A SOFTWARE MODEL FOR ASSESSING FATALITY RISK FROM EXPLOSION HAZARDS USING THE MULTI ENERGY METHOD AND BAKER STREHLOW TANG APPROACH

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When assessing the risks to people indoors and outdoors from explosions due to accidental releases of flammable material it is necessary to predict the

- Extent and movement of the Vapour Cloud and its interaction with areas of congested obstructions.
- Probability of ignition.
- Overpressures generated if the cloud is ignited whilst moving through a region of congested obstructions.
- Effects of the overpressure and impulse on people in the vicinity of the explosion, both inside different types of building and outside.

The calculations sequence in time is discharge, dispersion, ignition, explosion, damage and lethality. The focus of the current paper starts with the explosion step of the analysis.

Two of the most frequently used models for assessing explosion overpressure strengths from gas explosions in congested spaces are the Multi-Energy Method (Van Den Berg, 1985) and the Baker-Strehlow-Tang Model (Tang and Baker, 1999).

The former model is preferred for the assessment of overpressures from vapour cloud explosions (VCE's) in Europe and was originally developed as a more accurate alternative to the TNT-equivalence model previously adopted for simplicity in QRA calculations. This model could initially only be applied in a very general manner using safe and conservative assumptions. However, since it was first proposed, a number of initiatives have been undertaken such as the GAME, RIGOS and GAMES projects, to improve both its accuracy and usability. These have been accounted for in the software model described in this paper. The latter model, which relates the explosion overpressure to the scaled distance from the explosion centre for varying degrees of congestion, is the preferred model for the assessment of risk from gas explosions in The Americas.

This paper describes the implementation of both methodologies within the Phast Risk software tool allowing assessment of risks to population in the vicinity of VCE's. The tool is able to model the initial discharge of flammable material from its storage conditions, subsequent dispersion within the atmosphere, interaction between the dispersing cloud and obstructed regions and subsequent explosion overpressure distributions, should the cloud ignite. Overpressures are calculated using either the Multi-Energy or Baker-Strehlow-Tang (BST) methodologies. The tool also allows the geometric definition of buildings, population distribution and appropriate vulnerability levels based on a number of standards (American Petroleum Institute (API) and Chemical Industries Association (CIA), for example). In addition, the paper presents two case studies for a simple, typical hazardous installations based on the GAMES project.

The first represents an LNG Terminal and investigates the effects of defining congested volumes based on the guidance available in the literature on the overall calculated overpressures. The second represents a simple Chemical Plant with a number of buildings in its vicinity, each offering different levels of protection to their occupants, and compares the calculated risks for buildings offering different levels of protection. Results are presented in terms of traditional F/N curves for societal risk.

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 100 m in diameter exploded destroying the plant, damaging around 1800 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 it is highly likely there would have been tens or hundreds of fatalities.

Largely 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, more focus has been addressed to the accuracy with which the effects of fires and explosions on people, whether in buildings offering particular levels of protection or in the open-air, can be estimated.

As mentioned earlier, 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.

This paper describes the implementation of 2 models for quantifying step 2, the Multi Energy Method and the Baker Strehlow Tang Model, and a number of methods for step 3 in the industry standard Phast Risk process QRA software model (Cavanagh, 2001, Witlox and Worthington, 2002). This work is motivated by industries need to improve the prediction of the consequences of vapour cloud explosions and to quantify the associated risks to life.

EXPLOSION MODELLING
MULTI ENERGY APPROACH

The Multi-Energy model is based on experimental research which showed that only the combustion energy located inside obstructed and/or partially confined regions generates potentially lethal overpressure waves. An obstructed region is an area where obstacles are present generating turbulence which will accelerate the flame if a cloud is ignited within this region. To apply this model, each obstructed region should be treated separately as an explosion source if the separation distance is sufficiently large. Otherwise, obstructed regions are combined to form larger confined sources which will be discussed further below. Any remaining flammable cloud outside the obstructed regions forms an unconfined explosion source which is generally of less importance in terms of overpressure effects, and hence typically contributes less to the resulting hazards and associated risks.

The blast curves used in the Multi-Energy model were derived from modelling the effects of idealised ground level explosions. Important blast effects, such as side-on overpressure, dynamic overpressure and positive duration of a blast wave, are represented by a sequence of curves where the effects depend on distance from the explosion centre for ten different explosion strengths. Details of these curves are given in the TNO Yellow Book (1997).

