THEORY

OBSTRUCTED REGION EXPLOSION MODEL

DATE: December 2023

OREM is the vapour cloud explosion model developed for the SAFETI products Phast and Safeti. It includes the TNO Multi-energy and the Baker-Strehlow-Tang models and predicts the effects of vapour cloud explosions by taking into account the interaction of obstructed regions and the flammable cloud. It is based on published literature and predicts explosion damage in the form of peak overpressures, positive phase duration and impulse in the region around vapour cloud explosions for use in consequence and risk assessments.

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1	March 2010	For Safeti 6.6	Y Xu	D Worthington	
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Date: December 2023

Prepared by: Digital Solutions at DNV

ABSTRACT

An explosion model has been developed for use in DNV's risk software. It is named as the Obstructed Region Explosion Model and is referred to by the abbreviation OREM.

OREM includes functions to predict the effects of vapour cloud explosions using the TNO Multi-energy model[i,ii,iii] or the Baker-Strehlow-Tang methodology as described in the publications[iv,v,vi,]

In its most basic form, OREM provides look-up functionality for overpressure, duration of the positive phase and impulse based on a family of blast curves for an idealised vapour cloud explosions of a stoichiometric fuel-air charge.

OREM also contains routines that define the potential explosion sources in obstructed regions from accidental releases. Obstructed regions can be defined by following any guidance selected by the user or the steps defined in the Dutch Yellow book[i] for the Multi-energy model. Explosion sources are defined using the results of dispersion modelling and geometry of the obstructed regions. Separation between obstructed regions can be considered in deciding explosion sources using either separation distance or critical separation ratio.

Special methods have been developed to enhance the predictions for releases inside obstructed regions, '1/3 Rule' for the Multi-energy model and the ground correction method for the BST model.

The model predicts explosion effects in the form of peak overpressure, positive phase duration and impulse in the region around an explosion source when ignited. These results may be used for consequence and risk assessments.

Table of contents

Table of figures

1 INTRODUCTION

1.1 The Obstructed Region Explosion Model (OREM)

This document describes the theory of the Obstructed Region Explosion Model (OREM) as implemented in Phast and Safeti for predicting the consequence and risk of vapour cloud explosions in process plants. The model is based on the Multi-Energy model as described in the Dutch Yellow Book[i] for consequence modelling and other publications[ii,iii], and also on the Baker-Strehlow-Tang methodology as described in published papers[iv,v,vi]. OREM is only available in Phast or Safeti if you have the appropriate license for the Explosions Extension.

For brevity sometimes the Multi-energy Model will be referred to as 'ME' and the Baker-Strehlow-Tang Model as 'BST' in this document. The paragraphs marked with **ME** and **BST** are specific to the Multi-energy model and the Baker-Strehlow-Tang Model respectively.

ME in OREM predicts the consequences of vapour cloud explosions in the form of peak overpressures and duration in the region around the explosion using the blast curves developed by TNO for an idealised hemispherical stoichiometric fuel-air charge. Distance from the explosion may be specified and then overpressure and duration are calculated using ME. Alternatively a target overpressure or positive phase duration may be input and ME will return the distance to the targeted effect from centre of the explosion.

BST in OREM predicts the consequences of vapour cloud explosions in the form of peak overpressure and impulse in the region around the explosion using the flame speed table and the blast curves developed by Baker et al for an idealised stoichiometric fuel-air charge. Distance from the explosion may be specified and then overpressure and impulse can be calculated using BST. Alternatively, a target overpressure or impulse may be input and BST will then return the distance to the targeted effect from centre of the explosion.

Used in this way the model is a simple look-up function and it requires the user to describe the explosion source to work out two correlating parameters, i.e. total combustion energy and explosion strength of an explosion for consequence and risk assessments. There are two models to determine these parameters and their availability varies among products as given in
Table 1. The two models are:

1. ***Standard explosion model***
   ME Using ME a list of obstructed volumes is given for each modelled case. Each volume must be given a ME curve number. The modelling considers each volume as a separate explosion source. The energy of each explosion is determined based on total flammable mass in the cloud and obstructed volume and the explosion effects are calculated accordingly.
   BST Using BST one obstructed volume can be given for each modelled case. This volume defines one confined explosion with the explosion energy determined based on total flammable mass in the cloud and the given volume, and flame speed of the explosion can be given as an input or determined by BST using the flame speed table based on the characteristics of the obstructed volume.

2. ***Obstructed region explosion model (OREM)***
   ME The number of explosion sources from a case and their explosion energies are determined using the time-varying behaviour of the flammable clouds from dispersion modelling and layout of the obstructed regions around the accident release. The strength of each explosion can be given as an input or determined by ME using the GAME correlations based on key characteristics of the obstructed regions.
   BST BST calculates the explosion sources from a case and their explosion energies using the time-varying behaviour of the flammable clouds from dispersion modelling and layout of the obstructed regions around the release. Flame speed of each explosion can be given as an input or determined by BST using the flame speed table based on the key characteristics the obstructed regions.

The model results may be used directly by the analyst to assess the explosion hazards or may be used as input to vulnerability models to calculate risk. In Safeti the use of OREM is limited to use in the risk calculations as highlighted in the table below. In the product OREM is referred to as '3D Obstructed Region' while the standard method is '3D Purple Book'.

	Phast	**Safeti *Standard***	**Safeti *with the Explosions Extension***
Standard explosion model – Standalone consequences only	Yes	Yes	No – standalone explosion models not used in the risk calculations except the BLEVE Blast model

Standard explosion model – Linked	Yes	No – instead it uses '3D Purple Book' for the risk of explosions	No – instead it uses '3D Purple Book'' for the risk of explosions
Obstructed Region Explosion Model (OREM)	No	No	Yes (i.e. '3D Obstructed Region')

Table 1 Model options in Phast and Safeti

The introduction and model overview of this document (i.e. Chapters 1, 2 & 3) are applicable for both standard explosion model and OREM, but the rest focuses mainly on the theory of the obstructed region explosion model. The standard explosion model is only briefly described in Chapter 5.

Because BST and ME were implemented in parallel in Safeti, they share many methods, such as the methods for defining confined explosion sources and calculating explosion effects. Several features specially developed for the Multi-energy model are made available for BST.

1.2 Background

The acute damage potential of vapour cloud explosions has been proved by real-world incidents including significant potential for losses of life, property and production. The explosions at Flixborough in 1974 and at Texas City and Buncefield in 2005 are such examples. Consequently, vapour cloud explosions have been the subject of extensive research including the development of predictive models.

The earliest and simplest category of model correlates distances to damage levels (levels defined in terms of specific damage effects such as broken windows) to the energy released in an explosion. The TNT equivalent model extends this to predict peak overpressures vs distance from the explosion centre. These models are simple and easy to apply. As greater understanding to the physics of vapour cloud explosions is gained by research, advanced models have developed to solve the fundamental equations governing VCEs based on Computational Fluid Dynamics (CFD) techniques. Experimental results and insight provided by detailed modelling have made the limitations of the TNT equivalent models apparent. However, advanced mathematical models are usually too demanding of people and computing resources to be generally applicable and researchers have made efforts to derive a prediction method better than the TNT equivalent approach but less expensive than CFD modelling.

One key realisation from the research was that, as the vapour cloud burns and expands, the gases start to move, and turbulence is generated to cause a flame velocity much greater than the typical laminar burning velocity then consequently high overpressures may be generated. In the absence of this turbulence generation the cloud will burn as a flash fire with different hazard consequences and most importantly without the generation of high overpressures. However, significant turbulence can be generated by obstacles encountered by a flame as it propagates though the vapour cloud in obstructed regions. This process is subject to positive feedback, so that as more obstacles are encountered, more turbulence is generated and this further accelerates the flame. It is explosions that occur in the presence of obstacles that can generate overpressures with the potential for extensive damage.

It may help the reader to note that obstacle density is sometimes referred to as congestion and the region accommodating the obstacles as a congested region in the literature. In this document we use the terms, obstruction, obstacles and obstructed region.

A further key factor in determining the magnitude of overpressure generation is the degree to which the cloud is constrained from expanding. As the cloud burns it heats and expands and if the cloud is constrained to expand in only 1 or 2 dimensions then the positive feedback mechanism leads to higher overpressures than if the cloud can expand freely. For instance if the burning and thus expanding vapour cloud can move in 3 dimensions then the overpressures generated will be lower than if the cloud is constrained to expand in only 2 dimensions as beneath an elevated storage tank or 1 dimension as in a road tunnel. This expansion constraint is often referred to as degree of expansion or degree of confinement.

Simple explosion models that take into account the importance of obstruction and confinement on flame acceleration in vapour cloud explosions and subsequent generation of blast overpressure have been developed over the last decade and more. The TNO Multi-Energy model as described in the Yellow Book is one, the Baker-Strehlow-Tang model is another and both these models are available in Phast & Safeti for consequence and risk analysis.

Because of the increased complexity these models are less-easy to apply to envisaged accident scenarios compared to the simpler TNT equivalent type of model. A particular issue is that different analysts may make different assumptions and obtain divergent results. This has led to further research comparing the results of the Multi-energy model against more accurate models and measurements to produce guidance and a formal procedure on how to apply the Multi-energy model to real plants.

Between 1993 and 1995 a joint industry project sponsored by 12 organisations researched ways to provide "Guidance for the Application of the Multi-Energy Model" (project acronym 'GAME'). The work was published in 1995[ii]. Two correlations were developed in this project to estimate the initial peak overpressure of vapour cloud explosions based on characteristics of the cloud and of the obstructed regions the cloud has covered. The estimated overpressures are then used to select blast curves.

The GAME correlations have provided a systematic approach to apply the Multi-energy model. However, there are still uncertainties in selecting correlation and defining its parameters for real process plants. A further joint industry project followed to investigate the practical application of the GAME guidance to specific example scenarios. In this work the results of the Multi-energy model were compared with detailed information provided by CFD predictions and measurements. This work was published in 1998[iii] under the project acronym 'GAMES' (GAME, Second phase).

Parallel with this work the Yellow Book was being updated so some of the research and guidance was reflected in the 1997 version of the Yellow Book[i].

The Baker-Strehlow model was first published at the 28th Loss Prevention Symposium in 1994. It uses the Strehlow approach of selecting blast curves based on flame speed and the procedures of the Multi-energy model to determine explosion energy on the basis of confinement and congestion.
Since then, the model has evolved through ongoing research and applications in hazard analysis. The flame speed table has been updated to include a confinement of 2.5D in 1998 and a new table was published in 2005. The blast curves were updated in 1999 and the model was then renamed as Baker-Strehlow-Tang model.

Another area of particular uncertainty is the separation distance which prevents adjacent obstructed regions behaving like one big region. This is of sufficient concern that a further joint-industry project was funded to investigate it (the project acronym is RIGOS[x]). This work included an experimental program and gives insight into the influence of separation distance between obstructed regions on the explosion behaviour. The results were published in 2002.

OREM in Phast and Safeti has been developed to enable a user to model the blast effects from vapour clouds dispersing through regions containing obstacles according to the information published in the above collection of reports and papers.

1.3 Obstructed Region Explosion models vs CFD models

A real-world vapour cloud explosion in a chemical plant is not only a very hazardous event it is also very complex in terms of thermodynamics and fluid dynamics. To model these explosions directly is the object of the most complex explosion models belonging to the Computational Fluid Dynamics category. The application of such models is demanding in terms of people and computing resources and so can only be justified when there is a particular need to obtain the best possible predictions for a limited number of cases. These characteristics also make such methods unsuitable for routine inclusion in QRA studies.

OREM offers much simplified explosion models which still provide the main outputs necessary for consequence analysis and QRA. This model is also distinguished from the simpler TNT-equivalent model by including the effect of obstacles and partial confinement. The influences of these factors have been shown to give important characteristic differences between explosions from solid explosives and vapour cloud sources. The use of OREM means that these factors are accounted for in a hazard study and/or a QRA.

The Phast approach may also be used as a screening step to qualify the decision to conduct a CFD analysis and to select critical cases for the CFD analysis.

1.4 Scope of the current document

This document contains the theory associated with the obstructed explosion modelling in Phast. The main concepts of the Multi-energy Model are introduced in Chapter 2. This includes the blast curves for explosion overpressures and positive phase duration, and an overview of the Multi-energy model. Chapter 3 introduces the Baker-Strehlow-Tang model and includes the blast curves for overpressure and impulse. Further details on these models are included in Chapter 4 on the definition of obstructed regions. Chapter 5 explains the derivation of explosion sources and Chapter 6 on how to obtain explosion effects. Enhancements specially developed for Phast are included in Chapter 7. Chapter 8 references the verification and validation of the model predictions. Finally Chapter 9 summarises the main conclusions and recommendations.

Much of the model is common between the ME and BST approaches but where they differ it is made clear in the text and marked with *ME* or *BST*. Sections 2, 6.1.1, 6.2, 7.2.3 and 7.2.4 are unique to ME while 3, 6.1.2, 6.3 and 7.3 are unique to BST.

2. OVERVIEW OF THE MULTI-ENERGY MODEL

2.1 Blast curves for explosion effects

The Multi-energy model belongs to a group of models using blast curves to predict the consequences of VCEs. The other models in this group include the TNT equivalent model, the Baker-Strehlow-Tang model and the Congestion Area Assessment model (CAM). The blast curves are usually developed based on CFD simulations of idealised cases and provide side-on overpressure and impulse or duration of positive overpressure as a function of distance from the explosion.

The Multi-energy model consists of a family of blast curves for peak overpressures, dynamic pressure and duration against distance. These curves were derived from detailed model predictions for an idealised explosion scenario. The explosion is based on a ground-level hemi-spherical vapour cloud, filled with a fuel-air charge at stoichiometric[1] concentration. To generate the family of curves different flame speeds are assumed and these flame speeds are specified to be constant during the explosion.

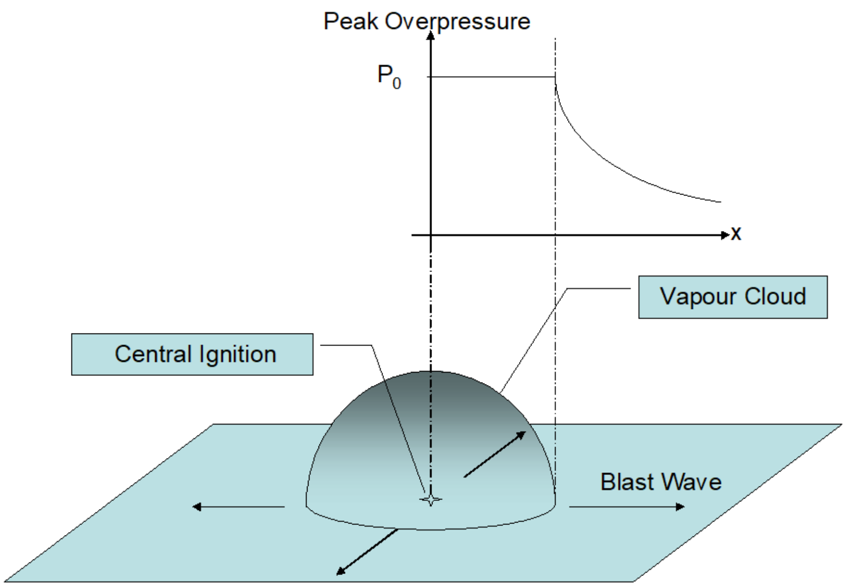

Figure 1 – Idealised Vapour Cloud Explosion as Basis for Multi-Energy Curves

Figure 1 illustrates the idealised scenario and the main features of the model. The geometry is rotationally symmetric with an initial radius r_0. The symmetry is preserved by prescribing central ignition. The flame front will then propagate symmetrically from the centre. Because of the symmetry a single curve may describe the explosion behaviour in all directions. The zone of combustion is characterised by a single constant initial peak overpressure, P_0. Then, outside this zone the explosion is modelled as a blast wave that decays with distance as shown in Figure 2 for the side-on overpressure and Figure 3 for dynamic pressure.

[1] Defined as the concentration of fuel in air that will provide exactly the required amount of air to burn all the fuel

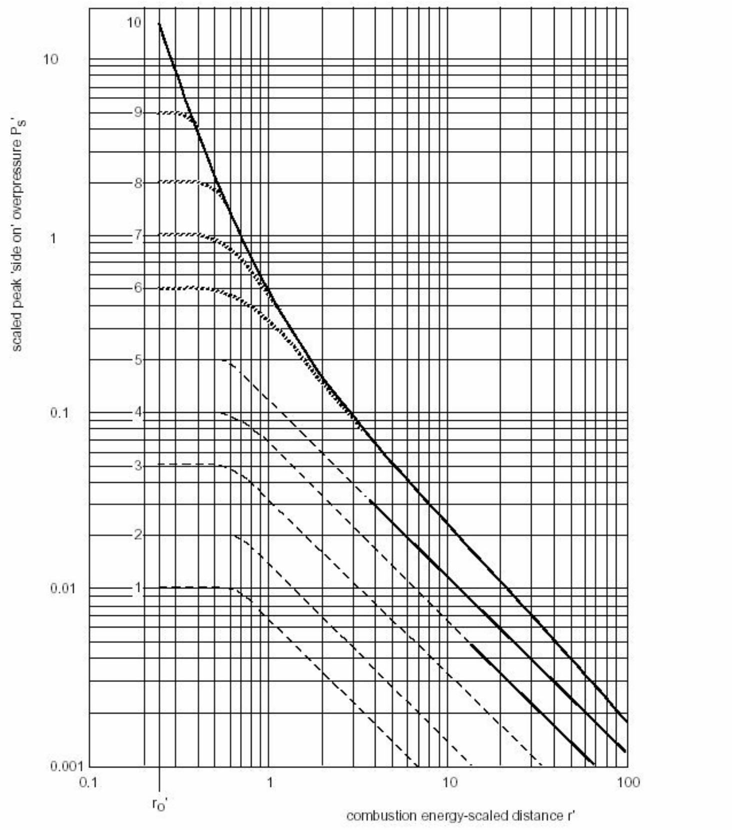

Figure 2 – Decay of Peak Side-on Overpressure Decay with Distance

The overpressure and distance are scaled to non-dimensional parameters as follows;

$$P'_S = \frac{\Delta P_S}{P_a} \quad (1)$$

$$P'_{dyn} = \frac{P_{dyn}}{P_a} \quad (2)$$

$$r' = \frac{r}{\left(E/P_a\right)^{\frac{1}{3}}} \quad (3)$$

Where E is the total combustion energy of the explosion, i.e. explosion energy, P_S is the peak side-on overpressure, P_a is the atmospheric pressure and r is the distance from centre of the explosion. In the original TNO multi-energy model, the total explosion energy is calculated assuming all the fuel present burns and 3.5MJ/m^3 was used as the representative heat of combustion for hydrocarbons. The choice the analyst must make to apply the Multi-energy model is to quantify E and select the most appropriate blast curve.

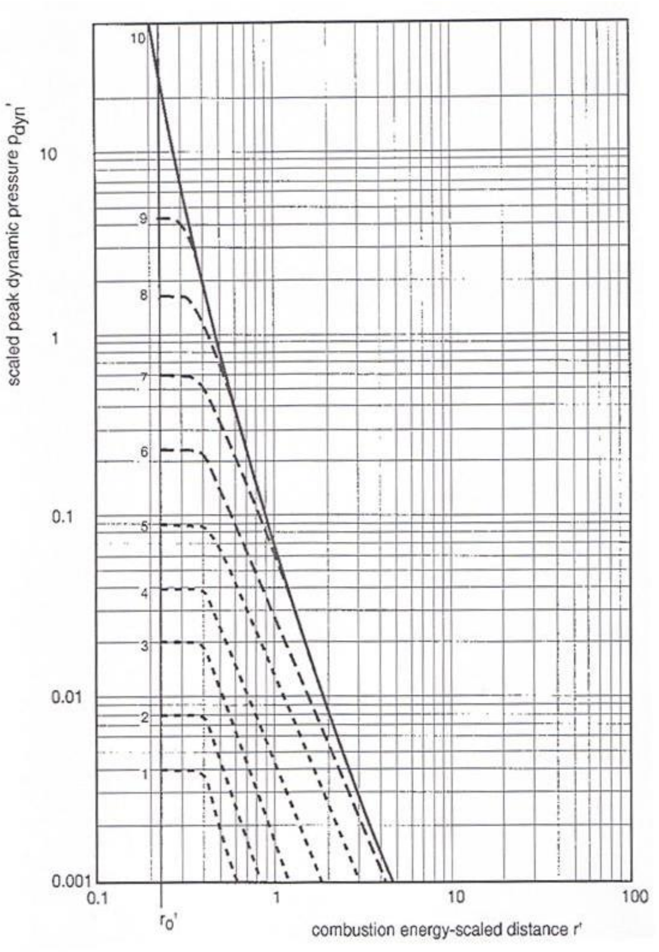

Figure 3 Decay of Peak Dynamic Pressure Decay with Distance

Duration of the blast wave is similarly obtained as a family of curves as shown in Figure 4.

