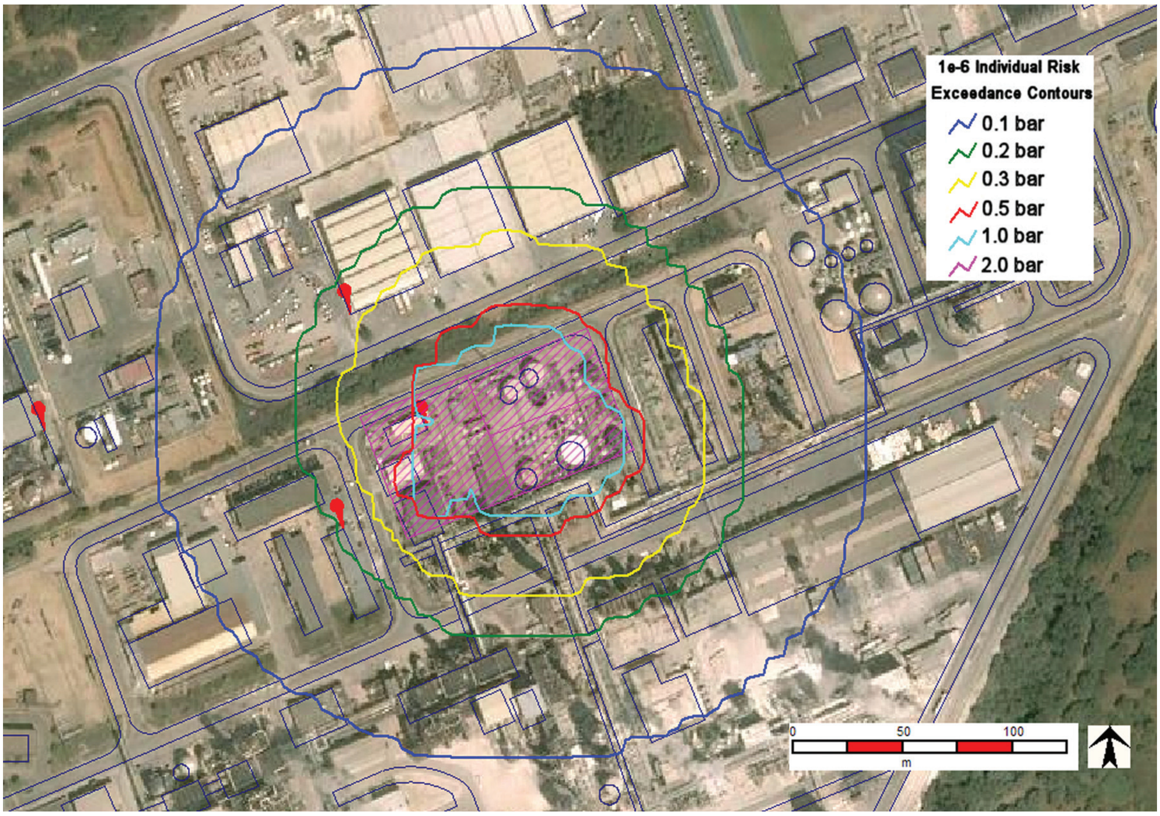

Figure 11. Risk Contours for 1×10^{-6} frequency of exceedance of overpressure levels of .1, 0.2, 0.3, 0.5, 1 and 2 bar