Because of the geometric complexity of real process plants, it is not trivial to apply this simple model to represent typical accident scenarios. A particular issue is that different analysts may make different assumptions about how a plant should be subdivided into regions with varying degrees of congestion; this can lead to significantly dissimilar results for essentially the same plant. This has lead to further research comparing the results of the Multi-Energy model against measurements and more rigorous models, such as CFD, to produce guidance and procedures on how to apply the model to real practical plant configurations. Between 1993 and 1995 a joint industry project sponsored by 12 organisations investigated ways to provide "Guidance for the Application of the Multi-Energy Model", commonly referred to as the 'GAME' project (Eggen, 1998). This research developed two correlations for the peak side-on overpressures at the explosion centre for 2D and 3D confinement. The estimated overpressure is then used to select the appropriate blast curves for consequence and risk calculations.

However, determining parameters for the correlations from the GAME project is not a straightforward task and a further joint industry project sponsored by 11 organisations followed to investigate the practical application of the

guidance to specific example scenarios. In this work the Multi-Energy results were compared with detailed information provided by measurements and CFD predictions of the explosion behaviour. This work was published in 1998 under the project acronym 'GAMES' (Werex et al., 1998). In parallel with this project the Yellow Book was updated so some of the research and guidance is reflected in the 1997 version (TNO Yellow Book, 1997).

BAKER-STREHLOW-TANG (BST) APPROACH

The Baker-Strehlow model was first published at the 28th Loss Prevention Symposium in 1994 (Baker et al., 1994). Like the Multi-Energy model, Baker-Strehlow employs a family of blast curves to predict the consequences of VCEs. In this approach the flame speed is used as the key curve selection criteria, instead of peak overpressure at the explosion centre as used in the Multi-Energy model.

This methodology provides a flame speed table, from which the appropriate flame speed can be selected according to the confinement, congestion and cloud reactivity of the obstructed regions, and a family of blast curves for overpressure and impulse at flame Mach numbers covering deflagration to detonation. Since 1994, the flame speed table has been updated to include a confinement of 2.5D (Baker et al., 1997), the blast curves were updated in 1999 and the model was then renamed as Baker-Strehlow-Tang (Tang et al., 1999), i.e. BST model. A new flame speed table was published in 2005 providing flame speed relative to a fixed observer, instead of relative to the moving gas as used in the original flame speed table, and excluding 1D confinement (Pierorazio et al., 2005). The BST model implemented in Phast Risk v6.6 uses the updated flame speed table and blast curves.

The key when applying the BST model is to determine the flame speed of an explosion which is then used to select blast curves for consequence and risk calculations. In Phast Risk v6.6, you can specify the flame speed directly for an obstructed region or provide a set of parameters to enable the software to determine a flame speed using the flame speed table described above. To use the BST flame speed table, the required parameters are:

Degree of confinement. The updated flame speed table includes three degrees of confinement, i.e. 2D, 2.5D and 3D. Degree of confinement refers to the ability of the flame to expand or accelerate in different directions. It is considered to be 3D if there is little or no obstruction to flame expansion, 2D if there is a single restricting plane and 2.5D where confinement is made of either a frangible panel or by a nearly solid confining plane (e.g. pipe rack where pipes are almost touching).

Congestion level. Congestion is classified as low, medium or high depending on area blockage ratio (ABR) and pitches (i.e. the distance between successive rows of obstacles) as:

– Low congestion level: a few obstacles in the flame's path or an ABR less than 10% and a few layers of obstacles.

– Medium congestion level: any thing falling between the low and high levels.
– High congestion level: closely spaced layers of obstacles with an ABR of 40% or higher.

In Phast Risk v6.6, the congestion level of an obstructed region can be given directly or decided by the software by providing it with diameter-to-pitch ratios of the obstacles or using engineering judgement based on volume blockage and assumed ratios as used by Fitzgerald (2001).

Reactivity. Reactivity of the cloud is rated as low, medium or high as suggested by TNO (Zeeuwen & Wiekema, 1978). Methane and carbon monoxide are the materials regarded as having low reactivity, whereas hydrogen, acetylene, ethylene, ethylene oxide and propylene are highly reactive, and all other materials are assigned a medium reactivity. In general, medium reactivity single component fuels have laminar burning velocities between 0.45 and 0.75 m/s, low and high reactivity fuels have velocities lower than 0.45 m/s and higher than 0.75 m/s respectively (Baker et al., 1997). In Phast Risk v6.6, reactivity can be specified directly or decided by the software using the laminar burning speed of the cloud.