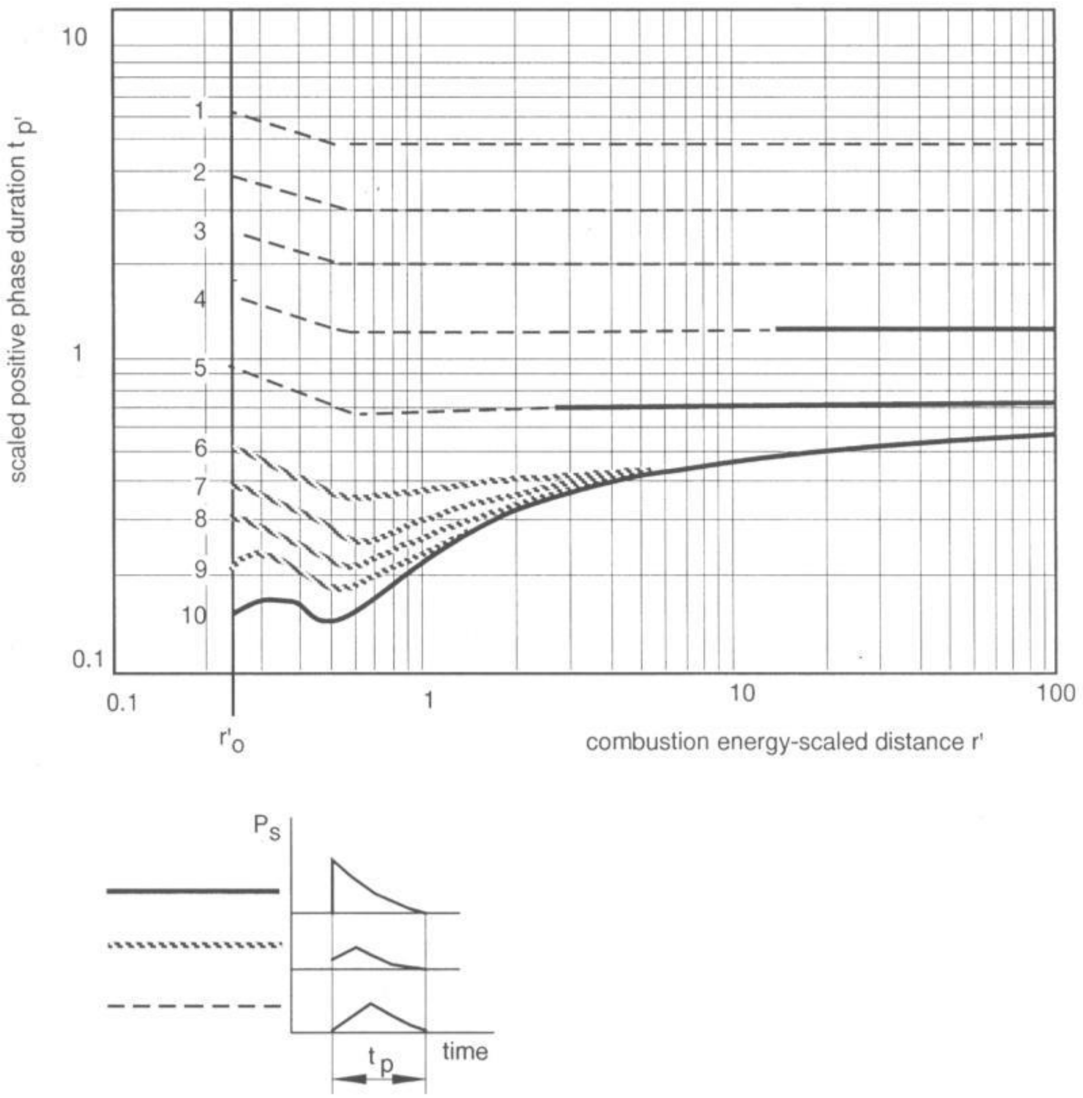

Figure 4 – Pulse Duration Vs Scaled Distance From Explosion Centre and Pulse Shape

The scaled positive phase duration is defined as;

$$t'_p = \frac{t_p v_a}{\left(E/P_a\right)^{\frac{1}{3}}} \qquad (4)$$

Where t_p is the positive phase duration and v_a is the speed of sound in air. Shape of the blast is indicated in Figure 4. The solid line indicates the range of shock wave behaviour (i.e. step change in overpressure) while the two dashed lines indicate a more gradual build up to the peak overpressure value of pressure waves.

To apply the model the analyst must convert the real-world scenario of concern into a nearest possible equivalent idealised hemispherical vapour cloud explosion and then use the appropriate curve to look up values for peak overpressures and duration at given distances from the centre of the explosion. The model is therefore very different to the CFD class of models where a specific explosion is modelled mathematically. As a result the CFD models may predict much more detailed outputs, such as overpressure behaviour with time and ignition location which may be at the edge of an explosion source, instead of central ignition. Using the Multi-energy model the outputs are limited to peak overpressures and positive phase duration and the explosion is symmetric.

2.2 Guidelines for application of the Multi-energy model

The task of converting a real-world explosion scenario into an equivalent idealised scenario is the main challenge for the analyst in applying the Multi-energy model. Ideally this process would be clear-cut and reproducible so different analysts will obtain identical and 'correct' results. In practice this is difficult to achieve. The 1997 Yellow Book and the projects of GAME, GAMES and RIGOS have all contributed towards making the application of the Multi-energy model accurate and reproducible. The ME model of OREM has been developed to automate the process based on a limited number of user-inputs and in this way contributes itself towards reproducibility.

The steps in applying the ME of OREM are as follows:

1. Define the release scenarios and weather conditions for consequence calculations (please refer to the manuals for discharge and dispersion models for details).

2. The process unit under consideration is divided into a number of obstructed regions; see Section 4 for details.

3. The explosion source is defined using GUI inputs and results of dispersion modelling (Section 5):

    3.1. The explosion sources are defined using vapour clouds from dispersion modelling and geometries of the obstructed regions (Section 5.1).
    3.2. The combustion energy E of each explosion source is estimated (Section 5.3).

4. The explosion effects are derived for explosion sources (Section 6)
    4.1. The peak overpressure P_o associated with each explosion
    4.2. Explosion results at a given point (overpressure, duration and impulse)
    4.3. Distance to a given overpressure or duration.
    4.4. Building damage

3. OVERVIEW OF THE BAKER-STREHLOW-TANG MODEL

3.1 Development of the model

The Baker-Strehlow-Tang (BST) model belongs to the same group of explosion models as the Multi-energy model using blast curves to predict the consequences of VCEs. The blast curves are usually developed based on CFD simulations of idealised cases and provide side-on overpressure and impulse or duration of positive overpressure as a function of distance from the explosion.

The Baker-Strehlow model was first published at the 28th Loss Prevention Symposium in 1994. It uses the Strehlow approach of selecting blast curves based on flame speed and the procedures of the Multi-energy model to determine explosion energy on the basis of confinement and congestion.

The Baker-Strehlow methodology includes a flame speed table and a family of blast curves for overpressure and impulse at flame Mach numbers covering deflagration to detonation. Since 1994, the model has evolved through ongoing research and applications in hazard analysis. The flame speed table has been updated to include a confinement of 2.5D in 1998 and a new table was published in 2005. The blast curves were updated in 1999 and the model was then renamed as Baker-Strehlow-Tang model[v].

3.2 The flame speed table

Strehlow suggested that the combined effect of confinement, fuel reactivity and congestion can be used to correlate flame speed and a table of 27 possible combinations of these three parameters was proposed based on 1D, 2D and 3D confinement. This is referred to as the old flame speed table in this documentation. This table has been updated twice to improve predictions because of new experimental and numerical results.

Process units normally have varying levels of confinement and congestion within them and it was found difficult to select either 2D or 3D confinement for hazard assessment. The solution for this was to introduce an intermediate level of confinement, i.e. 2.5D confinement, for the case where the confinement is made of either frangible panels or by near solid confinement panels[vi]. The flame speed for the 2.5D confinement was determined by simple linear interpolation from the flame speeds corresponding to the 2D and 3D confinement levels at the same congestion and fuel reactivity levels. Table 2 shows the updated flame speed table published in 2005 and it is used by the BST in OREM.

The 1D category in the old flame speed was not included in the updated table published in 2005 because the maximum flame speed achieved in 1D condition is usually a function of the ratio between length and diameter in addition to the three parameters required[iv]. So the BST methodology is not recommended for vapour cloud explosions of 1D flame expansion, and therefore BST of OREM can only be used for explosions with 2D, 2.5D and 3D confinement.

Because Phast and Safeti users may have studies created prior to version 6.6, 1D confinement has been kept in the Standard explosion model of Safeti as illustrated in
Table 1, but it is not available in the obstructed region explosion model.

Table 2 The updated Flame speed table for the BST model[iv]

Degree of confinement	Material reactivity	Congestion		
		Low	Medium	High
2D	High	0.59	DDT[2]	DDT
	Medium	0.47	0.66	1.6
	Low	0.079	0.47	0.66
2.5D	High	0.47	DDT	DDT
	Medium	0.29	0.55	1
	Low	0.053	0.35	0.5
3D	High	0.36	DDT	DDT
	Medium	0.11	0.44	0.5
	Low	0.026	0.23	0.34

3.2.1 Confinement

Confinement may also be described as degree of expansion. The new flame speed table has three confinement levels, i.e. 2D, 2.5D and 3D. An obstructed region is considered to be 3D if the flame is free to expand in all directions, 2D if the flame can only expand in two dimensions and is restricted in the third dimension and 2.5D where confinement is made of either frangible panels or by nearly solid confining planes (e.g. pipe rack where pipes are almost touching).

3.2.2 Congestion

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

- Low congestion level: a few obstacles in the flame's path or ABR less than 10% and a few layers of obstacles
- Medium congestion level: anything falling between the low and high levels.
- High congestion level: closely spaced layers of obstacles with an ABR of 40% or higher.

3.2.3 Reactivity

Material reactivity is rated as low, medium and high as by Zeeuwen & Wiekema[vii]. Methane and carbon monoxide are the materials regarded as low reactivity, whereas hydrogen, acetylene, ethylene, ethylene oxide and propylene oxide are highly reactive, and all other materials have medium reactivity. In general, medium reactivity single component fuels have laminar burning velocities between 0.45-0.75 m/s, low and high reactivity fuels have the velocities lower than 0.45 m/s (inclusive) and higher than 0.75 m/s respectively (Baker et al, 1997). However, laminar burning velocity is not the only variable determining material reactivity and there are materials which are classified to have high reactivity, but have a laminar burning speed less than 0.75 m/s, such as Ethylene.

3.3 Blast curves for explosion effects

The BST methodology consists of a family of blast curves for peak side-on overpressure and impulse against scaled distance for both the positive and negative phases of the blast wave of vapour cloud explosions. Because it is the positive phase which usually causes more damaging effects, BST only predicts the overpressure and impulse of the positive phase. These curves were derived from detailed numerical simulations of idealised free-air explosion scenarios with a fuel-air charge at stoichiometric[3] concentration.

[2] For DDT, the flame Mach number is assumed to be 5.2 for conservative predictions.

[3] Defined as the concentration of fuel in air that will provide exactly the required amount of air to burn all the fuel

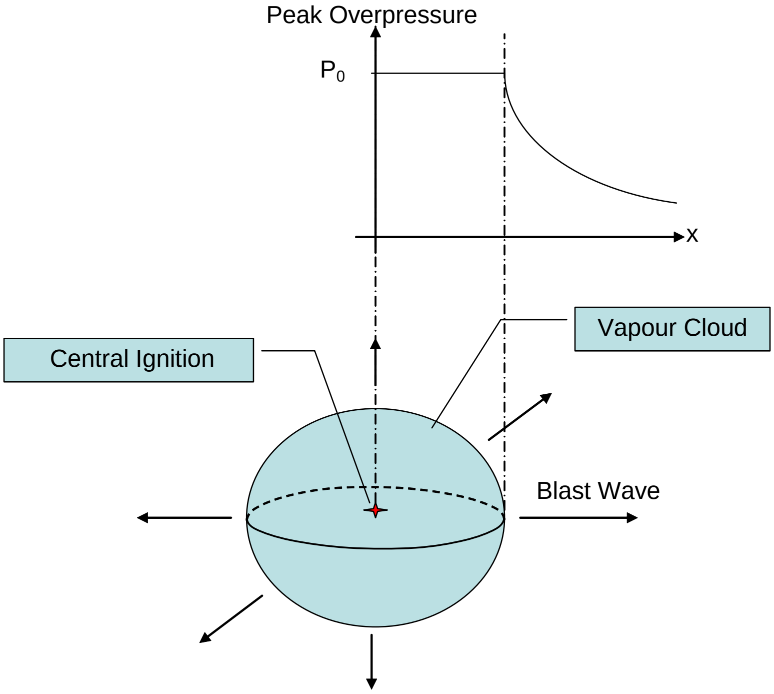

Figure 5 Idealised Vapour Cloud Explosion as the Basis for the BST blast curves

Figure 5 illustrates the idealised scenario and the main features of the model. The geometry is rotationally symmetric with an initial radius r_0. The symmetry is preserved by prescribing central ignition. The flame front will then propagate symmetrically from the centre. Because of the symmetry a single curve may describe the explosion behaviour. In the model the zone of combustion, i.e. within the explosion source, is characterised by a single peak overpressure level, P_0. Then, outside this zone the explosion is modelled as a blast wave that decays with distance as shown in Figure 6 for side-on overpressure Figure 7 for impulse. No blast curve is provided for dynamic pressure in the BST methodology.

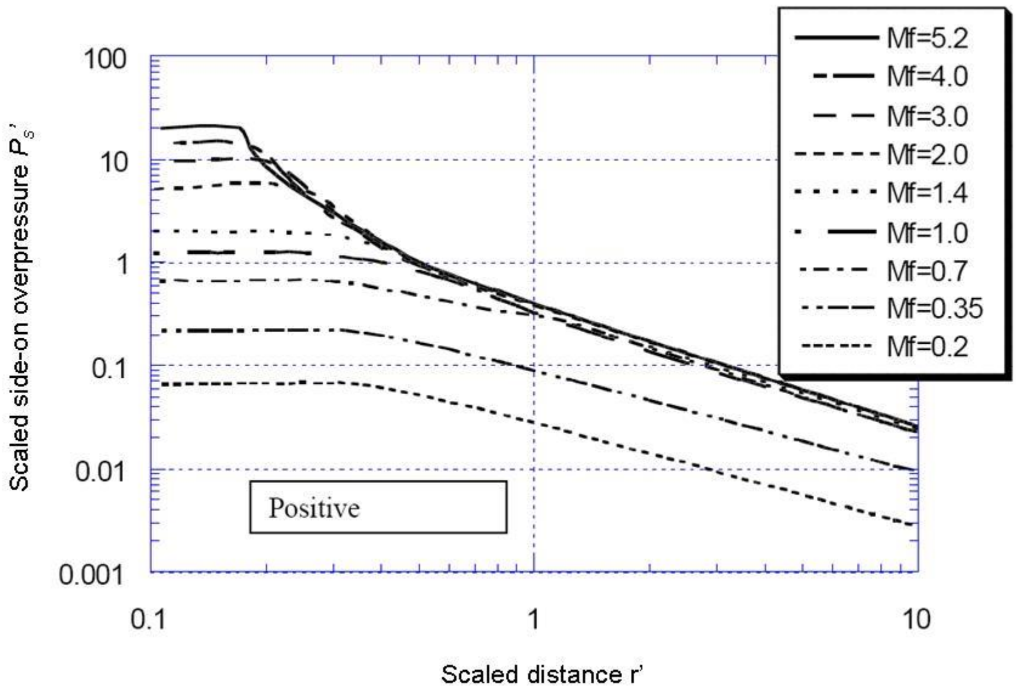

Figure 6 – Decay of Peak Side-on Overpressure Decay with Distance

The overpressure and distance are scaled as follows;

$$P'_S = \frac{\Delta P_S}{P_a} \tag{5}$$

$$r' = \frac{r}{\left(E / P_a \right)^{\frac{1}{3}}} \tag{6}$$

Where E is the total combustion energy, P_S is the peak side-on overpressure, P_a is the atmospheric pressure and r is the distance from centre of the explosion. The choice the analyst must make is to quantify E and select the most appropriate curve.

The family of curves for impulse is similarly obtained as the overpressure and is shown in Figure 7.

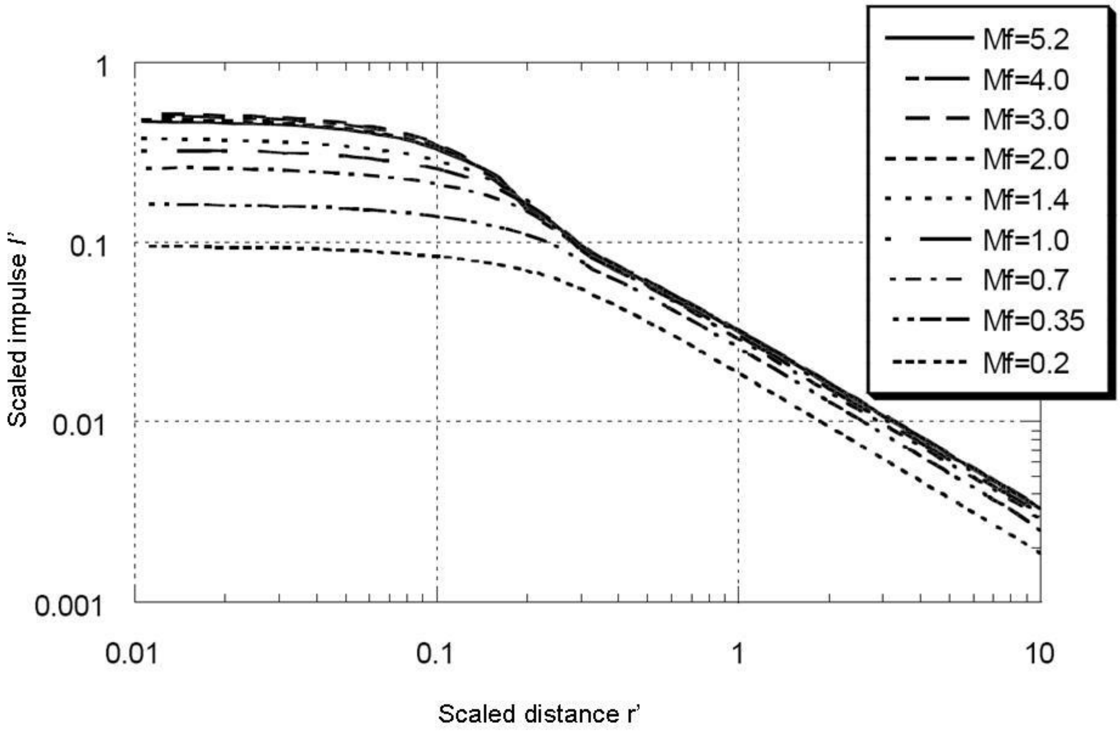

Figure 7 – Scaled Impulse Vs Scaled Distance From Explosion Centre

The scaled impulse is defined as;

$$I' = \frac{I v_a}{p_a \left(E / P_a \right)^{\frac{1}{3}}} \qquad (7)$$

Where I is impulse and v_a is the speed of sound in air.

To apply the model the analyst must convert a real-world scenario into a nearest possible equivalent idealised vapour cloud explosion and then use the appropriate curve to look up values for peak overpressure and impulse at given distances from centres of the explosion. The model is very different from the CFD class of models where a specific explosion is modelled mathematically with detailed description of the scenario. As a result the CFD models may predict much more detailed outputs, such as overpressure behaviour with time and ignition location which may be at the edge of an explosion source. With the BST model, the outputs are limited to peak overpressure and impulse and the explosion is symmetric.

3.4 Guidelines for application of the BST model using OREM

As for the Multi-energy model, the task of converting a real-world explosion scenario into an equivalent idealised scenario is the main challenge for the analyst in applying the BST model. Ideally this process would be clear-cut and reproducible so different analysts will obtain the identical and 'correct' results. In practice this is a difficult ideal to achieve. Baker et al[vi] had provided some guidance on applying the Baker-Strehlow methodology for process units, such as units with multiple explosion sources, elevated 2D confinement and fuel reactivity for mixtures. The BST model is designed to automate the process based on a limited number of user inputs and in this way contributes itself towards reproducibility.

The steps in applying the BST model in OREM are as follows:

1. Define the release scenarios and weather conditions for consequence calculations (please refer to the manuals for discharge and dispersion models for details).

2. The process unit under consideration is divided into a number of obstructed regions; see Section 4 for details.

3. The explosion source is defined using the GUI inputs and the results of dispersion modelling (Section 5):

    3.1. The explosion sources are defined using vapour clouds from dispersion modelling of consequence calculation and geometries of the obstructed regions as defined in Step 1 (Section 5.1).
    3.2. The combustion energy E of each explosion source is estimated (Section 5.3).