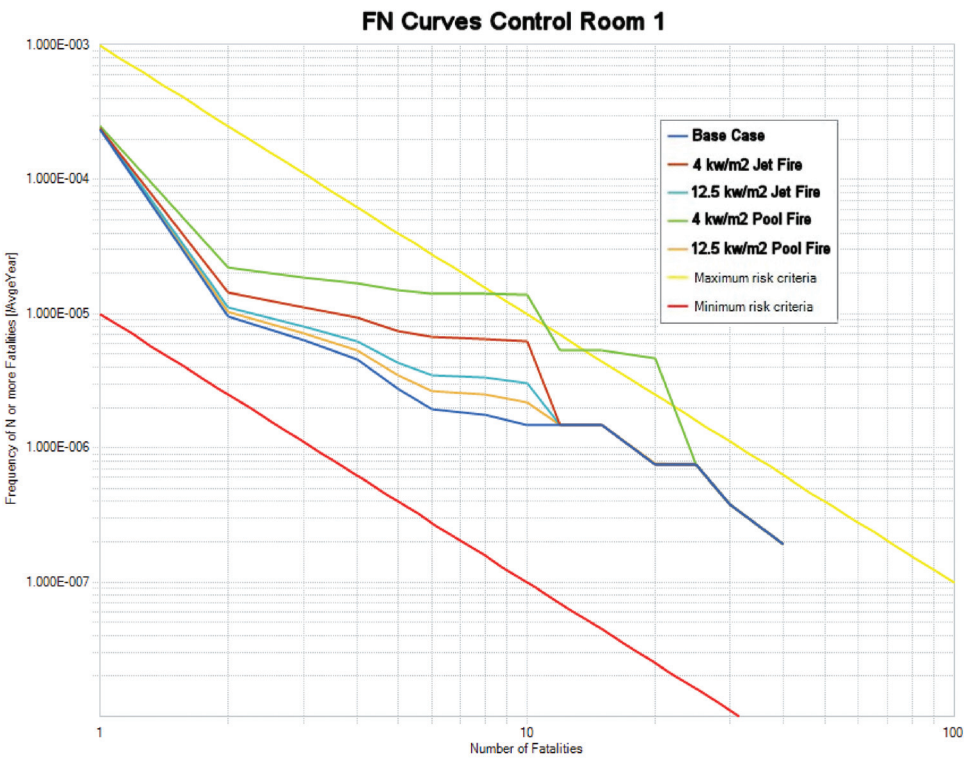

Figure 12. FN Curves for base case and Control Room 1 constructed to withstand jet fires and pool fires of 4 kW/m^2 and 12.5 kW/m^2 for 600 seconds duration

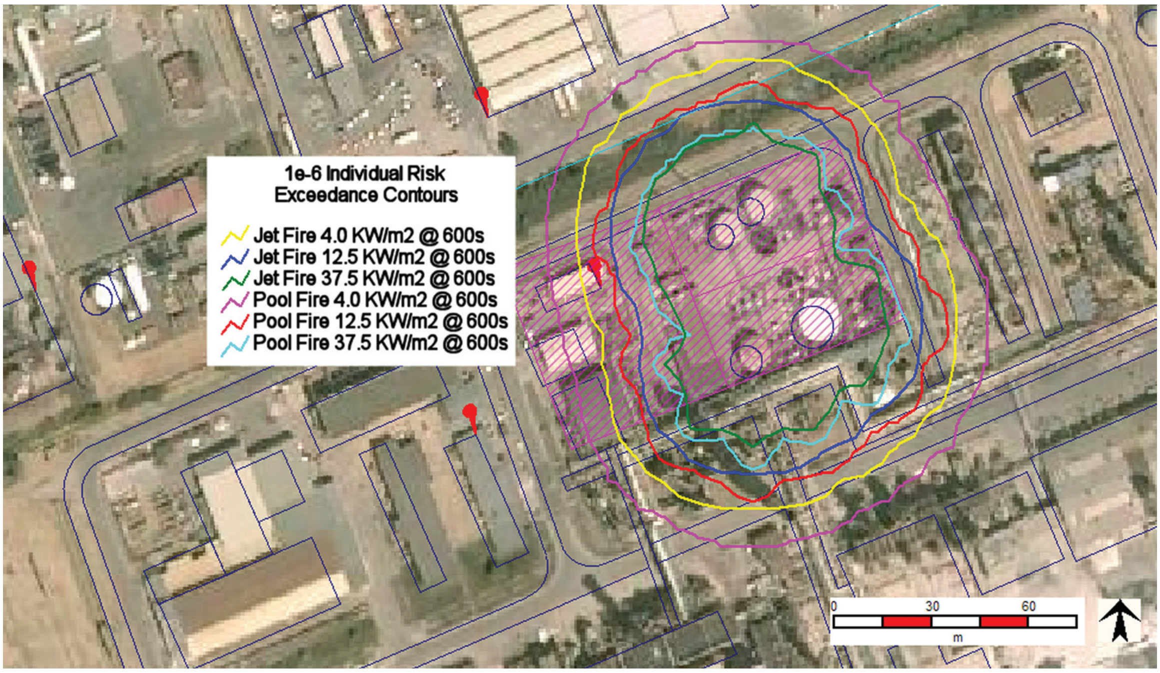

Figure 13. Risk Contours for 1×10^{-6} frequency of exceedance of jet fires and pool fires of 4 kW/m^2, 12.5 kW/m^2 and 37.5 kW/m^2 for 600 seconds duration