CRITICAL SEPARATION DISTANCE

An important aspect of applying the Multi-Energy and BST models is determining explosion sources. This is difficult if a flammable vapour cloud engulfs more than one obstructed region separated by open spaces. If the open spaces are sufficiently large, the VCE flame front will slow down significantly while travelling across them and the explosion will develop multiple separate blasts. However if the spaces are small, the explosion should be modelled as one single blast with summed energy for all obstructed regions. This is of sufficient concern that a further joint-industry project (project acronym RIGOS) was initiated to investigate this phenomenon (Van den Berg et al., 2002). This work included an experimental programme to provide insight into the influence of separation distance between obstructed regions on the explosion behaviour.

The critical separation distance between obstructed regions is the criterion that enables the determination of explosion sources for each scenario. The Yellow book (1997) defines a congested area as an area in which obstacles are located within a distance of 10 obstacle diameters from each other with an upper limit of 25 m for the application of the Multi-Energy model. This suggests a critical separation distance of 10 obstacle diameters with an upper bound of 25 m.

However, the RIGOS project has found the separation distance suggested by the Yellow book is not always conservative, especially in higher explosion overpressure ranges. Instead, RIGOS recommends a critical separation ratio based on the explosion overpressure as:

● A critical separation distance equal to $\frac{1}{2}$ of the donor dimension if the donor explosion overpressure is higher than 100 kPa.

- A critical separation distance equal to $\frac{1}{4}$ of the donor dimension if the donor explosion overpressure is lower than 10 kPa.
- A linear interpolation for the overpressures in between.
- Connecting obstacles with sufficient cross-sectional area between obstructed regions can substantially increase the separation distance.

Baker et al. (1997) suggested that obstructed regions with a separation distance greater than 5 m (16 ft) can be considered as separate explosion sources for the BST model.

OBSTRUCTED REGIONS AND EXPLOSION SOURCES

OBSTRUCTED REGIONS

The method for dividing a plant into a number of individual obstructed regions has to be decided upon by the analyst. This process usually starts with the definition of a bounding box that encloses all the relevant obstacles, followed by further refinement. How this is done in practice depends on the experience of the analyst and is open to interpretation. To aid the process, TNO Yellow Book (1997) has a "recipe" to help define obstructed regions for use with the Multi-Energy model.

In Phast Risk v6.6, obstructed regions for the Multi-Energy and BST models are created in a similar manner, but parameters specific to each model must be provided to complete their definition. These include obstacle diameter and flame path length for the Multi-Energy model and the level of congestion and fuel reactivity for the BST model. Because of this difference, two Obstruction Set types are available in Phast Risk, i.e. "Multi-Energy Obstruction Set" for the Multi-Energy model and "BST Obstruction Set" for the BST model.

Within each Obstruction set, two obstruction types are available. For the Multi-Energy Obstruction Set the obstruction types are "Defined Strength" obstruction and "Calculated Strength" obstruction. For Defined Strength obstructions, explosion strength (i.e. the blast curve number) is input directly by the user. For Calculated Strength obstructions the blast curve number is determined automatically based on parameters provided by the user including degree of confinement, Volume Blockage Ratio (VBR), typical equipment diameter and flame path length. For the BST Obstruction Set the obstruction types are "Defined Flame Speed" obstruction and "Calculated Flame Speed" obstruction. For Defined Flame Speed obstructions, flame Mach number is input directly by the user. For Calculated Flame Speed obstructions the Mach number is determined automatically according to the flame speed table based on parameters provided by the user including degree of confinement, VBR or volume of obstructions, level of congestion and fuel reactivity.

A Multi-Energy obstruction set can have one or more "Calculated Strength" obstructions and/or obstruction groups (a group is a folder containing one or more obstructed regions of the same type), and one or more "Defined Strength" obstructions and/or obstruction groups. A BST obstruction set has a similar structure to the Multi-Energy obstruction set.

Defining explosion sources

In Phast Risk v6.6, explosion sources can be specified directly by users or determined by the software using the critical separation distance criteria described below, or a combination of both. The explosion sources, determined using their relative positions, are initially considered as potential sources of explosions, only becoming active when a flammable cloud and an ignition source are present. Cloud concentration data is provided by the Unified Dispersion Model (UDM) or Building Wake Model (BWM) integrated into Phast Risk (see for example Witlox and Oke, 2008) and the ignition source data is provided by the user through the Phast Risk GIS.