4. The explosion effects are derived for explosion sources (Section 6)
    4.1. Selecting blast curve for each explosion (Sections 6.1 & 6.2)
    4.2. Calculating explosion results at a given point, i.e. overpressure, duration and impulse (Section 6.4)
    4.3. Calculating distance to a given overpressure or impulse (Section 6.5).
    4.4. Determining building damage by explosions (Section 6.6)

4. DEFINITION OF OBSTRUCTED REGIONS

A vapour cloud explosion involves a flame moving through a fuel-air mixture. In absence of any turbulence generation the cloud will burn as a flash fire without the generation of high overpressures. However, significant turbulence can be generated by obstacles encountered by a flame as it propagates though the vapour cloud in obstructed regions. This process is subject to a positive feedback so that as more obstacles are encountered, more turbulence is generated and this further accelerates the flame. It is explosions that occur in the presence of obstacles that can generate overpressures with potential for extensive damage. So defining the obstructed region is a very important part of applying OREM.

In contrast to the cloud description that is generated by the discharge and dispersion models, the obstructed regions must be entered by the analyst. This process starts with the definition of a bounding box that encloses the relevant obstacles. How this may be achieved in practice is open to interpretation and can cause large differences in consequence and risk predictions. To aid this process the Yellow Book[viii] explains how the obstructed regions should be defined for the Multi-energy model. The BST methodology does not have very detailed procedures to define the obstructed region, i.e. Potential Explosion Sites (PESs)[vi]. The recipe in the Yellow Book for the Multi-energy model is presented here, and can also be used as a reference for the users of BST. Examples of applying the recipe step-by-step in process plants for the Multi-energy model can be found in the Yellow book.

4.1 Yellow Book guidance on defining obstructed regions

The steps defined in the Yellow book (Section 5.5.3) are:

1. Evaluate the area of interest and break down into geometric shapes

The method starts with the appraisal of the objects within the area of interest. The limits of the area of interest may be derived from the downwind distance of the LFL boundaries of the possible vapour clouds and/or a consideration of the extent of the objects that can contribute towards cloud obstruction. Then the objects themselves (assumed to be plant items such as pipes, vessels, support structures etc) may be approximated as geometric shapes;

- Cylinders with length l_c and diameter d_c
- Boxes with dimensions b_1, b_2, b_3
- Spheres with diameter d_s

2. Assume an ignition location

This is a necessary step before judgements to be made in step 3. Of course, in practice the ignition location will be variable and may have an impact on the subsequent calculations. No attempt has made to automate this variation, so a representative location needs to be chosen for all ignition scenarios. The user can refer to the worked examples in the GAMES report for examples of how to apply this step in practice. For instance, if there is a single obstructed region then the normal assumption would be to assume ignition in the centre of the obstructed region. This is a consistently conservative assumption. If there are multiple obstructed regions, then the assumption of different ignition locations may lead to the definition of multiple obstructed regions depending on the results of applying the rules in step 4.

3. Determine obstacle orientation

Take the smallest dimension oriented in a plane perpendicular to the flame propagation direction to be D_1, then;

- $D_1= l_c$ or d_c for a cylinder
- D_1=smallest of b_1 and b_2, b_2 and b_3, or b_1 and b_3 for a box
- $D_1= d_s$ for a sphere

Take the obstacle dimension parallel to the flame propagation to be D_2.

4 Build-up of obstructed region

This step is to define what obstacles belong to the obstructed region. The method uses 3 parameters; a factor 10 as a multiple of D_1, 1.5 as a multiple of D_2 and a distance 25m. Working out from the centre of the obstructed region obstacles are added according to the criteria if the centre-to-centre distance between objects is less than 10 D_1 or 1.5 D_2 except if the separation distance exceeds 25m (the separation distance being based on the outer boundary and not the centre-to-centre distance).

5. Defining a box containing the obstructed region

Obstructed regions of OREM are limited to rectangular boxes as illustrated by the worked examples in the TNO report. The TNO guidance is to;

Include the space between the outer obstacles and any confining surface (eg the ground) if the separation distance meets the criteria <10 D_1 or <1.5 D_2.

Exclude parts of obstacles that extend beyond the obstructed region – eg the top part of chimneys, distillations columns and pipes.

The free volume of the obstructed region is defined as V_{void} and can be deduced by subtracting the volume of the obstacles from the volume of the bounding box.

6. Subdivision into multiple boxes

The obstructed region may also be subdivided into multiple boxes to reduce the amount of free space within the region when a single rectangular box has included too much free space. These sub-boxes are rectangular and adjacent without overlapping.

7. Define additional obstructed regions if appropriate

There could be more than one obstructed region on the plant. It is a subject of research to determine whether or not the explosions from each region should be treated together or separate blasts and this is discussed in section 5.2.

Having been through this process the result is one or more rectangular bounding boxes that represent an obstructed region. If there are other regions on the plant that contain obstacles then these may be described by repeating this process.

4.2 Characterising obstructed regions for ME & BST

By this stage the volume of the obstructed region V_{or} is quite well characterised and the next step is to complete the description of the obstructed regions so that appropriate blast curves can be selected for consequence calculations.

ME The two types of obstructed regions for ME are “Defined Strength” obstruction and “Calculated Strength” obstruction. Explosion strength, i.e. as indicated by the blast curve number, is input directly by the user for an explosion defined by a “Defined Strength” obstruction. The curve number of an explosion defined by a “Calculated Strength” obstruction is determined by the model using the GAME correlations based on the data provided by the user through GUI for the obstructed region.

The data required to define a “Calculated Strength” obstruction are:
- Degree of expansion, 2D or 3D
- Volume blockage ratio, i.e. the ratio between volume of all obstacles and total volume of the obstructed region.
- Typical diameter of obstacles. This can be given directly or calculated as the hydraulic diameter by supplying the model with the surface area of the obstacles.
- Flame path length. This can be supplied directly or calculated by the model by assuming a hemi-spherical cloud shape.

When multiple obstructed regions are included inside an explosion source, blast curves for the explosion are selected based on combined characteristics of the obstructed regions as given in section 6.2.

BST The two types of obstructed regions allowed in BST are “Defined Flame Speed” obstruction and “Calculated Flame Speed” obstruction. Flame Mach number is input directly by the user for an explosion defined by a “Defined Flame Speed” obstruction. The curve number of an explosion defined by a “Calculated Flame Speed” obstruction is determined by BST using the flame speed table as given in section 3.2 using the data provided by the user for the obstructed region.

The data required to define a “Calculated Flame Speed” obstruction are:
- Degree of confinement, 2D, 2.5D or 3D
- Volume blockage ratio, i.e. the ration between volume of all obstacles and total volume of the obstructed region.
- Congestion. This can be given directly as low, medium or high or determined by BST using one of the two methods given later (section 6.3.4)
- Material reactivity. This can be supplied directly or determined by BST using the laminar burning velocity of the material.

When multiple obstructed regions are included inside an explosion, Flame Mach number for the explosion are decided based on combined characteristics of the obstructed regions as given in section 6.

5. DERIVATION OF EXPLOSION SOURCES

5.1 Unobstructed and obstructed parts of a vapour cloud

We are concerned with the explosion hazard caused by the portion of a vapour cloud that is within the flammable limits at a given time. Therefore the LFL boundary of the cloud at a given time is the primary description of the cloud. To describe the cloud we take the output from the dispersion model being used (typically the UDM[ix]). Then various post-processing functions are applied to obtain the required description of the cloud at a given time, i.e. a cloud view.

A cloud view is divided into a given number of steps or steps with a given size. The data to define a cloud view are:

Time from start of segment Time step of the view Step size Step Number
Downwind positions of the steps
Height of centreline at the downwind positions
Half-width to LFL(fraction) at the downwind positions
Half-height to LFL(fraction) at the downwind positions
Flammable mass at the downwind positions

A number of cloud views, particularly for instantaneous releases, may be needed to accurately represent the dispersion from the release to the cut-off point when a cloud view is no longer considered by Phast and Safeti. An example of a ground-level view generated by the UDM is shown in
Figure **8**. The LFL corresponds to the 12000ppm contour.

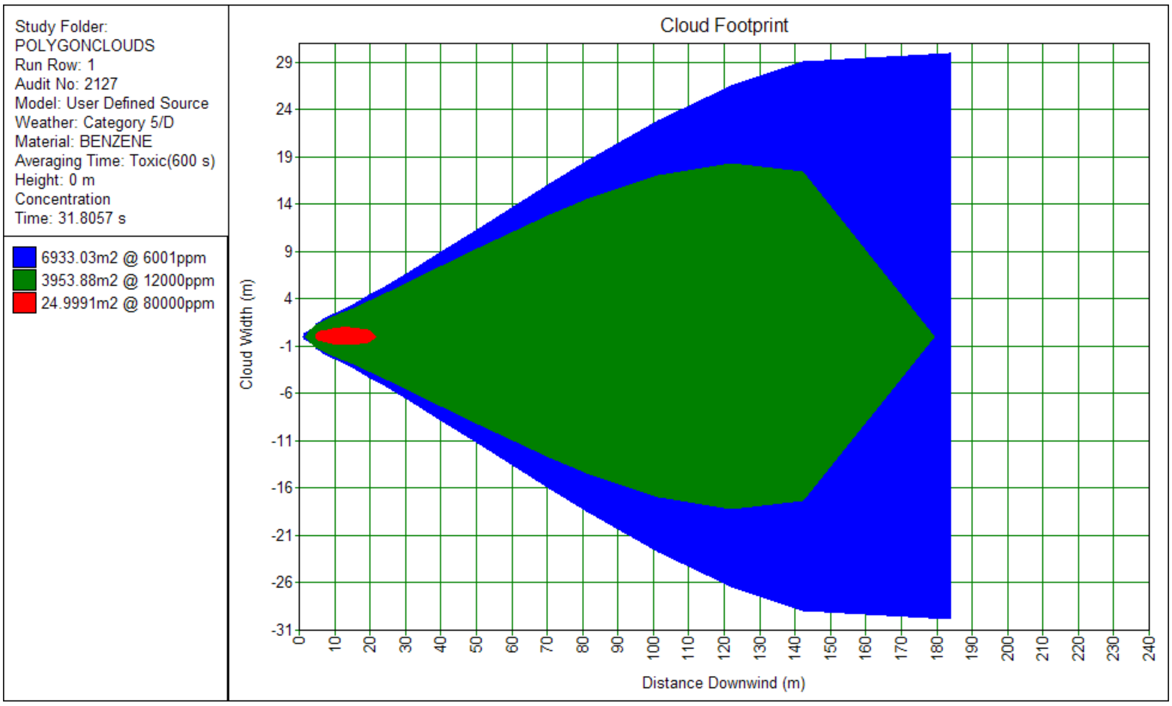

Figure 8 – Example of Cloud Boundaries at a Specific Time

A cloud may or may not exist within any obstructed regions. If it does not, then we have the simplest situation in the sense that we may have a single unconfined explosion source for this case for the Multi-energy model. Even so, we have still have to define the centre, determine which curve to use and the total combustion energy of the explosion. Typically, the blast damage from such an explosion will be limited since without the obstructions the overpressure generated will be low. So, this type of scenario is not of greatest interest for explosion. As to the BST model, which is not applicable to the unconfined explosion, so we have no explosion for this case.

Clouds where all or part of the flammable volume is within regions of obstacles have the potential to give much greater blast damage. Figure 9 illustrates a simple view of such a vapour cloud. It starts within an obstructed region and disperses downwind so that part of the cloud is within the obstructed region and part of it is outside. For BST, this defines only one confined explosion sources, i.e. a confined explosion source for flammable mass inside the obstructed region. Apart from the confined explosion, ME could also define an unconfined explosion source by the part outside the obstructed region.

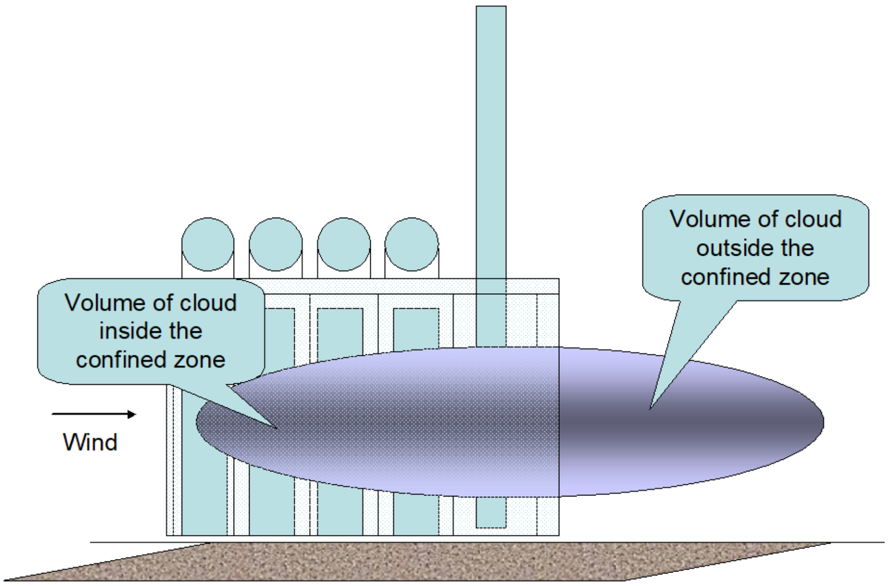

Figure 9 – Example of a Vapour Cloud Starting in an Obstructed Region

A key point becomes apparent when viewing the cloud in this way. The dispersion models being used do not explicitly model the obstructions. There are some inputs that may be set to affect the dispersion results in a general way. For instance, the release may be defined as 'impinged' and/or the surface roughness factor may be set high. However, the fact remains that the cloud does not interact directly with the obstructions.

To manage this important limitation three options are available to users;

1) influence of the obstructions on the cloud is already taken into account in the dispersion model, or
2) when the cloud starts in an obstructed region then this region fills up first before the cloud moves downwind[4]
3) a cylinder shape spreading in all directions is assumed for the cloud[5]

Option 1 enables the dispersion results of UDM to be used as inputs to the explosion model. Options 2 & 3 mean that the dispersion predictions are manipulated before being used by the explosion model. Details of options 2 & 3 are given in section 7.

Here we have given a simple example, but the general cases will be more complex. The vapour cloud may have multiple segments or be present in a number of obstructed regions, so one scenario can have multiple explosion sources. In those cases, the separation between obstructed regions becomes important.

5.2 Methods to apply the critical separation distance

An important aspect of applying the Multi-energy and BST models is determining explosion sources and this is difficult if a flammable vapour cloud covers more than one obstructed region separated by open spaces. If the open spaces are sufficient, the flame of a vapour cloud explosion will slow down significantly before reaching adjacent obstructed regions and therefore the explosion develops multiple separate blasts. However, if the spaces are small, the flame will travel into

[4] In this method the cloud is simply prevented from leaving the obstructed region until the cloud volume equals the volume of the obstructed region. Then, only the surplus volume in the cloud is modelled drifting downwind. It may then encounter other obstructed regions where it now behaves like the clouds in option 1.

[5] A cylinder shape with given height/radius ratio is used for a flammable cloud released inside an obstructed region.

the adjacent obstructed regions without significantly slowing down, consequently the explosion would produce only one single blast and should be modelled with the combined energy from all obstructed regions. Critical separation distance is the threshold distance that enables to discriminate between a single combined blast or multiple blasts.

The Yellow book[viii] 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 25m for the application of the Multi-energy model. This suggests a Critical Separation Distance equal to 10 obstacle diameters with an upper bound of 25 m.

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

The RIGOS[x] project has found the separation distance suggestion by the Yellow Book for the Multi-energy model is not always conservative, in particular in the higher explosion overpressure range. Based on measurements from a series of controlled tests, RIGOS recommended a critical separation ratio based on the explosion overpressure as shown in **Figure 10**:

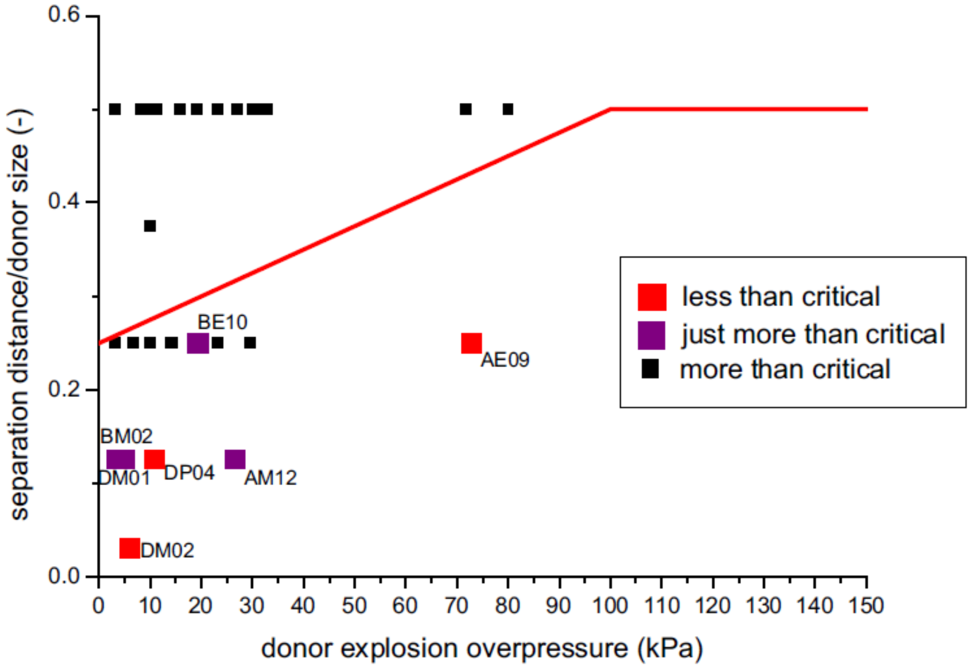

Figure 10 Critical separation distance recommended by RIGOS[x]

So the critical separation distance is not a fixed value for all explosions, but depends on overpressure of the donor explosion as:

- A critical separation distance equals to 1/2 of the donor dimension if the donor explosion overpressure is higher than 100kPa.
- A critical separation distance equals to 1/4 of the donor dimension if the donor explosion overpressure is lower than 10kPa.
- A linear interpolation for the overpressure in between.
- Connecting obstacles with sufficient cross sectional areas can substantially increase the threshold of separation distance.

OREM has provides two options to define the critical separation distance as:

- Option 1: Separation distance. In this method, users provide a separation distance directly as the recommendation by Baker et al for the BST model or the recommendation by Yellow Book for the Multi-energy model.

  Using this option, OREM will then calculate the shortest edge-to-edge distance between any two obstructed regions, a separation less than the specified separation distance indicates to combine the vapour cloud within them to form a combined explosion source, and separate explosion sources otherwise.

- Option 2: A critical separation ratio. In this case, users provide a critical separation ratio as recommended by RIGOS for the Multi-energy model. This is the default option with a ratio of 0.5 in Safeti.

  Using this option OREM will then compare the shortest edge-to-edge distance between any two obstructed regions to their longest dimension (i.e. length, width or height), a ratio less than the given value indicates to combine the vapour cloud within them to form a combined explosion source, and separate explosion sources otherwise. So the larger obstructed region is always assumed as the donor source in this process as a conservative approach.

  In OREM, the critical separation ratio is given as a constant and applied for all obstructed regions of a runrow and is not adjusted according to the predicted explosion overpressures as recommended by RIGOS. To apply the RIGOS recommendations rigorously, users are advised to work out the critical separation ratio based on their experiences or preliminary overpressure results of the largest explosion.

  BST The BST methodology has not recommended a separation ratio and the users should set the separation distance based on their experiences or the requirements of their study. The default setting is considered to be relatively conservative for both ME and BST.

5.3 Methods to define explosion sources

5.3.1 Introduction

One of the key tasks of applying ME or BST is to determine the combustion energy of each explosion. Since there can be multiple obstructed regions covered by a cloud there can be multiple explosion sources to calculate.

In Phast and Safeti, the flammable mass and its distribution in a cloud are known from dispersion modelling as briefly described in Section 5.1, so it seems logical to use this to define the total combustion energy and this was recommended for the BST methodology by Baker et al[vi]. However, no more than the stoichiometric concentration of a material may burn within the obstructed region because of the limited supply of air, so the combustion energy derived from the cloud has to be limited by the stoichiometric concentration locally.

The approach adopted by OREM for ME and BST is to use the LFL boundaries of the cloud and calculate the volume that overlap with obstructed regions and flammable mass within the volume. The explosion energy is then calculated with one of the two options:

- Integrated mass. The explosion energy of this method is defined by the combustion energy of the flammable mass contained inside the overlapped regions but limited by the stoichiometric concentration at locations of high vapour concentration and an efficiency factor as given in section 5.3.3. The efficiency factor has a default value of 100%.
- Stoichiometric concentration. In this method, the explosion energy is the product of the overlapped volume, the specific heat of combustion of the flammable vapour concerned and an efficiency factor as explained in section 5.3.4.