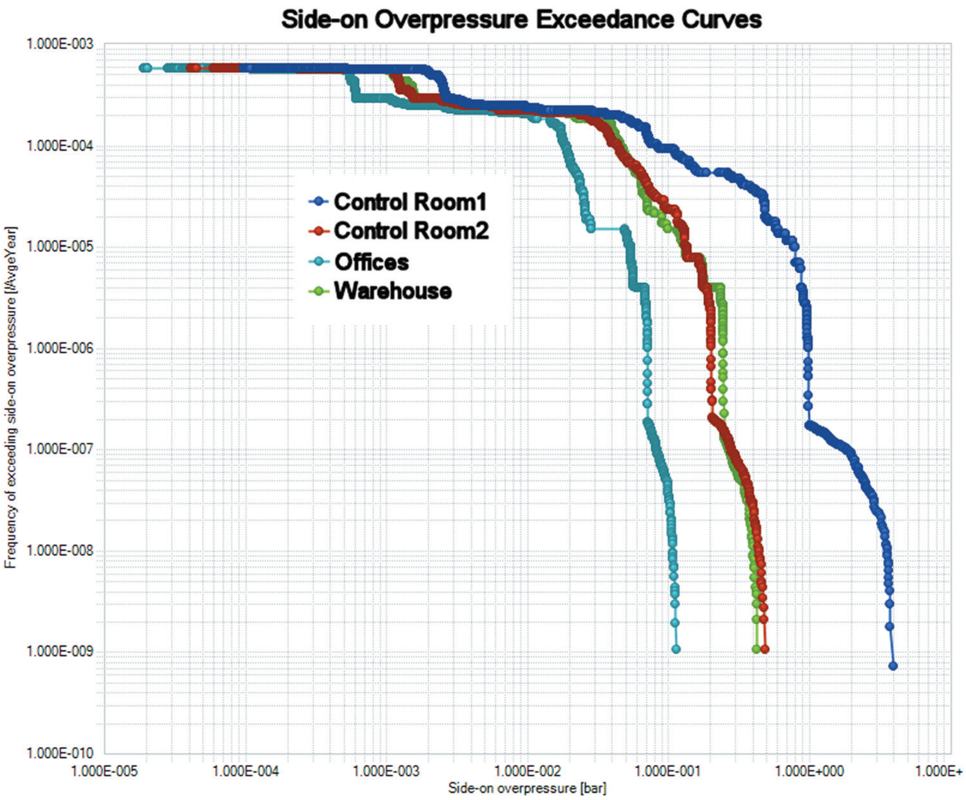

Figure 14. Side on overpressure exceedance curves at Control Room 1, Control 2, Warehouse and Office

Another useful metric when using risk as a basis for land use planning and facility siting are so-called "Exceedance Curves". These provide a location specific measure of the frequency with which particular levels of a given hazardous effect are likely to be exceeded. Figure 14 shows a set of Side-on Overpressure Exceedance Curves for the two Control Rooms, Office and Warehouse shown in Figure 8. Based on these four curves and the level of risk to which it is acceptable to expose the occupants of these buildings, you can provide input on both the required design and most appropriate location for your occupied buildings. For example, if your risk criteria allow for on-site staff in Control Rooms 1 and 2 to be exposed to individual risk of 1×10^{-5} and off-site personal in Offices and Warehouses to 1×10^{-6}, then from Figure 14 it can be seen that Control Room 1 must be able to withstand a side-on overpressure of approximately 0.8 bar, Control Room 2 approximately 0.15 bar, the Warehouse approximately 0.25 bar and the Offices approximately 0.07 bar.

CONCLUSIONS

This paper has outlined some recent advances in the capabilities of the Phast Risk QRA software tool in the areas of human vulnerability modelling and occupied building analysis. A case study has been presented outlining how these can be utilised when using risk as the basis for land use planning and in assessing the risks to those in occupied buildings, both on-site and off-site. A number of common risk metrics, both individual and societal, have been described, and examples presented of how these can be used in a practical way to help in managing risks to people. It has been shown how these metrics can be used together to identify most appropriate locations for occupied buildings and to ensure these are designed to offer sufficient protection to their occupants from a range of hazardous effects.

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