There are two options to specify critical separation distance as follows:

- Separation distance – Users provide a separation distance directly in line with the recommendations provided by the Yellow Book for Multi-Energy model (TNO, 1997) or by Baker et al. (1997) for BST model.
- Critical separation ratio – Users provide a critical separation ratio as recommended by RIGOS.

The following rules are applied to define potential explosion sources for all obstructed regions within each obstruction set:

- Each obstructed region not included in an obstruction group represents a potential explosion source regardless of its locations.
- Each obstruction group has a flag indicating whether the criterion of critical separation is to apply for the obstructed regions within the group.
- If the critical separation option is selected, distances between obstructed regions are checked to determine the number of potential explosion sources.
- If the critical separation option is not selected, all the obstructed regions within that group are summed to form one potential explosion source.
- Obstructed regions in different groups or sets cannot form a combined potential obstructed region.
- Overlap between obstructed regions within a set is not allowed, to avoid "double-counting" which could lead to over-estimation of the explosion volume.
- An automatic check for overlap has been implemented in the software.

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, 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, 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. A number of methods from published literature are described all of which, in principle, can be used in conjunction with any explosion model.

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.

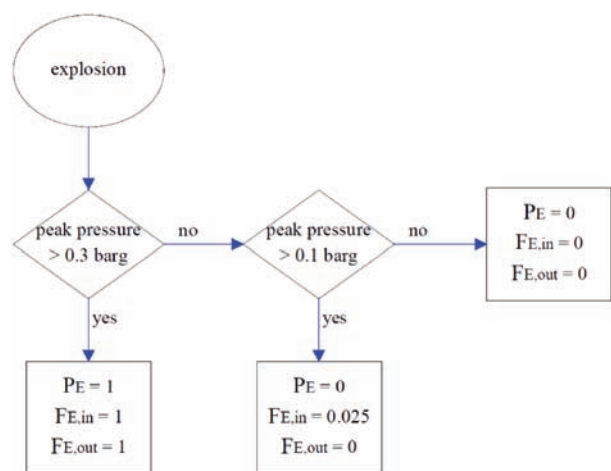One of the simplest models for vulnerability when calculating measures of risk, and that used up to now in

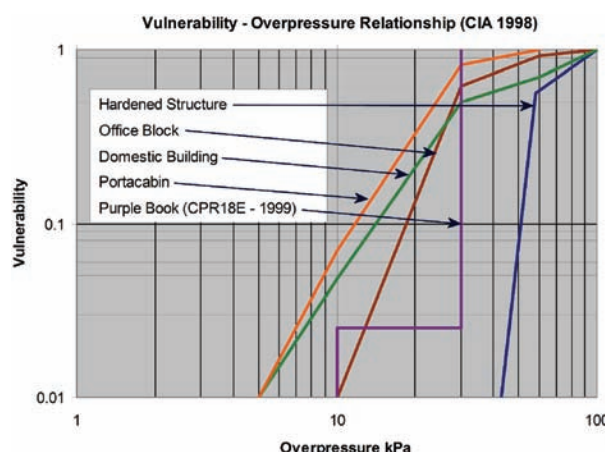**Figure 1.** Discrete overpressure vulnerability levels from CPR18E (1999)

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

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 2.2 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.

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 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.

The model is therefore being 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 4 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.

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. The model requires the definition of three points on each vulnerability curve, typically $P_{0,i}$, $I_{0,i}$ and one other point, and can then be used to estimate vulnerability for a given pressureimpulse either by interpolation or by discrete stepping between given vulnerability levels. An example of such a curve is shown in Figure 3.
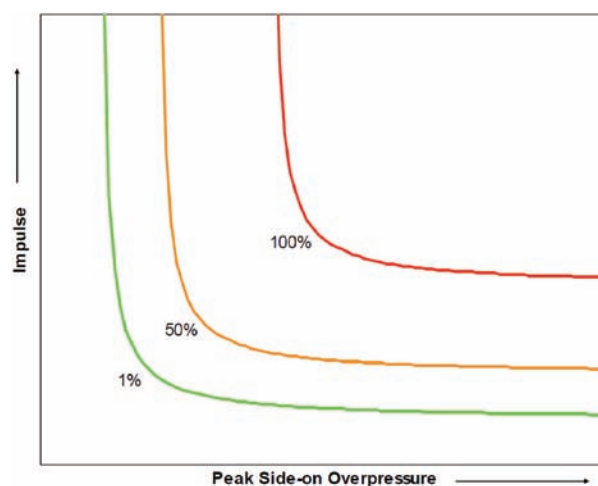