5.3.2 Volume and centre of the confined explosions

Thus evaluation of the obstructed flammable mass requires the calculation of the volume of flammable material trapped in obstructed regions and its centre. As illustrated in Figure 11 for a cloud dispersing through part of a plant, the obstructed region will in general be at an angle to the cloud. The volume of the obstructed cloud is obtained by integration over the extent of the obstructed regions.

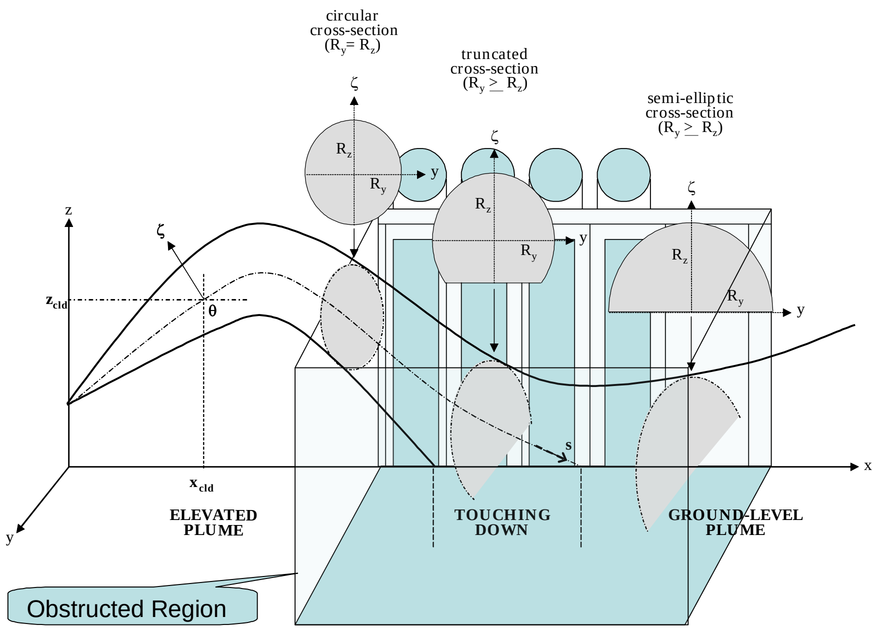

Figure 11 – Illustration of a UDM cloud moving through an obstructed region

<u>Evaluation of the obstructed cloud volume</u>

An integration is required along the path of the cloud in the downwind direction x to obtain the obstructed volume. The obstructed region can be made up of a number of sub-regions. These sub-regions do not overlap and can have different heights and gaps in between. As illustrated in Figure 12 the obstructed region is constructed from 3 sub-regions labelled A, B and C. The integration starts at the greater of the upwind x position of the flammable cloud, $x_{l,c}$ and the lowest x position of the obstructed regions, $x_{l,o}$. It finishes at the lower of the downwind limit of the flammable cloud, $x_{h,c}$ and the greatest *x* position of the obstructed regions, $x_{h,o}$.

Equation (8) defines the obstructed cloud volume by the *o-th* obstructed region and $A_{i,o}$ is the cross sectional area of the obstructed cloud in the obstructed region at i-th discretisation distance as given later.

$$V_{gr,o} = \sum_{i=1}^{i=N_X-1} [(x_{i+1} - x_i) A_{i,o}] \qquad (8)$$

The total obstructed volume V_{gr} of a confined explosion source is the summation of the intersections between the cloud and all obstructed regions as

$$V_{gr} = \sum_{i=1}^{i=N_X-1} \left((x_{i+1} - x_i) \sum_{o=1}^{o=N_O} A_{i,o} \right) \qquad (9)$$

Here N_o is the number of obstructed regions included in the explosion, N_X the number of downwind discretisation distances, and the downwind discretisation distances x_i *(i=1,… N_X)* given by

$$x_i = x_1 + \frac{i-1}{N_X - 1}\left(x_{N_x} - x_1\right), \quad with \ \ x_1 = \max[x_{l,c}, x_{l,o}], \ x_{N_x} = \min[x_{h,c}, x_{h,o}], \qquad (10)$$

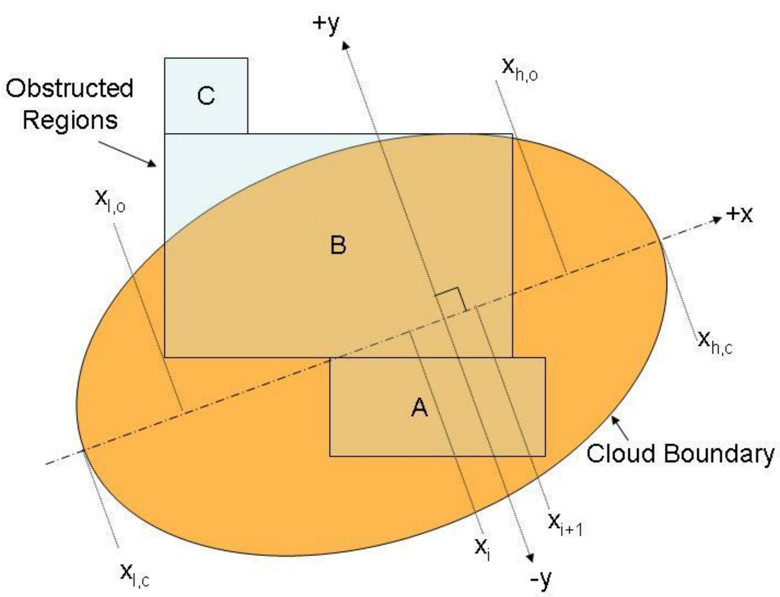

Figure 12 – Horizontal cross-section of a cloud view intersected by obstructed regions

The area $A_{i,o}$ is evaluated in the *y-z* plane at the midpoint between x_i and x_{i+1} and can be calculated from the limits of the obstructed region and cloud geometry in the *y* and *z* directions as shown in Figure 13.

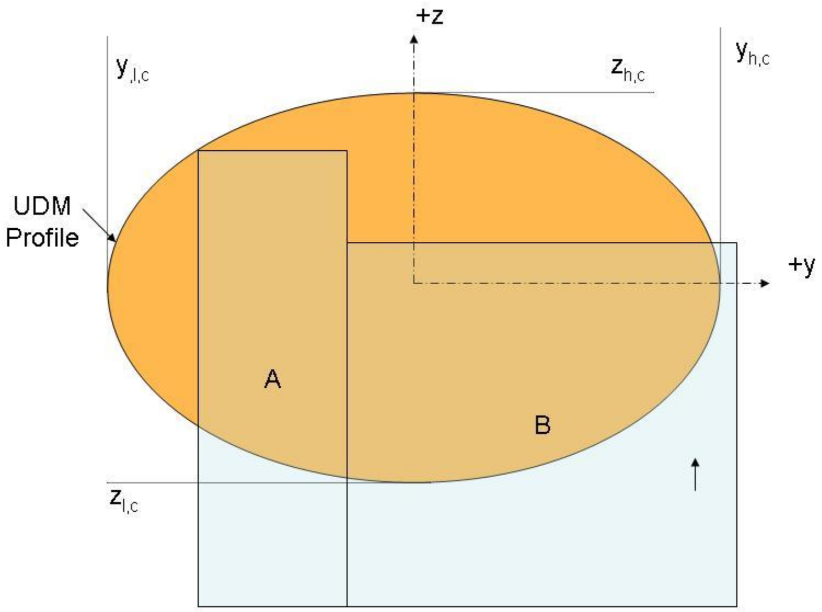

Figure 13 – Vertical cross-section of a cloud view and obstructed regions
[vertical plane located at downwind distance $(x_i+x_{i+1})/2$]

The algorithm used in OREM to calculate the cross-sectional area is based on the formula for a truncated ellipse. If a single truncation line is considered as shown in Figure 14 then the shaded area may be calculated according to equation (11). Successive applications of this formula may be applied to obtain the required values of $A_{i,o}$ and $A_{ttl,i}$.

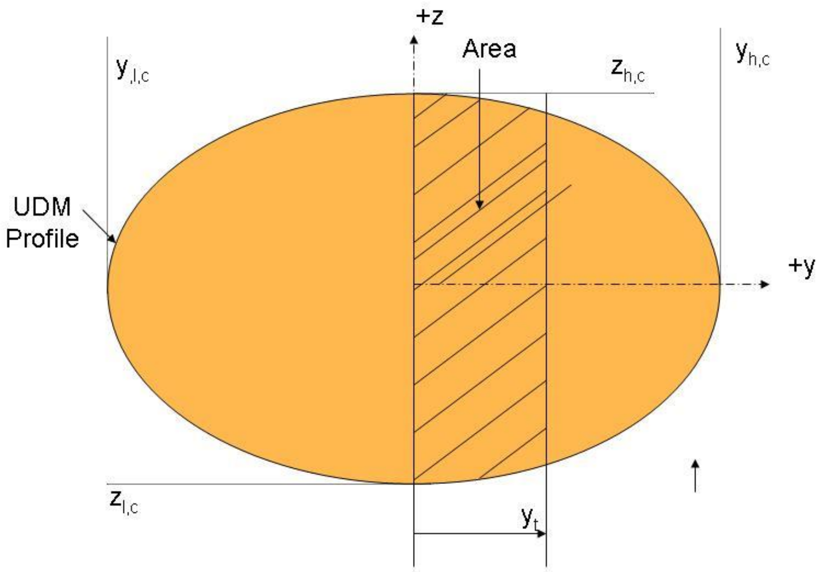

Figure 14 – Area of a Truncated Ellipse

$$A_t = by_t\sqrt{1-\left(\frac{y_t}{a}\right)^2} + ba\sin^{-1}\left(\frac{y_t}{a}\right) \tag{11}$$

The total cross-sectional area of intersection of the explosion at *i*-th discretision distances as

$$A_{ttl,i} = \sum_{o=1}^{o=N_O} A_{i,o} \tag{12}$$

Centre of the explosion

The explosion centre is needed to determine the distance from an explosion for consequence and risk assessment. This is defined as the weighted average centre of the overlapped volume as:

$$x_{ex} = \frac{\sum_{i=1}^{i=N_X-1}\left(\frac{(x_{i+1}+x_i)}{2}(x_{i+1}-x_i)\sum_{o=1}^{o=N_O}A_{i,o}\right)}{V_{gr}} \tag{13}$$

and

$$y_{ex} = \frac{\sum_{i=1}^{i=N_X-1}\left((x_{i+1}-x_i)\sum_{o=1}^{o=N_O}\frac{(y_{i,h,o}+y_{i,l,o})}{2}A_{i,o}\right)}{V_{gr}} \tag{14}$$

and

$$z_{ex} = \frac{\sum_{i=1}^{i=N_X-1}\left(\left(x_{i+1}-x_i\right)\sum_{o=1}^{o=N_O}\frac{\left(z_{i,h,o}+z_{i,l,o}\right)}{2}A_{i,o}\right)}{V_{gr}} \quad (15)$$

5.3.3 Explosion energy by concentration distribution integration

In this method, the explosion energy of an explosion is defined as the combustion energy of the flammable mass trapped inside the overlapped regions between a cloud and the obstructed regions within the explosion source but limited by the stoichiometric concentration at locations of high vapour concentration as equation (16).

$$M_{gr} = \sum_{i=1}^{i=N_X-1} \min[\frac{m_{cloud,i}}{A_{cloud,i}} A_{ttl,i}, A_{ttl,i}(x_{i+1}-x_i)C_{ST}\rho_v] \quad (16)$$

Here $m_{cloud,i}$ is the cloud flammable mass within *i*-th discretisation distance (i.e. between x_i and x_{i+1}) which is assumed to be distributed uniformly over the cross sectional area $A_{cloud,i}$ but varies with x position, ρ_v is density of the flammable material without mixing with air and C_{ST} is the stoichiometric concentration fraction of the material.

Fuel density ρ_v in equation (16) varies with cloud temperature and it is high at a low temperature. This indicates that the same volume would contain more flammable mass at a low temperature, and therefore more combustion energy. On the other hand, the VCE of a cloud at a low temperature usually burns at a slow speed initially, therefore, it leads to a lower explosion efficiency and then lower combustion energy. An accurate consideration of temperature effect on the combustion process of a VCE will need more advanced modelling tools, such as CFD. The balance adopted by OREM is to ignore the temperature effect on explosion efficiency f_e and this may slightly overestimate the explosion energy, and then to use the fuel density at the ambient temperature *as* ρ_v in equation (16) and this usually under-estimates the energy. Hopefully, these two effects counterbalance each other and the combustion energy of the explosion is calculated as

$$E = f_e H_{comb} \sum_{i=1}^{i=N_X-1} \min[\frac{m_{cloud,i}}{A_{cloud,i}} A_{ttl,i}, A_{ttl,i}(x_{i+1}-x_i)C_{ST}\rho_v^{'}] \quad (17)$$

Here $\rho_v^{'}$ is density of the flammable material without mixing with air at the atmospheric temperature.

5.3.4 Estimating explosion energy using stoichiometric concentration

When explosion energy is estimated using stoichiometric concentration as explained in section 5.3.1, it is calculated as

$$E = f_e H_{comb} C_{ST} \rho_v^{'} \min(V_{void}, V_{gr}) \quad (18)$$

Here V_{void} is the void volume of the obstructed regions within an explosion source and it acts as a upper limit here because the blockage of obstacles are not considered in V_{gr} as described in section 5.3.2, f_e is the efficiency factor of the explosion, and $\rho_v^{'}$ is density of the flammable material without mixing with air at atmospheric temperature as explained in section 5.3.3.

Equation (18) has assumed stoichiometric concentration inside the obstructed cloud, consequently, the equivalent flammable mass of that energy can be actually higher than the flammable mass trapped inside the obstructed volume if the cloud has a concentration generally lower than the stoichiometric concentration. So this method should always produce more conservative predictions than estimating explosion energy by cloud concentration integration as described in previous section 5.3.3. This method is similar to the approach adopted by GAME & GAMES for the Multi-energy model, but it is material specific because the heat of combustion of the material concerned is used here, instead of a typical value for all materials.

5.3.5 Explosion source from the Standard explosion model

In standard Phast or Safeti, obstructed regions were not considered in detail as described above to define explosion sources. Instead, the volume of obstructed regions is supplied through GUI with no geometry. The explosion source is defined with an explosion mass based on the obstructed volume supplied and explosion centre at either cloud front or cloud centroid when ignited. This method is named as the Standard model as explained in section 1.1.

<u>The Equivalent Stoichiometric Cloud</u>
The starting point of this method[6] is to obtain the cloud flammable mass M_c (fuel mass in cloud with concentration larger than LFL). Then an 'equivalent' stoichiometric cloud', i.e. a cloud with a flammable mass of M_c at the stoichiometric concentration C_{ST}, is defined with a volume given by;

$$V_{Total} = \frac{M_c V_F}{C_{ST}} \quad (19)$$

Where;

C_{ST}	Fuel stoichiometric concentration fraction (m^3 of fuel /m^3 of mixture) at atmospheric temperature.
M_c	Total flammable mass in the vapour cloud (kg)
V_F	Specific volume of the fuel calculated at atmospheric conditions (m^3/kg)
V_{Total}	Total volume of the equivalent cloud (m^3)

This calculation makes the assumption that the flammable cloud concentration is uniform, all vapour (i.e. no liquid fraction of fuel) and at atmospheric conditions (temperature and pressure) [7].

<u>Obstructed fuel mass</u>
The obstructed volume is specified as volume $V_{or,j}$, where $j=1$, N_{obstr}. The model works using fractions of the total volume so that the fraction is calculated according to[8];

$$f_j = Min\left[\frac{V_{or,j}}{V_{Total}} \min\left(\frac{V_{Total}}{\sum_{i=1}^{N_{Obstr}} V_{or,i}},1\right),1\right] \quad (20)$$

Where N_{obstr} is the number of obstructed volume supplied.

The flammable mass M_{gr} of a confined explosion is;

$$M_j = f_j M_c \quad (21)$$

ME For ME, the flammable mass of the unconfined explosion is calculated as:

$$M_{unconfined} = M_c - Min\left[M_c, \sum_{j=1}^{j=N_{Obstr}} M_j\right] \quad (22)$$

<u>Centre of the explosion</u>

[6] This method is the original method used in PHAST and does not take into account the location of the obstructed regions and the cloud. It could be improved by using more information about the cloud (volume, temperature etc)

[7] Note that these conditions are frequently not met during real vapour cloud dispersion

[8] These fractions can add up to more than 1. Perhaps this is the intention but it seems a little strange. The total volume is not returned by the entry point and this would be a useful output

When a flammable cloud reaches an ignition source, an explosion is then defined with its centre at either cloud front or cloud centroid as the user has selected (i.e. Parameters/Explosion parameters/Overpressures).

<u>Blast curve of the explosions</u>

ME The blast curve for each explosion is supplied as explosion strength through the GUI.

BST Flame Mach number for the explosion is either given as flame Mach number through the GUI or determined by BST using the Flame speed table with input of confinement, congestion and material reactivity.

6. EXPLOSION EFFECTS

6.1 Blast curves for explosion sources formed from single obstructed region

6.1.1 Multi-energy model

ME Two obstruction types are available for ME, i.e. “Defined Strength” obstruction and “Calculated Strength” obstruction. For an explosion formed by a Defined Strength obstruction, the explosion strength is input directly by the user (i.e. the blast curve number). Together with the flammable volume, mass and explosion centre of the explosion source as given in previous sections, the blast curve is used to carry out consequence and risk predictions.

For an explosion formed by a Calculated Strength obstruction, the blast curve number is determined by ME based on parameters defining the obstructed region, including degree of expansion, VBR, typical equipment diameter and flame path length using one of two[9] correlations (as described on page 9 in the section ‘Characterisation of the Source Strength’ of the GAMES report).

For 3D expansion;

$$P_0 = 0.84\left(\frac{VBR\,.\,L_P}{D}\right)^{2.75} S_L^{\;2.7} D^{0.7} \qquad (23)$$

and for 2D expansion;

$$P_0 = 3.38\left(\frac{VBR\,.\,L_P}{D}\right)^{2.25} S_L^{\;2.7} D^{0.7} \qquad (24)$$

Where P_o is the peak overpressure at the explosion centre (i.e. initial peak overpressure of an explosion), *VBR* is the volume blockage ratio of the obstructed region, L_p is the flame path length and *D* is the typical diameter of the obstacles. S_L is the laminar burning velocity which is a property of the flammable material.

Once P_0 is calculated the appropriate blast curve can be selected by comparing this value with the value of overpressure for each curve of the Multi-energy model at radii less than r'_0.

To use these GAME correlations, the user must specify further details of the obstructed region as given below.

<u>Degree of expansion</u>

Since there are two correlations it is necessary for the analyst to characterise the level of expansion and very often this will fall somewhere between 2D and 3D, for instance a region partially covered by panels at a height. The section ‘Choice of a Correlation’ (p13) in the GAMES guidelines state that the height over length ratio should exceed a value between 5 and 10 to separate the correlations but logically we interpret this as meaning the reciprocal of this ratio. This interpretation is confirmed by the description on page 96 where the advice is to use a ratio of 5 as the criterion. Furthermore, the examples indicate that the Multi-energy model tends to be conservative so the advice here is to specify 2D confinement only if the geometry is unambiguous or conservatism is desired.

<u>Typical dimension, *D*</u>

The typical dimension D can be calculated in various ways. Hydraulic diameter was found in the GAMES research to give reasonable overall predictions (see Conclusions and Recommendations section, p99). It is defined as:

$$D_{hym} = \frac{4V_{obst}}{A_{obst}} \qquad (25)$$

[9] The GAME work identified 6 such correlations; combinations of degree of confinement (1,2 and 3D) and ignition strength (High, Low); the available experimental data supported the derivation of only two of these combinations; Low energy ignition and 2 and 3D confinement. These cover the most common practical applications.

The hydraulic diameter is used as the typical diameter by ME if the surface area of obstacles is supplied at GUI, instead of typical diameter, to define an obstructed region.

Volume Blockage Ratio, *VBR*

The volume blockage ratio VBR is the ratio of the total volume of the obstacles divided by the volume of the obstructed region as

$$VBR = \frac{V_{obstr}}{V_{or}} \qquad (26)$$

Flame Path Length, L_p
In ME, flame path length may be specified directly by the analyst or use the method recommended by the GAMES report which sets the flame path length to the radius of a hemisphere of the same volume as the obstructed cloud as given by equation (27).

$$L_p = \left(\frac{3V_{gr}}{2\pi}\right)^{1/3} \qquad (27)$$

6.1.2 Baker-Strehlow-Tang Model

BST The two types of obstructed region for BST are “Defined Flame Speed” obstruction and “Calculated Flame Speed” obstruction. Flame Mach number is given by the user for the former and the flame Mach number for the latter is decided by BST using the flame speed table as given in section 3.1 based on details provided for the obstructed region, i.e. confinement, congestion and material reactivity.

For an explosion source formed by single obstructed region, the blast curves for the explosion are identified by the flame speed of its underlining obstructed region. Together with the flammable volume, mass and explosion centre for the explosion source as given in chapter 5, consequence and risk predictions can be carried out.

6.2 Blast curves for explosion sources formed from multiple obstructed regions using ME

ME Because of the complexity in process plants, such as obstacles with different sizes and orientations and separation between facilities, using a single obstructed region to represent all obstacles in a plant could have included a large volume of free space. The GAMES study has recommended to break a plant into multiple sub-regions and each has a small volume with its own characteristics for the Multi-energy model. Baker et al[vi] has recommended that congested zones with separation greater than 5m can be considered as separate potential explosion sites.

When an explosion source is defined by more than one obstructed region, a set of combined characteristics are needed to determine strength for the explosion.

6.2.1 “Defined Strength” obstructions

ME A blast curve is given directly for each obstructed region of this type when it is created and this is the explosion strength if the explosion is formed by this obstructed region alone. When a confined explosion sources is formed by more than one “Defined Strength” obstructions, the curve number for the explosion is usually higher than that of its underlining obstructed regions because of the scaling effect of the vapour cloud explosions. Experimental data have shown that geometrically similar explosions produce stronger blast on a large scale. This is also indicated by the GAME correlations, i.e. higher initial overpressures for explosions with longer flame path lengths. However, because of the uncertainty in selecting blast curve for obstructed regions, which is still largely dependent on judgement and experience of the analyst, and also in combining them for an explosion if different blast curves are given for the underlining obstructed regions, a simple volume-weighted approach is adopted in ME for ease of use.

The blast curve of the explosion is determined as

$$\bar{n}_c = \frac{\sum_{i=1}^{N_{obstr}} V_{gr,i} n_{c,i}}{\sum_{i=1}^{N_{obstr}} V_{gr,i}} \qquad (28)$$

Where:

N_{obstr} is the total number of obstructed regions in an explosion source.
$V_{gr,i}$ is the obstructed cloud volume in an obstructed region "*i = 1,…Nobstr*"
$n_{c,i}$ is the given curve number for the *i-th* obstructed region in the explosion source.
$\bar{n}_c$ is the net curve number for the explosion source.

In practice, selecting a blast curve for an obstructed region may be equally difficult as selecting a blast curve for an explosion, so it is more likely that a blast curve is selected for an explosion straightaway on the basis of study requirements or certain explosion parameters, such as reactivity of the cloud, instead of selecting a curve for each of the obstructed regions. After a blast curve has selected for an explosion, the same curve should be given to all obstructed regions forming it and this makes the volume-weight approach easy to use in controlling explosion strength.

6.2.2 "Calculated Strength" obstruction

ME A "Calculated Strength" obstruction is defined by a set of data supplied through GUI, i.e. degree of expansion, obstruction, typical diameter and flame path length. When more than one "Calculated Strength" obstructed regions are included in an explosion, the blast curve for the explosion is decided by ME using the GAME correlations with combined parameters as given below.

Volume blockage ratio ($\overline{VBR}$)

When volume blockage ratio is given for each obstructed region, the blockage volume of all obstacles within the region is then calculated as

$$V_{obst,i} = V_{or,i}\, VBR_i \qquad (29)$$

Then VBR of the explosion source is

$$\overline{VBR} = \frac{\sum_{i=1}^{N_{obstr}} V_{obst,i}}{\sum_{i=1}^{N_{obstr}} V_{or,i}} \qquad (30)$$

Typical diameter ($\bar{D}$)

Typical diameter of an obstructed region can be either given directly or estimated using the surface area of obstacles. If typical diameter is given for an obstructed region, the surface area of all obstacles within the region is then obtained from equation (25) as.

$$A_{obst,i} = \frac{4V_{obst,i}}{D_i} \tag{31}$$

After the surface areas are obtained for all obstructed regions within the explosion source, the typical diameter of the explosion source is calculated as:

$$\overline{D} = \frac{4\sum_{i=1}^{N_{obstr}} V_{obst,i}}{\sum_{i=1}^{N_{obstr}} A_{obst,i}} \tag{32}$$

Flame path length ($\overline{L_p}$)

This parameter represents the path length for flame to propagate through the obstructed regions to build up flame speed and overpressure and is related to the location of ignition sources and size of the obstructed regions. Flame path length can be given directly if known or can be estimated by ME by assuming ignition location at the centre of a hemisphere representing the explosion source using equation (27).

However, if flame path length is given for all obstructed regions, flame path length of the explosion source is derived as equation (33) by applying equation (27) for each obstructed region.

$$\overline{L_p} = (\sum_{i=1}^{N_{obstr}} L_{p,i}^3)^{1/3} \tag{33}$$

Laminar burning velocity (S_L)

Laminar burning velocity of a flammable cloud is a material property and can be found in the material database. Even though it is possible for a study to have explosions with different materials or mixtures due to different releases, but the material within the obstructed regions forming one explosion source must be always the same for each scenario.

For flammable mixtures, the Le Chatelier principle as recommended by Baker et al[xi] for the BST model is applied to calculate its laminar burning velocity as:

$$S_L = \frac{1}{\frac{x_1}{S_{L,1}} + \frac{x_2}{S_{L,2}} + \frac{x_3}{S_{L,3}} + \ldots} \tag{34}$$

Where:

S_L: laminar burning velocity of the mixture
$x_1, x_2, x_3, \ldots$: molar fractions of the components in the mixture
$S_{L,1}, S_{L,2}, S_{L,3}, \ldots$: laminar burning velocities of the components in the mixture

Degree of expansion

Different correlations have been developed by GAME for explosions with 2D and 3D expansion. In practice, the level of confinement often falls somewhere between the two and/or is different among obstructed regions within an explosion source. Guidance on the selection of correlation has been discussed in the GAMES report. Normally either 2D or 3D expansion is applied for a scenario.

However, when obstructed regions within an explosion source do differ in degree of expansion significantly, i.e. some obstructed regions are clearly 2D and the others are 3D expansion, selecting the correlation for 2D expansion for the explosion can be overly conservative. For these explosions, ME offers an option to estimate the peak overpressure of the explosion using a hybrid approach as:

$$P_o = (1-\alpha)P_0^{2D} + \alpha P_o^{3D} \quad (35)$$

Here P_o^{2D} and P_0^{3D} are the initial peak overpressures estimated by the GAME correlations for 2D and 3D expansions, i.e. equations (23) &(24), using the parameters derived for the explosion. The constant α is defined as:

$$\alpha = \frac{\sum_{i=1}^{N_{obstr}} V_{gr,i}(n_{dx,i}-2)}{\sum_{i=1}^{N_{obstr}} V_{gr,i}} \quad (36)$$

Here $n_{dx,i}$ is the degree of expansion of the *i-th* obstructed region, which is either 2 for 2D expansion or 3 for 3D expansion.

2D expansion should be always selected for all obstructed regions if conservative consequence and risk predictions are required or there is any doubt of this hybrid approach.

6.3 Blast curves for explosion sources formed from multiple obstructed regions using BST

BST As for the Multi-energy method the Baker-Strehlow-Tang methodology[vi] recommends that the obstructed regions are averaged into a single area of confinement and congestion and the average can either be based on engineering judgement or based on volume average. BST has methods to enable these recommendations as described in the following section.

6.3.1 "Defined Flame Speed" Obstructions

BST The blast curves of the BST methodology are marked by flame speed, i.e flame Mach number. A flame Mach number is given directly for each "Defined Flame Speed" obstruction when it is created. When a confined explosion source is formed by more than one "Defined Flame Speed" obstruction, flame Mach number for the explosion is usually higher than that of the obstructed regions forming it because of the scaling effect of vapour cloud explosions. Experimental data have shown that geometrically similar explosions produce stronger blast on a large scale. This is also indicated by the GAME correlations for the Multi-energy model, i.e. higher initial overpressure for longer flame path length. However, because of the uncertainty in selecting flame speed for obstructed regions, which is largely dependent on judgement and experience of the analyst, and also in combining them for the explosion, a simple volume-weighted approach is adopted in BST for ease of use.

The blast curve of the explosion is determined as

$$\overline{Sp} = \frac{\sum_{i=1}^{N_{obstr}} V_{gr,i} Sp_i}{\sum_{i=1}^{N_{obstr}} V_{gr,i}} \quad (37)$$

Where:

N_{obstr} is the number of obstructed regions in an explosion source.
$V_{gr,i}$ is the obstructed cloud volume in an obstructed region "$i = 1, \dots N_{obstr}$"
Sp_i is the given flame Mach number for the *i-th* obstructed region in the explosion source.

$\overline{Sp}$ is the net flame speed for the explosion source.

In practice, selecting a flame speed for an obstructed region may be equally difficult as selecting a flame speed for an explosion, so it is more likely that a flame speed is decided for an explosion source directly on basis of the study requirement or certain explosion parameters, such as reactivity of the cloud. After a flame speed is selected for an explosion, the same speed is then given to all obstructed regions forming it and this makes the volume-weight approach easy to use in controlling explosion strength.

6.3.2 "Calculated Flame Speed" Obstructions

BST For a "Calculated Flame Speed" obstruction, details are provided for the region, i.e. confinement, congestion and material reactivity. In BST, the confinement and congestion levels of an explosion source formed by multiple obstructed regions can be determined using one of the four options given in
Table 3.

This section describes the methods used by BST to decide the volume averaged parameters (i.e. confinement level, congestion level) for the determination of flame speed of a confined explosion source covering multiple "Calculated Flame Speed" obstructions.

Option	Confinement Level	Congestion Level
1 (Default option)	Volume average of all obstructed regions	Volume average of all obstructed regions
2 (The worst-case scenario)	Highest confinement among the obstructed regions	Highest congestion among obstructed regions
3	Volume average of all obstructed regions	Highest congestion among obstructed regions
4	Highest confinement among obstructed regions	Volume average of all obstructed regions

Table 3 Options for confinement and congestion levels of an explosion source defined by multiple obstructed regions

6.3.3 Averaged confinement level

BST The confinement is determined by the ability of the flame front to expand in 1, 2 or 3 dimensions. The confinement of obstructed regions is defined as 2D, 2.5D or 3D for the BST methodology. An obstructed region is considered to be 3D if the flame is free to expand in all directions, 2D if the flame can only expand in two dimensions and is restricted in the third dimension and 1D if the flame is allowed to expand in only one dimension. The 1D category in the old flame speed has not included in the updated table because the maximum flame speed achieved in 1D condition is also a function of the ratio between length and diameter in addition to the other three parameters required. 2.5D is an intermediate level for confinement falling between 2D and 3D.

BST calculates the volume averaged confinement level of the explosion source as:

$$\overline{C_f} = \frac{\sum_{i=1}^{Nobstr} V_{gr,i} C_{f,i}}{\sum_{i=1}^{Nobstr} V_{gr,i}} \qquad (38)$$

Where:

N_{obstr} is the number of obstructed regions in an explosion source.
$V_{gr,i}$ is the flammable cloud volume inside the *i-th* obstructed region.
$C_{f,i}$ is a value corresponding to the confinement level for the *i-th* obstructed region in the explosion source concerned. A value of 2, 2.5 or 3 is given for confinement level of 2D, 2.5D or 3D respectively in equation (38).
$\overline{C_f}$ is the net confinement of the explosion source. The net confinement is then converted to a confinement level of 2D, 2.5D or 3D using the conversion given in
Table 4.

Confinement Level	Volume averaged confinement estimated by Equation (38)
2D	<=2.25

2.5D	>2.25 & <=2.75
3D	>2.75

Table 4 The relationship between confinement level and the estimated net confinement of an explosion source from multiple obstructed regions in BST

The BST methodology has not recommended a method to determine the representing confinement of an explosion source covering multiple obstructed regions with different confinements. Attempts have been made to make the conversion in Table 4 more conservative, but they were found to give the same confinement as the option 2. So, if there is any doubt of the volume-averaged approach of equation (38), more conservative approaches should be used.

6.3.4 Averaged congestion Level

BST Congestion is needed to determine flame speed in the BST methodology. It is classified as low, medium and high depending on area blockage ratio (ABR) and pitch (i.e. the distance between successive rows of obstacles) in the flame path as:

- Low congestion: a few obstacles in the flame's path or ABR less than 10% and a few layers of obstacles
- Medium congestion: anything falls between the low and high levels.
- High congestion: closely spaced layers of obstacles with an ABR of 40% or higher.

BST calculates the volume averaged net congestion of the explosion source as:

$$\overline{Cg} = \frac{\sum_{i=1}^{Nobstr} V_{gr,i} Cg_i}{\sum_{i=1}^{Nobstr} V_{gr,i}} \qquad (39)$$

Where:

Nobstr is the number of obstructed regions in an explosion source.
$V_{gr,\,i}$ is the flammable cloud volume in the *i-th* obstructed region.
Cg_i is the congestion level for the *i-th* obstructed region. A value of 1, 2 or 3 is given for the congestion level of high, medium and low in equation (39).
$\overline{Cg}$ is the net congestion of the explosion source. The net congestion of an explosion source is then converted to a confinement level of high, medium and low using the conversion given in the table below:

Congestion level	Net congestion estimated by Equation (39)
High	<=1.5
Medium	>1.5 & <= 2.5
Low	>2.5

Table 5 Relationship between congestion level and the estimated net congestion of an explosion source from multiple obstructed regions in BST

The BST methodology has not recommended a method to determine the representing congestion level of an explosion source formed by multiple obstructed regions with different congestion levels. If there is any doubt of the volume-averaged approach, other more conservative approaches, as given in
Table 3 should be used.

6.3.5 Methods to determine the congestion level of an obstructed region

Apart from a few idealized cases, the ABR and pitch required to define congestion level of an obstructed region are likely to vary with position and direction in a process plant. The process to determine it can be subjective. In contrast, the volumes of obstruction can be estimated from the physical sizes of obstacles so the volume blockage ratios (VBRs) of obstructed regions could be calculated more easily and consistently. Depending on the data available, BST has three methods to define congestion level of an obstructed region as given in
Table 6.

Method	Input variable
Option 1:	Congestion level is given directly as low, medium and high
Option 2:	VBR & Diameter-to-Pitch ratios are assumed to be the same as in a base case.
Option 3:	VBR & Given diameter-to-pitch ratios in all directions.

Table 6 Methods to determine the congestion level of an obstructed region in BST

In option 1, users gives the congestion level as high, medium and low directly based on their experiences and requirement of their study. Higher congestion level can be assumed to obtain more conservative consequence and risk predictions. Option 2 or 3 are developed to obtain more accurate congestion levels using VBR with more input data or assumptions as given here.

The BST methodology uses ABR and pitch, i.e. the distance between rows of obstacles, to determine the congestion level of an obstructed region. The following assumptions are made by BST to determine ABR of an obstructed region:

- Constant pitch between obstacle rows in each direction
- ABR can vary between obstacle rows and it is the ABR crossing the row of obstacles that is used to define congestion level.
- Constant obstacle diameters in all directions

With these assumptions, obstructed regions are simplified to a setup similar to the typical geometry of the EMERGE tests as shown in Figure 15. Figure 16 illustrates the obstacle central lines between two rows, i.e. a base unit. When an obstructed region has a reasonable number of base units in each direction, the ABR and VBR of the base unit become representative of the whole obstructed region.

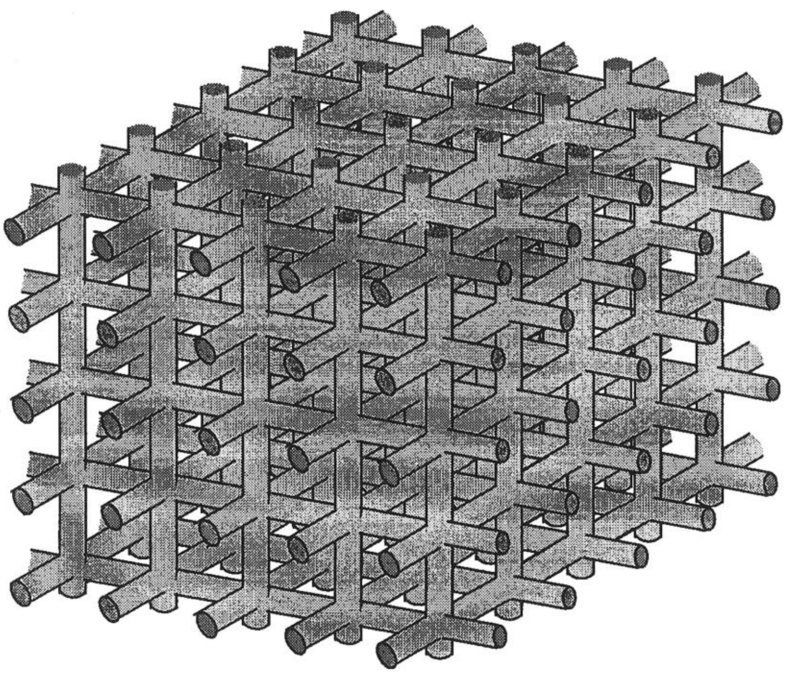

Figure 15 A typical setup of the EMERGE tests

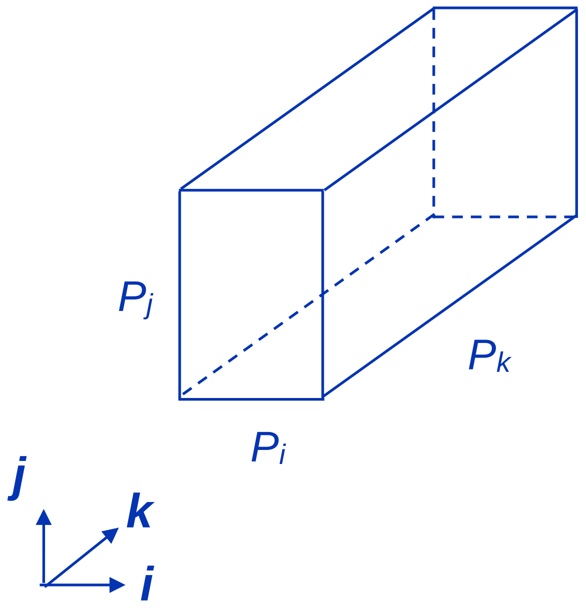

Figure 16 Schematic diagram showing the central lines of obstacles of an idealized obstructed region as shown in Figure 15

For the base unit shown in Figure 16, assuming $p_i < p_j$ and $p_j < p_k$, the ABR crossing the obstacles in *ij* plane can be expressed as:

$$ABR = \frac{(p_i + p_j)d - d^2}{p_i p_j} \tag{40}$$

And the VBR of the base unit is:

$$VBR = \frac{\pi}{4}\frac{d^2(p_i + p_j + p_k - 2d)}{p_i p_j p_k} \tag{41}$$

Because of the assumption of $p_i < p_j$ and $p_j < p_k$, the *ij* plane would have the highest ABR of all directions and the equations above can be expressed as:

$$ABR = DPR_i + DPR_j - DPR_i DPR_j \tag{42}$$

$$VBR = \frac{\pi}{4}(DPR_i DPR_j + DPR_j DPR_k + DPR_k DPR_i - 2DPR_i DPR_j DPR_k) \tag{43}$$

The diameter-to-pitch ratios are defined as

$$DPR_i = d / p_i$$

$$DPR_j = d / p_j$$

$$DPR_k = d / p_k$$

When diameter-to-pitch ratios are known in all three directions, VBR and ABR can be calculated using equations (42) & (43).

Determining diameter-to-pitch ratios requires detailed information of the obstructed regions and careful assessment of them. Congested regions in process installations are normally complex with wide variations in obstacle size and distribution. It is usually difficult to determine these diameter-to-pitch ratios accurately. However, it may be relatively easier to obtain the relative pitch ratios among the three directions by inspecting the plant. Equations (42) & (43) are then arranged as

$$ABR = DPR_i(1 + PR_{ij} - DPR_i\, PR_{ij}) \quad (44)$$

$$VBR = \frac{\pi}{4} DPR_i^2 (PR_{ij} + PR_{ik} + PR_{ik} PR_{ij} - 2DPR_i PR_{ij} PR_{ik}) \quad (45)$$

Where the relative pitch-to-pitch ratios are defined as

$$PR_{ij} = p_i / p_j$$

$$PR_{ik} = p_i / p_k$$

Among the two parameters required to determine the congestion level in the BST methodology, ABR is a parameter for the most congested plane inside an obstructed region. The pitches measure the directional distribution of obstacles. There is normally an optimum pitch value for flame propagation. A large pitch would cause the flame front to slow down between obstacles and unburnt gas pockets may exist between successive obstacles if the pitch is too small.

To help the user to determine congestion level consistently and conservatively with confidence, BST developed two criteria using ABR and VBR to determine the congestion level for obstructed regions. In them, the effect of the pitch is considered through the VBR.

Option 2: VBR & assumed diameter-to-pitch ratios

Fitzgerald[xii] assumed uniform pitches in all directions for the cases without preferential venting and a pitch increase of 50% in the direction of preferential venting if it is identified. Process plants are hardly homogeneous, so a base case has assumed to have the same pitch in two directions (i.e. the *i* and *j* directions as shown in Figure 16) and preferential venting in the *k* direction with a pitch increased by 50% as

$PR_{ij} = 1$ & $PR_{ki} = 1.5$

Substituting the relative pitch ratios into equations (44) & (45), the relationship between ABR and VBR of the base case can be established as shown by the red line in Figure 17. The ABR of 10% and 40% has corresponded to VBR of 0.6% and 8% respectively in the base case.