Figure 3. Typical pressure impulse curves showing 1%, 50% and 100% vulnerability

CASE STUDIES
LNG TERMINAL

To develop guidance for applying the correlations derived by the GAME project for the Multi-Energy model, predictions using the model were evaluated against measurements and the results of AutoReaGas (a CFD model) for three test cases in the GAMES project. The LNG terminal case from GAMES has been used here to demonstrate the use of the Multi-Energy and BST models implemented in Phast Risk v6.6. Detailed validation and verification of the models can be found in the documentation for Phast Risk v6.6 and a paper by Xu et al. (2009).

Details of the LNG Terminal can be found in the report by Merex et al. (1998) and Figure 4 illustrates the obstructed regions used to represent the terminal. This case contains a number of long pipebridges (OSR-5, OSR-6, OSR-7 and OSR-8), which connect the largest obstructed region, OSR-1, with the smaller regions OSR-2 and OSR-3. Obstructed region OSR-4 is isolated from the others. OSR-1, 2, 5 and 7 are broken down into sub-regions to provide a more accurate representation of their layouts and characteristics. In this case, the pipebridges have enclosed a large open volume between OSR-1, 3, 6, 7 & 8.

In the GAMES study, four reduced cases were investigated for this test case and Figure 5 shows the Multi-Energy obstruction sets created for these reduced cases using Phast Risk v6.6. Even though ME Obstruction Set A has included both obstructed regions OSR-1 and OSR-2 for the two simple reduced cases investigated, separate explosion sources were defined for each since they were placed in different obstruction groups in the set according to the rules adopted for Phast Risk v6.6, as explained above. Figure 6 shows the predicted overpressure along a transect crossing the long pipebridge OSR-5 and obstructed regions OSR-1 and OSR-2. Central ignition is assumed for all scenarios.
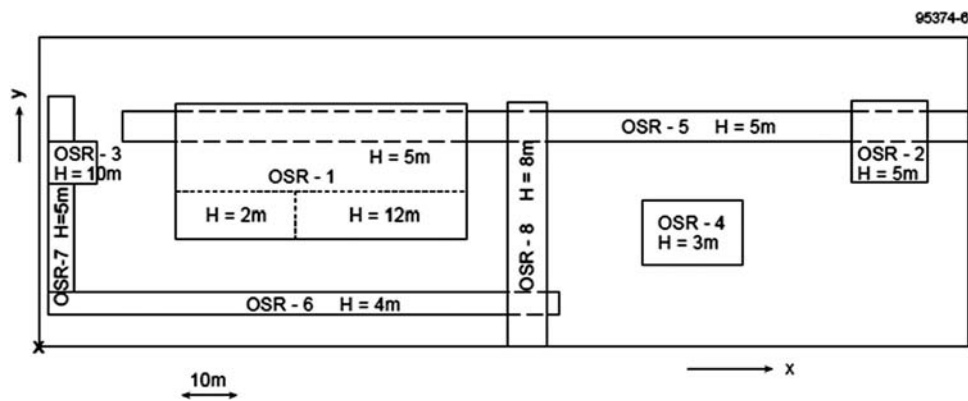
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Figure 4. Plan view of the LNG terminal (Merex et al., 1998)
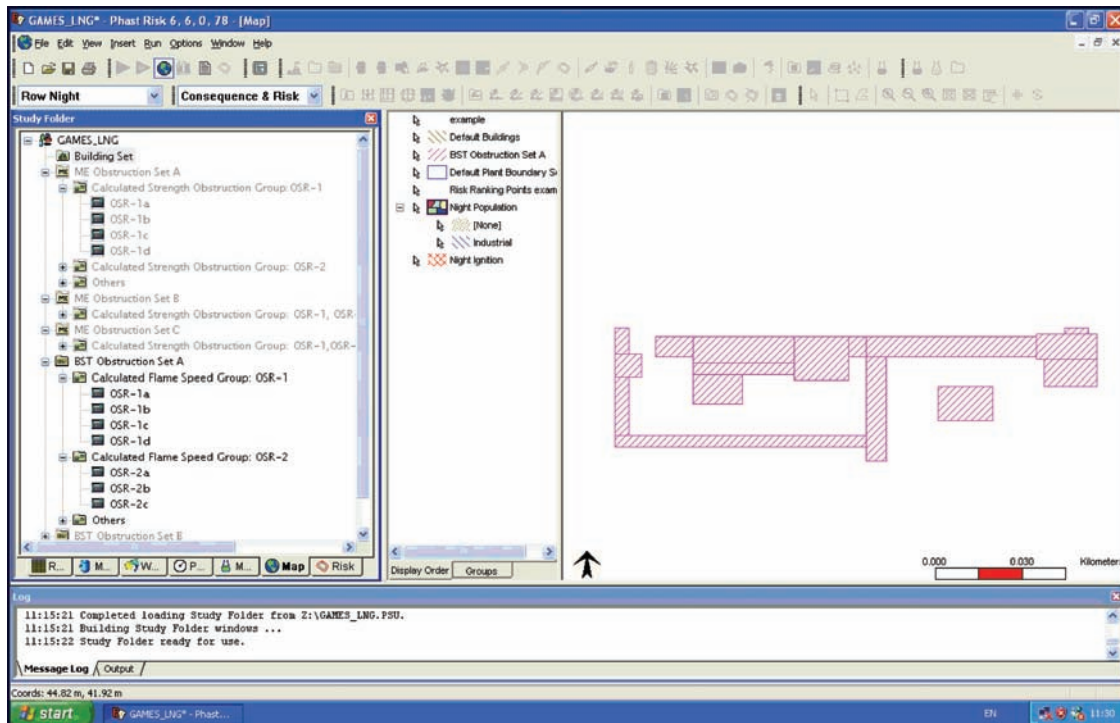