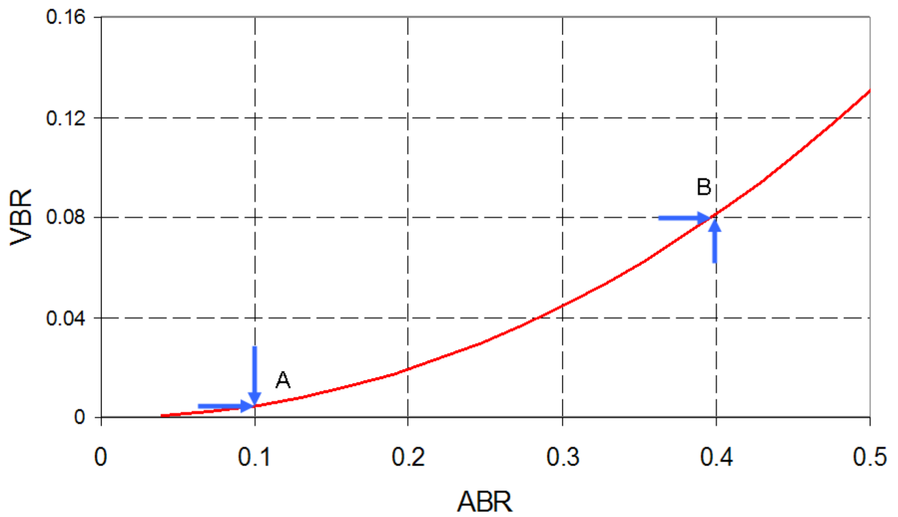

Figure 17 The relationship between ABR and VBR for PR_{ij} =1 & PR_{ki} =1.5

When option 2 is selected to determine congestion level for an obstructed region, the congestion level is then determined by BST using VBR with the assumption of PR_{ij} =1 & PR_{ki} =1.5 as for the base case. Therefore an obstructed region with a VBR lower than 0.6% will have a low congestion level because it corresponds to an ABR less than 10% in the base case, and high for the regions with a VBR equal or higher than 8%, which corresponds to an ABR less than 10% in the base case, and medium for the regions with VBR in between.

Option 3: VBR & given diameter-to-pitch ratios in all directions

When the diameter-to-pitch ratios are available for an obstructed region in all three directions, ABR and VBR can be calculated more accurately using equations (42) & (43) and then BST offers a more accurate method to determine its congestion level. In this method, the domain of VBR and ABR as shown in Figure 17 is divided into nine zones by the lines of constant ABR of 10% and 40% and constant VBR of 0.6% and 8%. The congestion levels of the nine zones are assumed as shown in Figure 18.

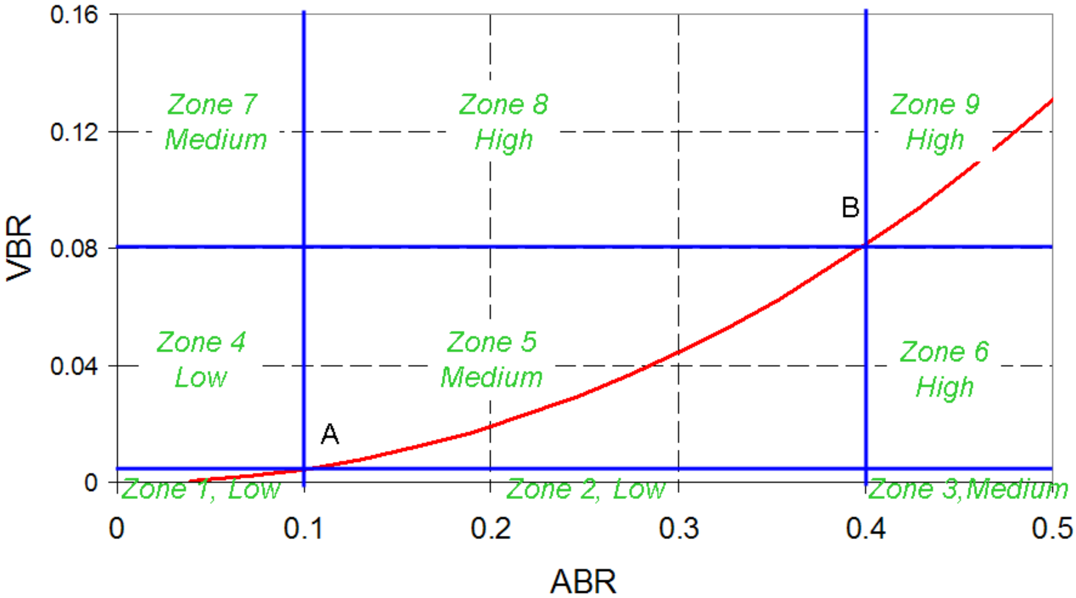

Figure 18 Congestion if detailed data are given for an obstructed region

Compared with the congestion level defined using ABR of the BST methodology, the proposed criterion in Figure 18 would give the same congestions in zones 1, 4, 5, 6 & 9, more conservative congestion in zones 7 & 8 and less conservative only in zones 2 & 3. In the two less conservative zones, i.e. zones 2 & 3, the VBR is less than 0.6% but the ABR is high; this indicates high pitch values, so the flame is likely to slow down between obstacles in such obstructed regions and the assigned congestion levels by Figure 18 may be reasonable.

The congestion level defined using the criterion shown in Figure 18 was also validated against a range of available test cases. The classified congestion levels are consistent with the congestion levels given by Fitzgerald[xii] for all the cases of BFETS2, BFETS3a and EMERGE experiments with VBR between 4.8% and 10%.

Table 7 compares the congestion levels given by the BST methodology and Option 3 of BST for the test cases used to develop the updated flame speed[iv]. VBRs and diameter-to-pitch ratios were reported for these cases. The criterion shown Figure 18 is found to be more conservative for the lowly congested case, and consistent with the BST methodology for the cases with medium and high congestion.

Case No.	**Congestion Level by the BST methodology**	VBR (Actual)	*1/DPR_i*	*PR_ik*	*PR_ij*	ABR (est.)	VBR (est.)	**Congestion Level given by Safeti**
A	**Low**	1.5	7.6	1	0	13.8	1.4%	**Medium**
B	**Medium**	4.3	4.3	1	0	23.4	4.2%	**Medium**
C	**High**	5.7[10]	3.1	1	0	33.0	8.4%	**High**

Table 7 Comparing the congestion level given by the BST methodology[iv] and Option 3 of BST

6.3.6 Material reactivity

BST The reactivity of a flammable material is rated as low, medium and high by Zeeuwen & Wiekema[vii] and this was adopted by the BST methodology. In BST, the reactivity of a flammable material can be given directly as low, medium or high directly or to be determined using its laminar burning velocity as given in section 3.2.3.

As to flammable mixtures, Baker et al[vi] recommended using Le Chatelier's principle to calculate its burning speed as given in section 6.2.2

6.4 Explosion results at a given point

The model contains a number of result methods (point, transect, grid and building) for consequence and risk calculations. Since these are extensions of the point method, so the description here has limited to the point method.

A point is a position in space. No attempt is made to predict the behaviour of the explosion results with height so the results are height-independent. The point is therefore described by its x and y coordinates and the distance from an explosion is the distance in *x-y* plane. The explosion results at a point are peak side-on overpressure, reflected overpressure, impulse and the methods used to calculate these values are described here.

BST Having taken the steps to determine the total explosion energy of an explosion source as given in Section 5 and select a blast curve as described above, the peak side-on overpressure $P_{s,i,}$ and impulse I_i may be obtained. This is achieved in the model using a number of fitted functions with constants set to match each of the lines in the curves of the BST methodology.

ME For the Multi-energy model, the peak side-on overpressure $P_{s,i,}$, $P_{dyn,i}$ and positive phase duration $t_{p,i}$ are obtained. The total overpressure is calculated as

$$p_{ttl,i} = p_{s,i} + p_{dyn,i} \quad (46)$$

When a blast wave hits a building, the blast wave is disturbed and, consequently, the building walls are subjected to reflected overpressures. Calculation of the reflected overpressure is explained below.

The impulse I_i is obtained directly for the BST model from the impulse blast curves. It is assumed as half of the product of the peak side-on overpressure and duration[11] as:

$$I_i = \frac{1}{2} P_{s,i} t_{p,i} \quad (47)$$

6.4.1 Reflected overpressure (P_{ref})

Reflected overpressure is higher than the side-on overpressure because of the impact of a blast wave to a receiving plane (e.g. a building wall) and is mostly used for building risk assessment. The ratio between the reflected overpressure and

10 For case C, the actual VBR is lower than the predicted value because not all obstacles of the given pitch ratios were placed in the test rig.

11 Green Book and page B3 of the GAME report

the side-on overpressure at the point of impact is dependent on the incidence angle, side-on overpressure at the point of impact and type of the blast wave as explained in the Green Book by TNO[xiii]. The perpendicularly reflected overpressure of a shock wave can be calculated using a formula as:

$$P_{ref,90} = 2P_s + \frac{(\gamma+1)P_s^2}{(\gamma-1)P_s + 2\gamma P_a} \quad \textbf{(48)}$$

γ	=	Ratio of specific heats ($\gamma \approx 1.4$ for air)
P_a	=	Ambient pressure [N/m^2]

However, it is relatively rare to have detonation and DDT in vapour cloud explosions resulting from accident releases in the open (Yellow Book[viii]). Inhomogeneity of the vapour cloud, which is inherent to the process of atmospheric turbulent dispersion, generally prevents detonation from propagating. Therefore, most VCEs in obstructed regions are likely to produce pressure waves.

Without obtaining an analytic formula specifically for reflected overpressure of pressure waves, equation (48) is used to estimate reflected overpressure for all blast waves in the model. At a incidence angle of 0° (i.e. perpendicular reflection), the reflected overpressure ($P_{ref,\,0}$) can be estimated from the side-on overpressure (P_S) of the wave at the point of impact by the following expression[12] derived from equation (48):

$$P_{ref,0} = \frac{AP_S^2 + BP_S}{P_S + C} \quad \textbf{(49)}$$

Where:

$$A = 2 + \frac{(\gamma + 1)}{(\gamma - 1)}$$
$$B = \frac{4\gamma P_a}{\gamma - 1} \quad \textbf{(50)}$$
$$C = \frac{2\gamma P_a}{\gamma - 1} = \frac{B}{2}$$

There is a need a to model $P_{ref,\,\tau}$, i.e. the reflected overpressure at any incidence angle τ, however no simple analytical expression has been found to relate $P_{ref,\,\tau}$, $0 \le \tau \le \pi/2$, as a function of τ and P_S. Thus, the following relationship is assumed:

$$P_{ref,\tau} = P_S + \left(P_{ref,90} - P_S\right)\cos\tau \quad \textbf{(51)}$$

$P_{ref,\,\tau}$ is at its maximum as given by equation (49) at τ = 0°, while at τ = 90°, $P_{ref,\,90} = P_S$.

Substituting $P_{ref,\,0}$ in equation (49) into equation (51) and recalling from equation (50) that $B = 2C$ yields the following expressions:

$$P_{ref,\tau} = \frac{JP_S^2 + KP_S}{P_S + C} \quad \textbf{(52)}$$

Where:

$$J = 1 + (A - 1)\cos\tau$$
$$K = C(1 + \cos\tau) \quad \textbf{(53)}$$

[12] Note: the expression provided here is only valid for shock waves resulting from explosions involving ideal behaving fluids

Even though equation (49) is derived for the reflected overpressure of shock waves and the assumed relationship of equation (51), equation (52) have reasonably predicted the reflected overpressure of pressure waves as illustrated in Figure 19.

As shown by Fig.5 in the TNO Green book[xiii], the reflected overpressure of shock waves does not behave as the assumed relationship of equation (51) with incidence angle. For a shock wave explosion, the reflected overpressure is almost the same as the reflected overpressure of perpendicular reflection for a wide range of incidence angles, e.g. between 0- 25º for P_s/P_o > 2.73 and between 0- 75º for P_s/P_o = 0.136. No simple analytic formula has been developed to estimate the reflected overpressure for shock waves in the model. For conservative predictions, instead of using the assumed relationship of equation (51), it is recommended to use a fixed incidence angle of 0º for the estimation of reflected overpressure for shock wave explosions.

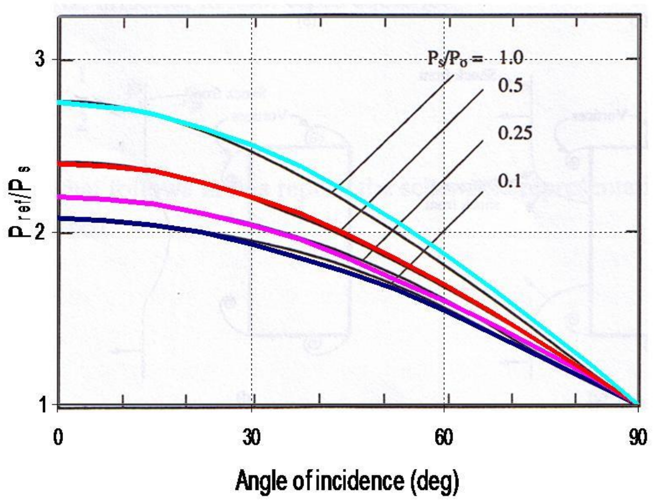

Figure 19 Validating the reflected overpressure predicted by equation (52) for pressure waves (Source data: The green Book by TNO, 1989)

6.4.2 Multiple explosion sources

When there are multiple explosion sources there will be multiple sets of peak side-on overpressure and impulse at any given observation point. It is assumed that blast waves arrive at different times so do not combine. As a result the peak side-on overpressure for the point is simply the maximum calculated for all the sources. The duration and impulse are set to the values corresponding to this maximum overpressure blast. This is to avoid confusing combinations of values for different blast waves and because vulnerability models for risk calculation may use overpressure and impulse together.

6.5 Calculate distance for a given overpressure

The evaluation of the distance for a given overpressure, requires the reverse of the calculation of the overpressure at a given distance. The equation: “P_S = Target value” is solved by a bisection method. This is a simple bracketing algorithm starting from an initial distance of 100m. A second point is searched to bracket the solution. The 2nd point is found either by doubling the distance or halving the distance, depending on the value for the new point. The algorithm terminates when the distance is bracketed within sufficient accuracy.

6.6 Building Risks

6.6.1 Explosion effects

When a blast wave hits a building, the blast wave is disturbed and, consequently, a load is exerted on the building walls. The load is dependent on size, shape and location of the building and characteristics of the blast wave and varies with time. Assuming the front wall of the building is not broken by the impact, Figure 1 below illustrates the interaction between a blast wave and a building in four phases and Table 8 lists the loads on building walls. Because the model doesn't predict the behaviour of the explosion results with height, interaction between the blast wave and the building roof is not considered for building risk calculations.

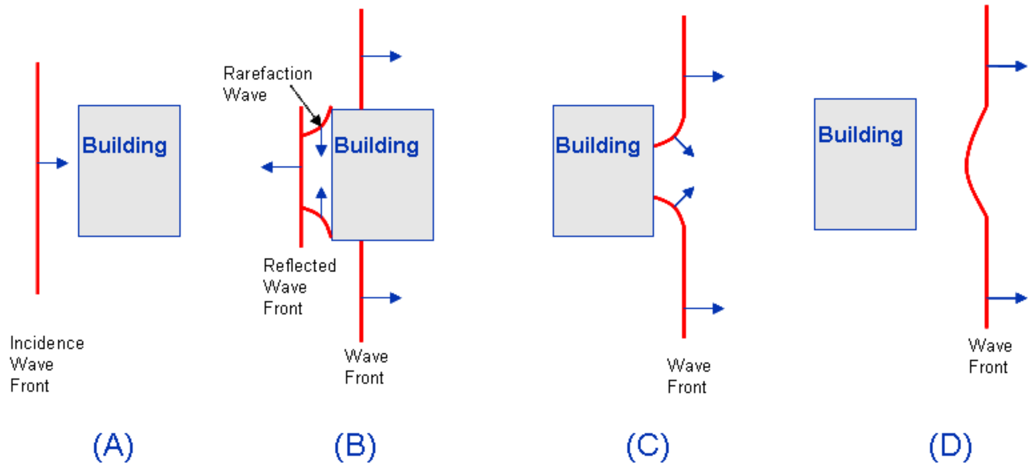

Figure 20 Blast wave and building interaction

Phase of interaction	Load on the building walls by a blast wave
(A) Before the impact.	No extra load
(B) The wave front reaches and is reflected from the front walls of the building	Load on the front walls (i.e. facing toward the explosion source) will rise due to the reflected overpressure
(C) The blast wave envelopes the building	The pressure drops on the front walls due to rarefaction, and increases to either side-on or reflected overpressures on other walls
(D) The blast wave has passed the building	Explosion load on the building reduces to a negative overpressure (i.e. < P_a) first and gradually returns to zero. The overpressure of the first positive phase are usually much higher than that of the negative phase

Table 8 Loads exerted on building by an incident blast wave

In the obstructed region explosion model for Safeti, the risk of buildings and the populations inside them due to explosions is related to explosion loads on the building walls through vulnerability methods. The vulnerability methods link the vulnerability of a building (i.e. probability of death to the population inside) to overpressures and/or impulse on the building walls from consequence calculations. Two methods are provided for building risk calculation as:

(1) Worst point (default)
(2) Arithmetic mean

Worst point (default)

In this method, the vulnerability of a building is represented by the point on the building where the highest vulnerability is predicted using the vulnerability methods selected. The worst point is determined by calculating the explosion consequences and risk on all building walls. The maximum vulnerability of a building by an explosion normally occurs on the nearest wall facing to the explosion source because it subjects to the highest overpressure and impulse. This method predicts the worst-case scenario for building damage.

The overpressure for the vulnerability model is decided by the user and can be one of the four options for ME and of the two options for BST as:

1 Side-on overpressure
2 Dynamic pressure (ME only)
3 Dynamic + Side-on overpressure (ME only)
4 Reflected overpressure (Default)

The impulse of the selected overpressure is calculated as:

$$I_i = \frac{1}{2} P_i t_{p,i} \quad (54)$$

Arithmetic mean

In this method, the vulnerability of a building is represented by the mean of the maximum vulnerabilities on the building walls. This method should produce more accurate building damage for large buildings or buildings with a very large aspect ratio (i.e. length/width).

As mentioned above, the maximum vulnerability of a building by an explosion normally occurs on the nearest wall facing to the explosion source. The minimum vulnerability usually occurs on the back walls facing away from the explosion source. The model calculates the overpressures on these back walls as if the blast wave traverses through the building, maybe due to window breakage or damage to the walls on its path, and so the back walls also subject to reflected overpressures. This assumption should lead to conservative estimations of the reflected overpressure on building walls and, consequently, conservative estimations of vulnerabilities if the reflected overpressure is selected for building risk assessment.

As for the Worst Point method, there are four pressure types for ME and two types for BST and the default option is the reflected overpressure.

6.6.2 Flash Fire Effects

The risk to buildings and the populations inside them due to flash fire is related to the fraction of the buildings within a flammable cloud at ignition. The volume of the *i-th* building within the cloud, i.e. $V^b_{gr,i}$, is determined in the same way as described in section 5 to work out the overlapping volume between a cloud and an obstructed region by three-dimensional integration. So the flash fire risk is calculated with consideration to the building geometry (including height) in relation to 3D view of the flammable cloud in OREM.

Vulnerability of the building, i.e. probability of death to the population inside, due to flash fire of that cloud is defined as:

$$Prob_{ff} = V^b_{gr,i} / V^b_i \quad (55)$$

Here V^b_i is the building volume of the *i-th* building and $V^b_{gr,i}$ is the volume overlapped with the flammable cloud.

7. ENHANCED CAPABILITIES

7.1 Release inside an obstructed region

The UDM does not explicitly model the interaction between vapour clouds and obstacles. Even though some inputs may be set to affect the dispersion results in a general way, such as ‘impinged’ release or increased surface roughness, it remains that the cloud does not interact directly with the obstructions. For releases inside an obstructed region, dispersion of the flammable cloud could be predominantly determined by surrounding obstacles, this can cause the risk prediction using UDM clouds to be non- conservative. To address this issue, two simple methods have been developed for OREM as given below, i.e. Fill-the-obstructed-region-First and Cylinder cloud.

The dispersion of the vapour clouds is always predicted first in Phast and Safeti without reference to the obstructed regions. Then the default method is to use the calculated cloud views to determine explosion sources as explained in sections 5.1.

For flammable clouds released from within an obstructed region, the cloud views can be reconstructed using one of the two simple methods developed for OREM. The reconstructed cloud views reshape the cloud and redistribute the flammable mass around the release point and tend to produce more conservative consequence and risk predictions.

It is expected that the user will specify how likely it is that the cloud will disperse normally according to the default or in an obstructed manner according to methods 1 and 2 (i.e. as given below) through the combination factors of runrows.

7.1.1 Method 1: Fill the obstructed region first

This method assumes that the obstructed region would retain the flammable cloud inside until it is fully filled So this method simply prevents the flammable mass of a cloud view from leaving the obstructed region where the cloud is released (and the regions which are combined with it if the critical separation distance has applied, as given in section 5.2), unless the flammable mass is more than that the obstructed regions can accommodate so that the obstructed region is over-spilled.

No overspill of the obstructed region

If the flammable mass of a cloud view is less than what the obstructed regions can accommodate, all cloud mass will be redistributed in these regions to form a confined explosion source. The explosion mass equals the flammable mass of the cloud with a volume as:

$$V_{rd\_cloud} = \frac{M_c}{\rho_1} \quad (56)$$

Where;

V_{rd_cloud}	Volume of the flammable vapour to be redistributed
M_c	Flammable mass of a cloud (kg).
ρ_1	Density of the vapour to fill the obstructed region (kg/m^3). This could be either the average density of the cloud or the density of stoichiometric concentration at atmospheric temperature as explained in sections 5.3.3 & 5.3.4.

The mass is redistributed around the release point between $x_{h,o}$ and $x_{l,o}$, as shown in Figure 21, with the upwind and downwind extents determined as:

$$l = \min\left(\frac{M_c}{V_{void}\rho_1}, 1\right)(x_{h,o} - x_{l,o}) \quad (57)$$

$$x_{upext} = \max[x_{l,o}, \min(x_{rp} - l/2, x_{h,o} - l)] \quad (58)$$

$$x_{downext} = \min(x_{h,o}, x_{upext} + l) \quad (59)$$

Where x_{rp} is the x coordinate of the release point.

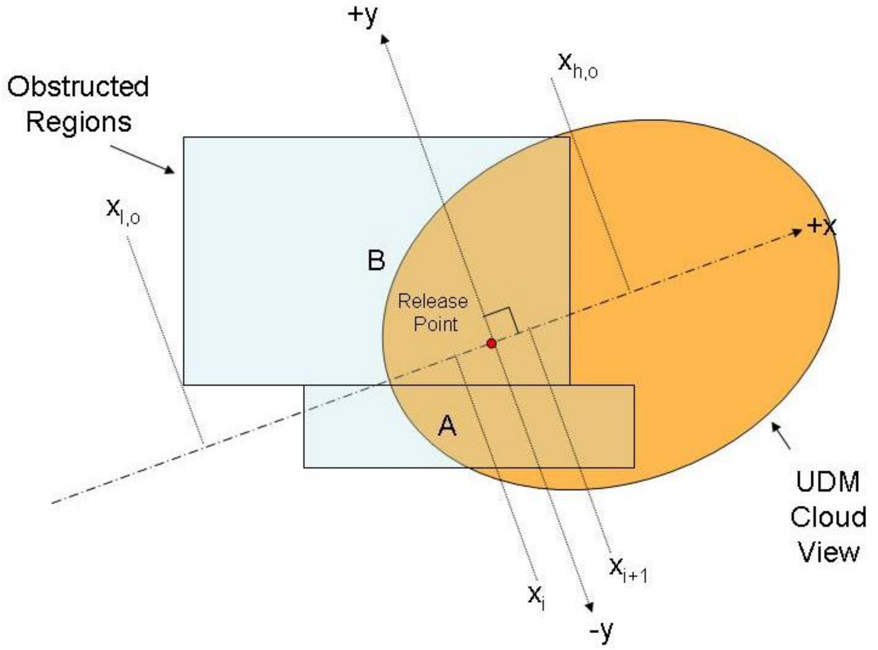

Figure 21 Redistributed cloud for releases inside obstructed regions (Plan view)

The cross section of the redistributed cloud at interval x_i is assumed to be a rectangular shape as shown in Figure 22:

$$halfwidth = (y_{h,c} - y_{l,c})/2 \quad (60)$$

$$halfheight = (z_{h,c} - z_{l,c})/2 \quad (61)$$

$$Centerheight = (z_{h,c} + z_{l,c})/2 \quad (62)$$

Equations (57)-(62) work well for releases from an obstructed region which is not to combine with others to form an explosion. Otherwise, it is likely that volume of the redistributed cloud by equations (57) - (62) differs from the volume given by equation (56), however this is not considered to be a big problem because the explosion energy is calculated using V_{rd_cloud} or cloud mass M_c depending the method selected to calculated explosion energy as described in sections 5.3.3 & 5.3.4.

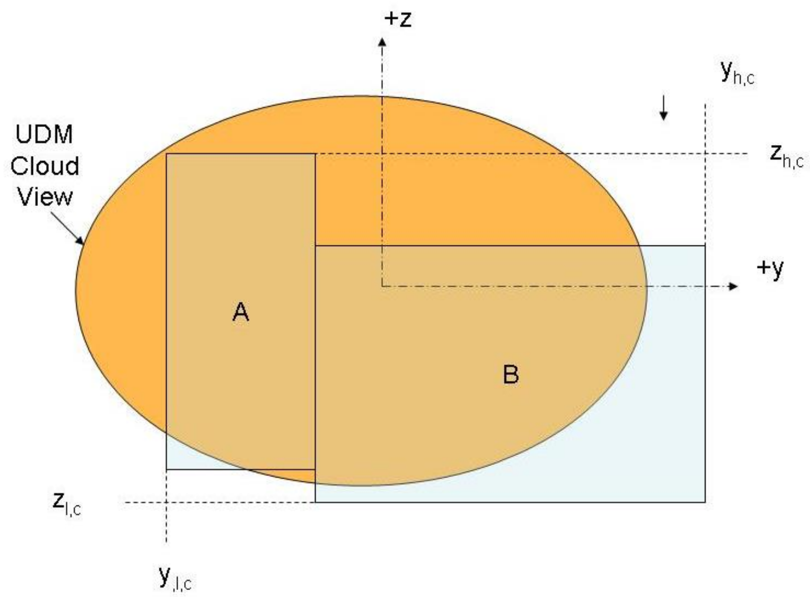

Figure 22 Schematic diagram of redistributed cloud view for releases inside obstructed regions (side view)

Overspill of the obstructed regions

However, if the flammable mass of a cloud view is more than the obstructed region can accommodate, the surplus volume would drift downwind as illustrated in Figure 23. In this case, the new cloud view has two parts, the part inside the obstructed region and the part drifted outside. For the part kept inside the obstructed regions, it forms a confined explosion with a cloud volume equal to the void volume of the obstructed regions and centred at the centroid. The explosion mass of this confined explosion is:

$$M_{gr} = \min(V_{void}\rho_1, M_c) \quad (63)$$

The cloud drifted out may encounter other obstructed regions where it behaves like the normal dispersing cloud. Its shape is scaled from the original cloud view with a scaling factor as:

$$\alpha = (M_{overspilled} / M_C)^{1/3} \quad (64)$$

Where $M_{overspilled}$ is the flammable mass drifted out of the obstructed regions.

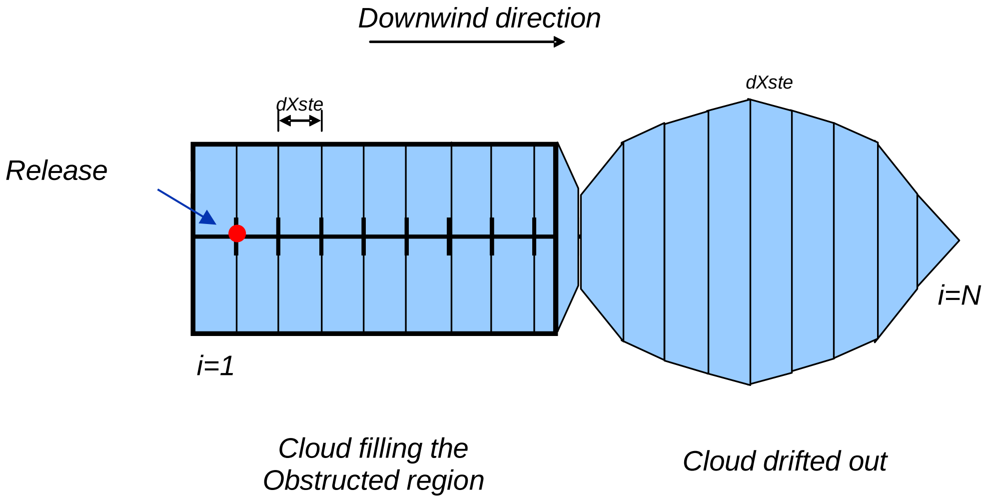

Figure 23 Release inside an obstructed region: Flammable cloud is drifting out of the region after it is fully filled

7.1.2 Method 2: Cylinder Cloud

In this method, a cylinder shape is assumed for the cloud with a given height/radius ratio *β*. This cylinder is centred at the release point with a volume as given by equation (56) and its radius and height as given by equation(65).

$$R_c = \left(\frac{V_{rd-cloud}}{\pi\beta}\right)^{1/3} \qquad (65)$$

$$h_c = \beta R_c$$

The cylinder is also limited by the ground or any plane around the release point defined as 'Elevation of floor or ceiling' in the Safeti parameters (i.e. Parameters/General Risk parameters/Explosions). If this plane is below the release point as shown in Figure 24 or if the cylinder cloud touches the ground, i.e. the release height is less than half of the estimated cylinder height h_c, the cloud height below the release point is then fixed, the height above the release point is kept to be half of the given height/radius ratio i.e. *β/2,* and the radius is adjusted to give the volume $V_{rd\text{-}cloud}$.

If the vapour cloud is released below an upper plane defined as 'Elevation of floor or ceiling' in the Safeti parameters (General Risk>Explosions), OREM will assume the release is between that plane and the ground (i.e. z=0). Cylinder radius and height are adjusted to give the volume $V_{rd\text{-}cloud}$ depending on whether it is limited by the plane and/or the ground.

Depending on the release point inside an obstructed region and the cloud volume, such as for a release at the edge of the obstructed region, part of the cylinder cloud can be outside of the obstructed regions before they are fully filled. Consequently, only the part inside the obstructed regions contributes to the confined explosion, so this method would not be as conservative as the Fill-Obstructed-Region-First method and is expected to be suitable for low-momentum releases inside or near to densely congested regions.

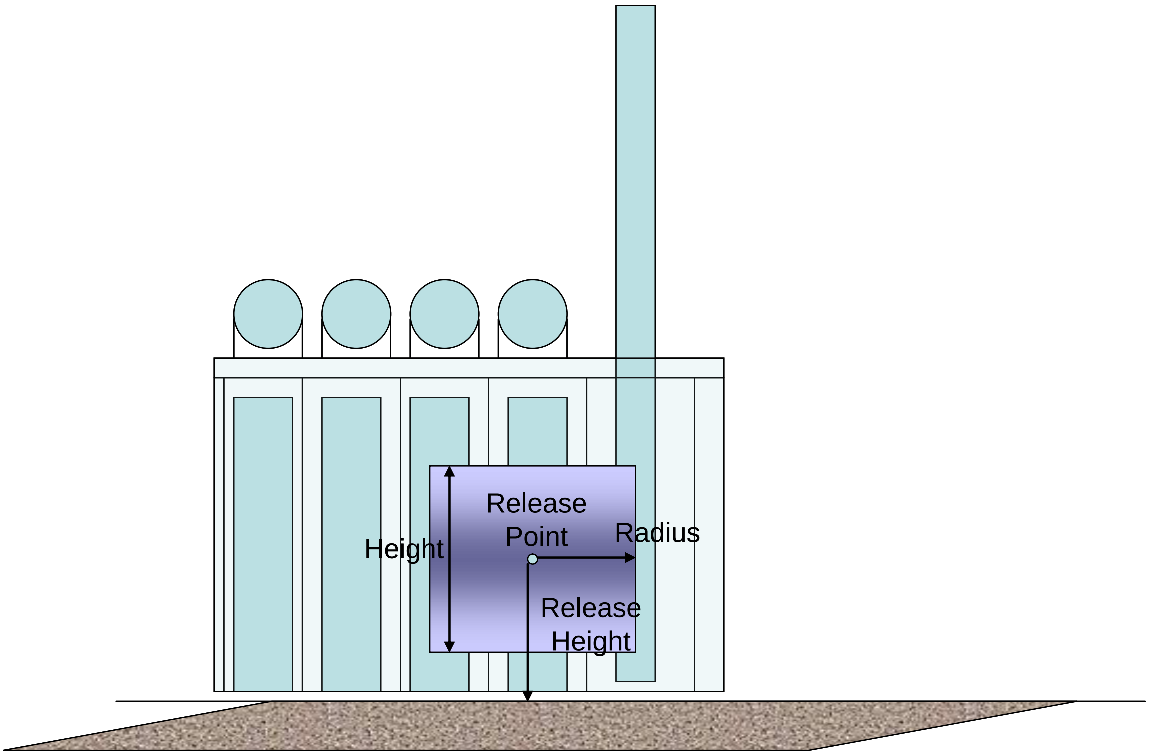

Figure 24 Cylinder cloud for releases inside an obstructed region

7.2 Cylinder cloud for releases outside obstructed regions

The cylinder cloud option is also made available for releases outside obstructed regions. This option is expected to be used for very limited cases, such as a release very near to an obstructed region.

7.3 Explosion efficiency

7.3.1 100% explosion efficiency

The Multi-energy method recommended that all the energy available for combustion inside an explosion source is used for consequence predictions. This implies an explosion efficiency of 100% in equations (17) & (18). This is the most conservative estimation of explosion energy and is the default option in OREM.

7.3.2 Overpressure dependent explosion efficiency

The conservative estimation of explosion energy with an explosion efficiency of 100% was considered as a limitation of the Multi-energy model and was investigated in the GAME study[ii]. Because both the initial peak overpressure P_0 and the explosion energy of an explosion are dependent on and are determined by the same underling parameters, i.e. cloud material, ignition and obstruction, so they are related and the GAME study postulated that the explosion efficiency of a confined explosion can be expressed in terms of the initial peak overpressure P_0. The following relationship was recommended:

- Less than 0.5 bar initial peak overpressure P_0, 20% explosion efficiency
- More than 1.0 bar initial peak overpressure P_0, 100% explosion efficiency
- Between 0.5- 1.0 bar initial peak overpressure P_0, 50% explosion efficiency

This efficiency was used in the Fitzgerald study for the Multi-energy model[xii].

BST This option is also provided for use with BST. Its validity has not been tested.

7.3.3 "1/3 Rule" (Multi Energy Only)

ME This rule is based on the modelling results of Pappas[xiv] as shown in the CMR gas explosion handbook[xv]. Pappas made some simple calculations on the explosion effect of having only a part of a compartment filled with a gas cloud. Assuming that the ignition point and the gas cloud are far from the vent opening, Pappas found explosion overpressure of a filling ratio about 30% (i.e. one third of the compartment is filled with flammable cloud) is the same as that when the compartment is fully filled. Validity of this rule for VCEs in obstructed regions is very much dependent on the ignition location, relative position of the cloud inside the obstructed region (i.e. cloud volume and elevation, venting position). Please note this rule cannot be used in combination with the overpressure dependent explosion efficiency as given above.

The '1/3 Rule" has indicated two possibilities for the predictions by the Multi-energy model as:

Case A: For a fully filled obstructed region with an ignition location for the worst-case scenario, the Multi-energy model may have overestimated the explosion energy, because part of the flammable mass inside the obstructed region will be pushed out of the obstructed region during flame propagation and will not contribute to the confined explosion, but it has been included in the estimated explosion mass and energy as described in Section 5.

Case B: For a partly filled obstructed region with an ignition location for the worst-case scenario, the Multi-energy model may have under- estimated the peak overpressure because the flame path length estimated using equation (27) is based the volume of vapour cloud before explosion and so has no consideration of the expansion of combusting vapour which would result the flame accelerating into the regions which are unfilled initially. This would lead to longer flame path lengths, consequently higher overpressures.

This rule was implemented in ME as:

'Defined Strength' Obstructions

The blast curve is specified for each "Defined Strength" obstruction, so only the explosion energy is adjusted by this rule as:

- **Case A** (i.e. fully filled obstructed regions), only one third of the flammable mass inside the obstructed regions contributes to the confined explosion, and the rest contributes to the unconfined explosion.

-**Case B** (i.e. partly filled obstructed regions), the explosion mass is calculated as:

$$V_{gr} = \min[V_{Cld}, V_{void}/3] \quad (66)$$

$$M_{gr} = M_c V_{gr} / V_{Cld} \quad (67)$$

'*Calculated Strength' Obstructions*

For explosions defined by 'Calculated Strength' Obstructions, both explosion energy and/or the flame path length are adjusted for this rule as:

- **Case A**: only one third of the flammable mass inside the obstructed regions contributes to the confined explosion, and the rest contributes to the unconfined explosion. The flame path length is calculated using volume of the obstructed regions or the given flame path lengths if supplied.

-**Case B:** the explosion mass is decided using equation (67). Flame path length of the explosion source is calculated as:

$$L_p = \min\{\left(\frac{3V_{or}}{2\pi}\right)^{1/3}, \left(\frac{9V_{gr}}{2\pi}\right)^{1/3}\} \quad (68)$$

Figure 25 below compares the results with/without the "1/3 Rule" for the Gas Process case of the GAMES study[iii]. The obstructed regions were fully filled with propane which was ignited at the centre, i.e. Case A. For this case, the "1/3 Rule" has produced the best predictions among the three efficiency methods.

7.3.4 Explosion efficiency for unconfined explosions (Multi Energy Only)

ME Unconfined explosions are formed by the unobstructed part of the cloud. ME can also be applied for scenarios with no obstructed region, therefore there will be only unconfined explosions for these scenarios. To apply the Multi-energy model for unconfined explosions, both blast curve and efficiency need to be supplied through GUI. By default, ME assumes an efficiency of 100% for unconfined explosions.

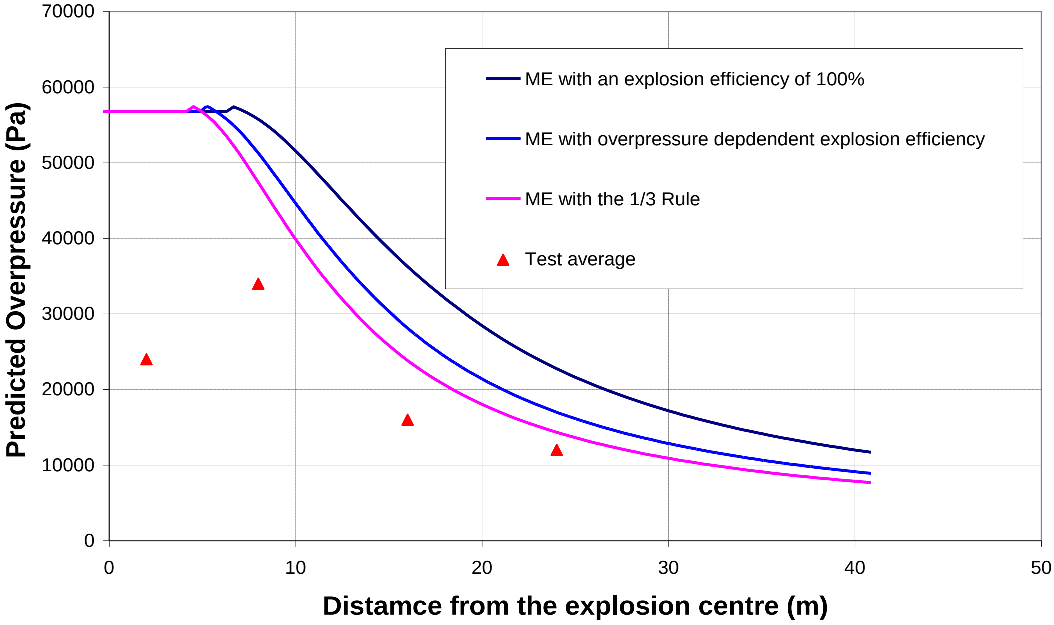

Figure 25 Validating the "1/3 Rule" for the Gas Processing case of the GAMES study: fully filled obstructed regions

7.4 Correction for the Ground effect using BST

BST The blast curves developed for the BST methodology were based on the predictions of spherical free-air explosions. Corrections are required to account for the ground effect for explosions on or near to ground. The current approach is to apply a ground reflection factor to the explosion energy.

Fitzgerald[xii] used a reflection factor of 2 to correct the explosion energy for ground vapour cloud explosions. Correcting the explosion energy has improved overpressure predictions, particularly in the far field. However, the corrected BST model still under-predicts overpressures of ground VCEs significantly in the near field to the explosion source as shown in the Fitzgerald paper.

Accurate predictions of peak overpressures of VCEs are often sought after, especially for the design of process installations. Simple models, such as the BST and the Multi-energy models, are particularly useful at the early stage of design because the details required by CFD models are often unavailable. A simple method, named as the ground correction method, was developed for BST to correct predictions for the ground effect, particularly in the near field.