Figure 5. GUI setup for the LNG terminal scenarios

CHEMICAL PLANT
The second case study, also based on an example from the GAMES report, represents a typical Chemical Plant. In GAMES, a CFD model of the plant was created against which the Multi Energy model was validated for accuracy of explosion over-pressure results. This model was divided into a number of obstructed regions using the Yellow Book guidelines (CPR14E, 1997) and has been recreated in Phast Risk v6.6 in order to exemplify the importance of combining accurate prediction of over-pressure and impulse with building vulnerability modelling. In addition to the obstructed regions from the GAMES report, a

number of buildings have also been included in the model. As shown in Figure 7, two control rooms and an office building have been added in order to demonstrate the influence of different building vulnerabilities on the overall societal risk results. Some off-site population has also been included in the model but is not shown in Figure 7.

Population information has been included for all buildings and some obstructed regions, and the affect of adjusting building vulnerability on societal risk, for example, is illustrated. Typical building vulnerability data for the discrete over-pressure method, similar to the purple book approach shown in Figure 1, and for the interpolated
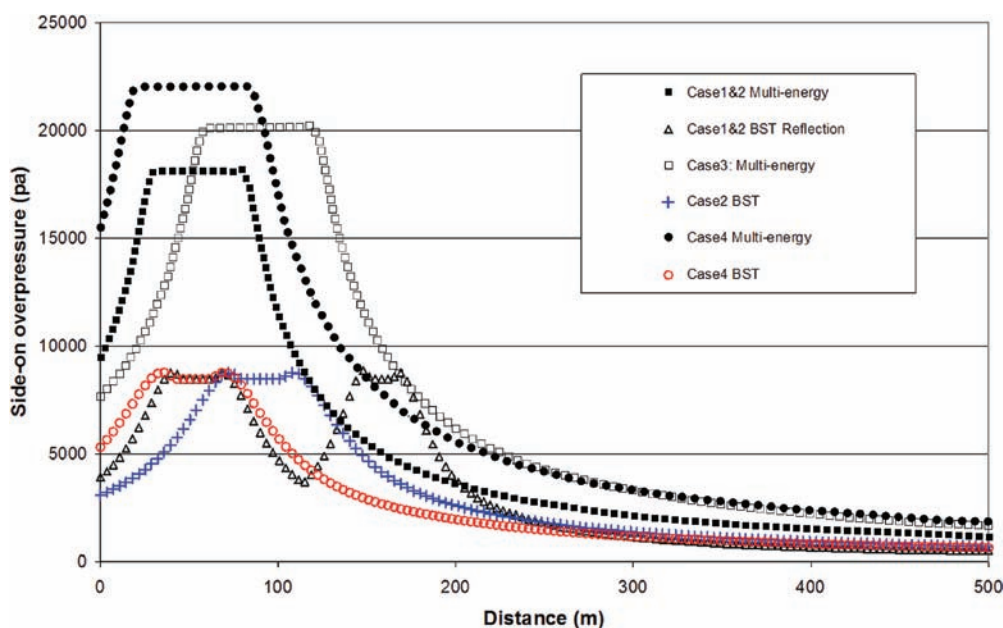
Figure 6. Calculated overpressures along pipebridge OSR-5 between OSR-1 and OSR-2 as illustrated in Figure 4
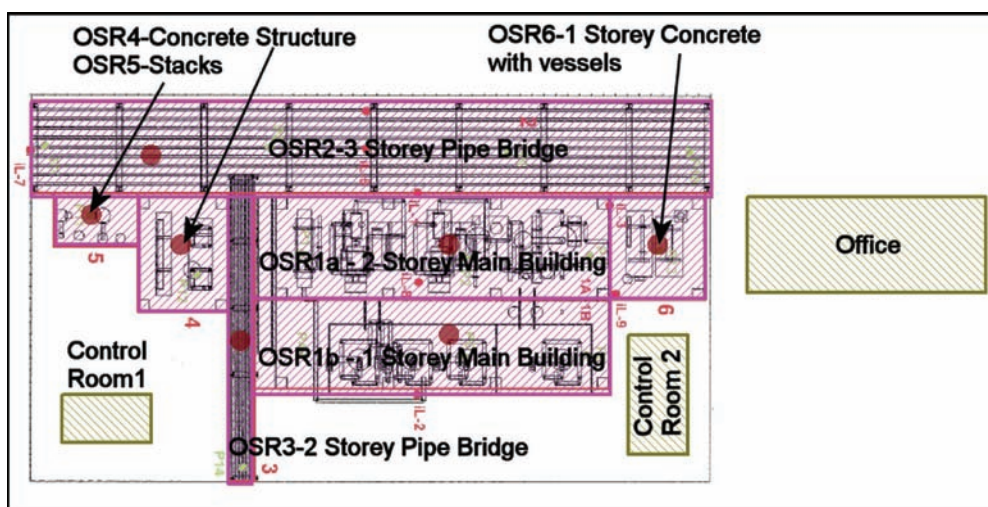

Figure 7. Chemical plant obstructed regions model reproduced from GAMES with occupied buildings added

vulnerability method, similar to the CIA approach illustrated in Figure 2, are shown in Figure 8.

For the purpose of demonstration a range of pressurised methane gas release scenarios are located at the centre of each obstructed region (indicated by the circles within each obstructed region in Figure 7) for a range of hole sizes, each with a typical release frequency assigned to it. Typical wind rose data is also used for three weather conditions, F stability 1.5 m/s, D stability 1.5 m/s and D stability 5 m/s, and a prevailing wind direction from the

west. Point ignition sources are located as described in the GAMES report and annotated "IL" on figure 7. Additional background ignition probabilities are assigned for the plant and buildings.

By using a range of building types with different vulnerability properties for the control rooms and office in the model shown in Figure 7, we can assess the overall societal risk against some suitable acceptance criteria. Figure 9 shows F-N curves for 4 different building configurations along with some typical "ALARP" acceptance criteria.
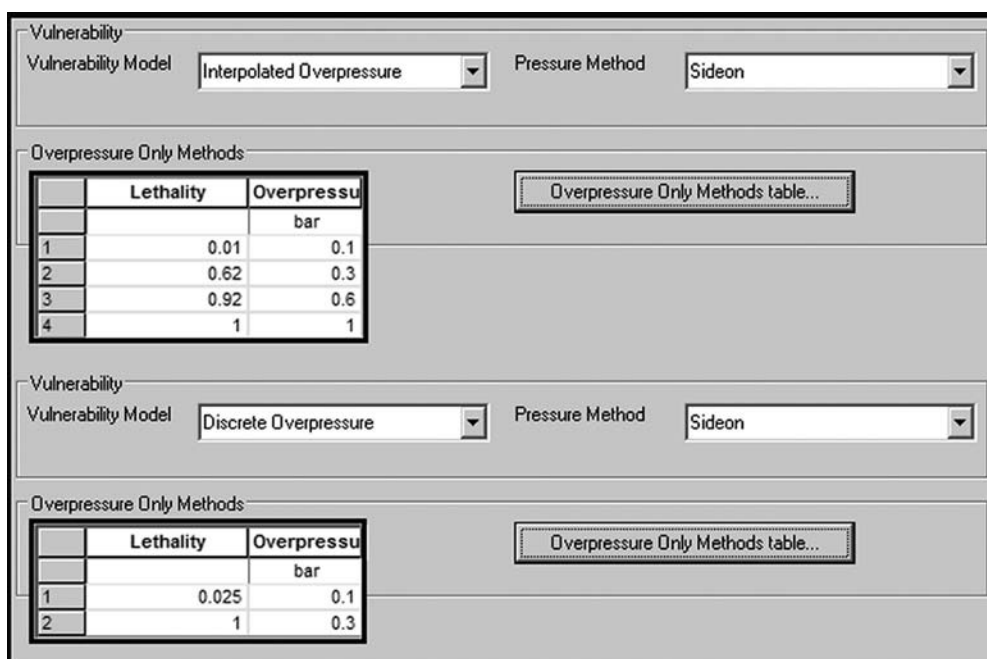
Figure 8. Typical building vulnerability data using interpolated and discrete overpressure methods

The first F-N curve is for a simple discrete overpressure vulnerability model and we can see that the criteria shown are not satisfied. Moving to an interpolated overpressure vulnerability model and using data appropriate to typical brick buildings for both control rooms and offices, we can see from the second F-N curve that, although the

overall societal risk has reduced, it still exceeds the criteria in the 10 to 30 fatality range. By replacing the control rooms with stronger concrete structures, we can see that the overall societal risk reduces further and is now within the ALARP region. The final curve illustrates how further risk reduction can be achieved by replacing the control rooms with blast resistant structures and upgrading the office block to a concrete construction.

Of course this is a very simplified example intended to illustrate the relevant concepts, particularly the effect of refining vulnerability models to take account of use of different building types to improve protection to personnel and the general public. In practice for decision making, all hazards would be considered including toxic and other flammable effects (radiation and flash fires). Phast Risk supports the analysis of these additional effects. Then, by applying techniques such as cost-benefit analysis, it can be decided whether the risk reduction which can be achieved by using different types of building warrants the extra construction costs. In the same way, by looking at a range of locations for different buildings, the model can be used to optimise the location of occupied building to minimise societal risk.
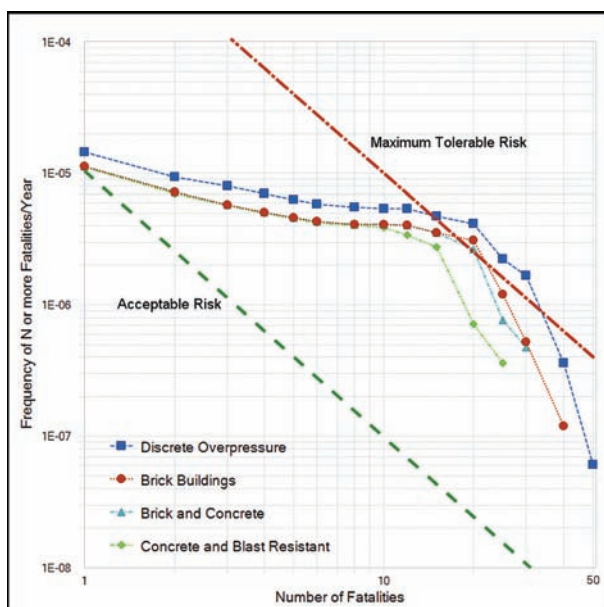

Figure 9. F-N curves for chemical plant model for a range of building vulnerability sets

CONCLUSIONS
This paper describes recent advances in a software model for assessing the risks to people from explosions on hazardous installations. The model takes account of congestion and confinement and the various levels of protection offered by buildings of different construction. New implementations of both the Multi-Energy and Baker-Strehlow-Tang explosion models have been included,

taking account of a number of guidelines from the literature including the GAME, GAMES and RIGOS joint industry projects. A number of building vulnerability models have also been included. Both explosion and vulnerability modelling have been implemented in an "open" way, so that future research and subsequent guidance from industry can also be taken advantage of.

In addition, two example studies have been included to exemplify the results from the extended explosion modelling. The first example illustrates the results in terms of over-pressure decay for both the ME and BST model implementations, comparing results from the two models. The second example illustrates the effect of the improved vulnerability modelling on the overall calculated societal risk measures. Both examples have been taken from the GAMES project and will be used in the future for detailed validation of the modelling. Initial validation of the explosion modelling is described by Xu et al. (2009). In the first example, the effect of obstructions on overpressure is illustrated, whilst in the second, the effect of building design on risk is shown using the F-N curve measure of societal risk. These examples serve to illustrate the combined importance of accurate modelling of explosion effects and human vulnerability to these effects on managing the risks from hazardous facilities.

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