7.4.1 Ground correction method

Figure 26 illustrates a VCE near to the ground. The ground correction method corrects the peak overpressure for the ground effect, in addition to the correction of explosion energy as used by Fitzgerald (2001). The ground correction factor is related to flame path length and area of the venting surface of an explosion as.

$$Cf = \left(\frac{R'}{R_0}\right)^{\alpha} \left(\frac{S'}{S_0}\right)^{\beta} \qquad (69)$$

With

R' Radius of the truncated sphere representing an explosion as shown Figure 26. Assuming ignition at the centre, it is also flame path length of the explosion.
S' Venting area of the truncated sphere representing the explosion
R_0 Radius of the sphere of equivalent volume to the VCE. Assuming ignition at the centre, it is the flame path length of the explosion if it is represented as a spherical free-air VCE.
S_0 Surface area of the sphere of equivalent volume to the VCE
Cf Ground correction factor

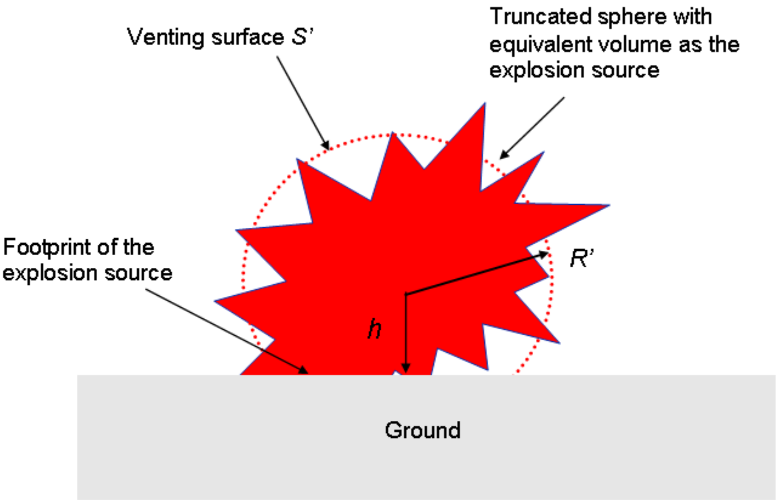

Figure 26 An elevated vapour cloud explosion and its representation by a truncated sphere

The effect of flame path length on peak overpressure is assumed to be the same as in the GAME correlations. Where α has a value of 2.75 for 3D confinement and 2.25 for 2D confinement. For 2.5D confinement of the BST methodology, a value of 2.5 is interpolated for α.

Obstruction to venting by the ground should have also contributed to the increased peak overpressure of a ground VCE, but it is considered to be less than that of flame path length for VCEs with a degree of confinement of 2D or higher and part of its influence may have been considered in estimating the flame path length. Also because no data was found to calibrate parameter *β* confidently, the effect of venting surface is not considered further here. The ground correction factor is simplified to:

$$Cf = \left(\frac{R'}{R_0}\right)^{\alpha} \qquad (70)$$

The ground correction factor by equation (70) depends on both volume and position of the VCE. For a VCE high above the ground, the correction factor is:

$R' = R_0$
$Cf = 1$

This is the case of a free-air explosion and has the minimum correction factor of 1.

For a ground explosion, the correction factor would be:

R' equals the radius of the hemisphere representing the explosion.
Cf = 1.88 for 3D confinement
Cf = 1.77 for 2.5D confinement

Cf = 1.68 for 2D confinement

For an elevated vapour cloud explosion near to the ground as shown in Figure 26, the centre and radius of the representing sphere (maybe truncated) are determined as:

- If the explosion source (i.e. the flammable cloud inside obstructed regions) does not touch the ground, the sphere is located at the centre of the explosion source and its radius is adjusted to ensure its volume the same as the explosion source. The sphere would be truncated if its radius is larger than its height *h* as shown in Figure 26.
- If the explosion source touches the ground, the height and radius of the truncated sphere are both adjusted so that the sphere has same volume as the explosion source and the same footprint area as the explosion source until the height becomes zero, i.e. the explosion is represented as a ground explosion.

7.4.2 Correcting the explosion energy

The explosion energy is corrected for the ground effect in the same way as done by Fitzgerald[xii]. A correction factor of 2 is used for vapour cloud explosions near to or on the ground. This may not be accurate in all cases, but is considered to be conservative.

7.4.3 Implementing the ground correction method

The steps to apply the ground correction method in OREM for BST are:

(1) Determine the flame speed using the updated flame speed table[iv] for an explosion. No ground correction should be applied if the flame Mach number is already the highest Mach number in the table, which is 5.2.

(2) Estimate the peak overpressure at the explosion source using the correlation given by Tang and Baker[v] as

$$\frac{P_{max} - P_0}{P_0} = \frac{2.4M_f^2}{1 + M_f} \qquad (71)$$

(3) Estimate a ground correction factor as described in above and correct the peak overpressure obtained from Step (2).

(4) Take the corrected peak overpressure into equation (71) and determine a corrected flame speed. The corrected flame Mach number is capped at 5.2.

(5) For consequence and risk calculations, the blast curves are then selected using the corrected flame speed and explosion energy is corrected using a factor as given in section 7.4.2.

The predictions by this correction method were validated again measurements and predictions by other models and this is given in the validation document[xvi]. Significant improvement in predictions was achieved by BST when used with the ground correction method.

7.5 Detonation

The evidence at Flixborough explosion strongly suggests that DDT occurred in highly confined and congested areas and the resulting detonation propagated widely through the extensive cloud around the plant. The investigation into Buncefield explosion also pointed to possible DDT initiated by an ignition in the pump house and propagated through dense vegetation. The consequences of DDT and detonation are devastation. However, it is difficult to accurately predict DDT. Two simple methods are implemented in OREM to enable detonation to be included in risk assessment using Phast and Safeti with the Explosions extension.

Detonation scenarios in Phast/Safeti are controlled by the user through a GUI explosion parameter as: Explosion parameters/BST and ME (3Doptions)/Detonation of VCE in the obstructed regions/Model option, i.e. Normal explosion or Detonation.

- For Normal explosion, the explosion strength of a VCE is modelled using ME or BST method as described in sections 2 & 3.
- If the option of detonation is selected, an explosion scenario is modelled as detonation if it meets the criteria specified, as given below.

7.5.1 Method 1: VBR based detonation

Based on the observation that DDT usually occurs in highly congested area, detonation can be modelled in Phast/Safeti if an explosion occurs in obstructed regions with VBR (i.e. volume blockage ratio) above a threshold. The default value is 0.15.

7.5.2 Method 2: flame speed based detonation

DDT is likely if the flame speed has accelerated to a value which could cause auto ignition of the fuel just ahead of the flame front. This method will activate detonation in Phast/Safeti when the predicted flame speed reaches a threshold. The default flame speed for detonation is Mach number 0.8. In case of ME explosions, flame speed is calculated using equation (71).

7.5.3 Selecting a detonation method

To model detonation using Phast/Safeti, the user must select the required method under Explosion parameters/ME and BST (3D options). The default option is Normal Explosion, i.e. no detonation.

7.5.4 Modelling detonation

When a detonation method is selected and the corresponding criteria are met, then the worst-case scenario is modelled as:

- Blast curve 10 for is selected for ME model as shown in Figure 2 and Mach number 5.2 is used for BST model as shown in Figure 6.
- All mass of the flammable cloud is assumed to participate the explosion.
- Explosion is centred at the cloud centre.

7.5.5 Detonation probability for risk calculation

Not all explosion scenarios meeting the criteria of methods 1 & 2 develop to detonation. Probability of detonation can be provided in Safeti for risk assessment. When one of the detonation method is selected under the Explosion parameters, all release scenario which meets the corresponding criteria for detonation would produce detonation with the given detonation probability. The remaining probability (i.e. 1- detonation probability) is taken by normal explosion.

7.6 Overpressure capping

It is known that significant turbulence can be generated by obstacles encountered by a flame as it propagates through the vapour cloud in obstructed regions and this can generate overpressures with potential for extensive damage. However, it is difficult estimate the overpressure inside the obstructed region accurately. For ME and BST, the peak overpressure inside the obstructed regions is particularly important. For ME, the GAME correlations have been used to estimate the initial peak overpressure and it is then used to select blast curves. Even though the initial peak overpressure is not used explicitly in BST it is directly related to the flame speed determined by the flame speed table.

The GAME correlations of ME and the flame speed table of BST are based on limited experimental data. Because of the complexity in process plants and uncertainty in their input parameters, the estimated initial peak overpressure can be too high for some cases and leads to significant over-predictions of consequence and risk of vapour cloud explosions. To overcome this limit, OREM offers an option to cap the initial peak overpressure of explosions. When this option is selected, a capping overpressure can be supplied. Whenever the initial peak overpressure of an explosion of the scenario concerned is higher than the capping overpressure, the initial peak overpressure of the explosion will be reset to the capping overpressure, and it is used to select the blast curves for that explosion.

By default, no capping is applied in OREM.

7.7 Explosion source checking

In some cases, particularly for designing new process units, user may want to know the likely maximum initial peak overpressure inside the units without carrying out detailed consequence modelling. OREM has a method to enable a quick explosion source check after obstructed regions have been created using Safeti.

To enable the checking, OREM determines the explosion sources using the system parameters for critical separation distance and assumes the obstructed regions are fully filled with a material of a given laminar burning velocity and central ignition for each explosion.

Results of the checking are reported in Safeti as:

- number of potential explosion sources and the obstructed regions forming them
- the maximal initial peak overpressures of these explosions
- whether the capping overpressure is likely to be applied if it is required.

Please note that the overpressure given by this checking is independent of any consequence and risk calculations and the results are indicative only. Based on these results, users may alter the design or decide whether overpressure capping is necessary. When OREM is applied for a QRA, the peak overpressures of confined explosions are calculated using the procedures described in previous sections with the actual cloud views from dispersion modelling and can be lower than the indicative overpressures given by the checking.

8. VERIFICATION AND VALIDATION

The verification and validation work for this model is reported in the separate document MDE_OREM_Validation[xvi].

9. RECOMMENDATIONS FOR FURTHER WORK

The current model is based on the Multi-energy and the Baker-Strehlow-Tang methods from published papers. These models have been implemented in previous releases of Phast & Safeti using a simplified approach which is effective for assessing the worst-case scenarios. OREM has extended these models to model obstructed regions and clouds directly as described in this document. The results of OREM are expected to be more realistic and enable more effective measures to reduce and control plant risk.

Improving the explosion models is an ongoing process determined by the user feedback. Based on the current status further work is recommended as follows:

1. New explosion models, such as explosions inside offshore modules.
2. Extend to include the height of objects being affected – building height for instance
3. Determine the explosion mass and energy using cloud temperature
4. Additional verification and validation of the model when new data are obtained.

APPENDIX 1 - ERRORS WARNINGS AND INFORMATION MESSAGES

9.1 Errors

MULT 1: User supplied flammable mass is less or equal to zero
MULT 2: Calculated heat of combustion is less or equal to zero
MULT 3: User supplied atmospheric pressure is out of range
MULT 4: User supplied input distance is negative
MULT 5: User supplied explosion strength is out of range
MULT 6: The user supplied input blast effect is out of normal range
MULT 9: User supplied atmospheric temperature is out of range
MULT 10: User supplied number of confined spaces is out of range
MULT 11: User supplied confined volume is out of range
MULT 14: Calculated total cloud volume is zero or less than zero
MULT 15: User specified method for splitting total cloud volume is unknown
MULT 16: Different ground correction methods are specified for obstructed regions in an explosion source
MULT 17: Different ground reflection factors are specified for obstructed regions in an explosion source
MULT 18: Different material reactivity methods are specified for obstructed regions in an explosion source
MULT 19: error in the calculation of correction factors for overpressure and energy using Ground correction method
MULT 20: Requested worst case input flag is invalid
MULT 21: Supplied input data type is invalid (Blast shape)
MULT 22: Supplied input contour plane is invalid (angles between x and y-axis is zero i.e. a straight line)
MULT 23: The user specified maximum contour points is less than the total number of active explosion sources
MULT 24: Invalid building type specification
MULT 25: Invalid Blast Data type is required. This maybe is caused by the requiredment to calculated Pdyn, Ps+Pdyn, Is(Pdyn), Is(Ps+Pdyn), Is (Pref) for he BST model, these data are available for ME model
MULT 26 "Material laminar burning velocity is not defined or not correct"
MULT 40: Failed initialisation of MULT with allocatable array information in MultRunControl
MULT 41: Failed initialisation of MULT with allocatable array information in MultTransectPoint
MULT 42: Failed initialisation of MULT with allocatable array information in MultContours
MULT 43: Failed initialisation of MULT with allocatable array information in MultBuildings
MULT 44: Failed initialisation of MULT with allocatable array information in MultWeathers
MULT 45: Failed initialisation of MULT with allocatable array information in "iBldEnclosePointCheck"
MULT 46: Failed initialisation of MULT with allocatable array information in MdeMultCldViewsResolve
MULT 47: Failed to set up obstructed regions as buildings or as building for it to be used as ignition source
MULT 60: MultRunControl has not been successfully initialised: insufficient information to run MULT
MULT 61: MultWeather has not been successfully initialised: insufficient information to run MULT
MULT 62: MultGrid has not been successfully initialised: insufficient information to run MULT
MULT 63: MultTransectPoints has not been successfully initialised: insufficient information to run MULT
MULT 64: MultBuildings has not been successfully initialised: insufficient information to run MULT
MULT 65: MultContours has not been successfully initialised: insufficient information to run MULT
MULT 66: MultConsequence has not been successfully initialised: insufficient information to run MULT
MULT 67: ObstructedRegion has not been successfully initialised: insufficient information to run MULT
MULT 68: BST ObstructedRegion has not been successfully initialised: Dia/Pitch ratio is less than zero or higher than one
MULT 69: MULT ObstructedRegion has not been successfully initialised: VBR is less than zero or the obstacle volume is more than the obstructed volume
MULT 70: Error in the initialisation of elevated ignition source
MULT 71: "1/3 Rule" is not applicable to BST model
MULT 72 "Zero diameter for cylinder cloud"
MULT 73 "Calculated area of a plane ignition source in cloud is less than zero"
MULT 80: Invalid x co-ordinate supplied as input to building integration routine
MULT 81: The blaeve blast curve has discretised points less than 2 or either overpressure and impulse Is less than zero
MULT 82: Dynamic pressure isn't available for the selected Vulneribility method
MULT 90: ! Errors in the calculated building damage results
MULT 100: Zero number of weathers supplied to MULT: FATAL error!!!
MULT 110 "MULT failed in estimating cloud upwind extent at the effect height"
MULT 111 "MULT failed in estimating cloud downwind extent at the effect height"
MULT 112 "Inappropriate overpressure method for offshore area method in initial release area"
MULT 113 "Ignition source %1%integer% has unsupported shape"
MULT 114 "Ignition source %1%integer% has 0 internal area, this is not supported."
MULT 115 "Allocation error in %1%string% "
MULT 116 "CERC initialization error"

MULT 117 "CERC execution error"
MULT 118 "CERC termination error"
MULT 119 "CERC Getting Negative Values in Fe"
MULT 120 "CERC Vector size 0"
MULT 121 "CERC Not defined error"
MULT 122 "CERC Null value error"
MULT 123 "CERC Index value error"
MULT 124 "CERC Infinite value error"
MULT 125 "Array size mismatch for plane explosion source"

9.2 Warnings

MULT 1004 "Conflict in capping overpressure between obstructed regions in an explosion source"
MULT 1009 "Explosion modelling using CERC"
MULT 1010 "Explosion optimization calculations (using interpolation and/or distances to overpressure thresholds) turned on under General Risk Parameters"

9.3 Messages

MULT 2001 "No confined volume data supplied by user: number of confined volumes specified by user is %1%integer%, only unconfined explosions will be simulated"
MULT 2002 "Overpressure thresholds only explosion optimization calculations not valid for non-discrete or non-static overpressure vulnerabilities: optimization disabled."
MULT 2003 "Mass used in calculating explosion scaling constant %1%real% is zero or negative"
MULT 2005 "Diff. flame path length methods are used for obstructed regions of an explosion (ME)"
MULT 2010 "Cloud is not growing symmetrically in time, reference cloud view recalculated"
MULT 2020 "The cloud is released between ground and an upper floor "

APPENDIX 2 – DIAGNOSTIC OUTPUTS

Diagnostic files can be generated to help understanding the explosion results and investigate particular concerns. It includes input data for the explosion model, explosion sources created by OREM using the obstructed regions defined and critical separation criterion selected, predicted explosion effects at risk ranking points and along transects and contours of targeted explosion effects. The creation of the diagnostic data is controlled by parameters under Options/Preferences/Risk Preferences/General. It is recommended to only use this capability for investigating limited cases, not for a whole medium to large studies, because these files can be very large in size. Examples of diagnostic outputs are given below.

9.4 Explosion input data

An example file of the input data of a ME study

<<<Run Control Input>>>					
Dynamic Mode Flag		0			
Flammable Mass Calculation Flag		1			
Cloud Integration Calculation Flag		0			
Discrete/Polynomial Blast Curve Flag		0			
Blast Curve Discretisation Points		30000			
Fill Obstructed Region Concentration Flag		0			
Fill Obstructed Region Method Flag		-1			
Minimum explosion energy (Damage Zone Method)		0.00E+00			
<<<Weather Input>>>					
Number of Weathers		1			
		Air Pressure (N/m2)	Air Temperature (K)	Air Mole Weight (kg/kmol)	Speed of Sound (m/s)
		101325	283	28.966	337.23173
Number of Wind Directions		17			
		MPACT Wind Rose (rad)	MULT Wind Rose (rad)		
		-5.10509	5.10509		
		-4.71239	4.71239		
		-4.31969	4.31969		
		-3.92699	3.92699		
		-3.53429	3.53429		
		-3.14159	3.14159		
		-2.74889	2.74889		
		-2.35619	2.35619		
		-1.9635	1.9635		
		-1.5708	1.5708		
		-1.1781	1.1781		
		-0.7854	0.7854		
		-0.3927	0.3927		
		0	0		
		0.3927	-0.3927		
		0.7854	-0.7854		
		1.1781	-1.1781		
<<<Buildings Related Input: General>>>					
Number of Buildings		1			
Number of Building Types		3			
Building Type		Pressure-Impulse Lethality Basis			
	1	4			
	2	4			
	3	4			
Maximum number of reported fixed-effect positions		1			
Blast Input Identifier: Locate		12			
Building Risk Evaluation Method		1			
Blast Output Indentifier: Max		12			
Blast Input Value for Effect Location Calculations		2.09E-301			
<<<Buildings Related Input: Specific>>>					
		Array Position	Building Type	Lethality Basis	Number of Geometry Points
		1	3	4	4
<Specific Building Geometry>					
		Building Array Position	Geometry Array Position	X co-ordinate (m)	Y co-ordinate (m)
		1	1	56.01241	-7.12344
		1	2	97.39071	-7.12344
		1	3	97.39071	-27.10994
		1	4	56.01241	-27.10994

9.5 Explosion source results

Table 9 & Table 10 show the data reported for each explosion source. Unconfined explosion sources usually don't produce strong explosions and are not reported here to limit size of the file.

----- Multi-Energy model (confined explosion sources Only)-----
Model name
Outcome Key
Weather index
Wind Angle(degree)
Ignition Time(s)
Explosion Source Key
Explosion Strength
Exploded Volume [m3]
Exploded Mass [kg]
Explosion Energy [J]
Centre X co-ordinate [m]
Centre Y co-ordinate [m]
Cloud Equiv. Hemispherical Radius [m]
Index of dominant obstructed region (0=unobstructed explosion)
Peak Overpressure [N/m2]
Capping? Blank for Uncapped or No capping
Net Dhym [m], i.e. hydrodynamic diameter *(for calculated strength obstruction)*
Net Flame Path Length [m] *(for calculated strength obstruction)*
Net Level of Confinement *(for calculated strength obstruction)*
Net VBR [-] *(for calculated strength obstruction)*

Table 9 Data reported for the confined explosion sources in the diagnostic file (ME)

----- BST explosion model -----
Model name
Outcome Key
Weather index
Wind Angle(degree)
Ignition Time(s)
Explosion Source Key
Explosion Strength
Exploded Volume [m3]
Exploded Mass [kg]
Explosion Energy [J]
Centre X co-ordinate [m]
Centre Y co-ordinate [m]
Cloud Equiv. Hemispherical Radius [m]
Index of dominant obstructed region (0=unobstructed explosion)
Peak Overpressure [N/m2]
Capping? Blank for Uncapped or No capping
Net Congestion level [1=High, 2=Medium & 3=Low] *(for calculated strength obstruction)*
Net Confinement [2=2D, 2.5=2.5D & 3=3D] *(for calculated strength obstruction)*
Net Reactivity [1=High, 2=Medium & 3=Low] *(for calculated strength obstruction)*

Table 10 Data reported for the confined explosion sources in the diagnostic file (BST)

An example of the diagnostic data of confined explosion sources of a ME study

Case Name	Outcome Key	Weather index	Wind Angle(deg)	Ignition Time(s)	Explosion Source Key	Explosion Strength	Exploded Volume [m3]	Exploded Mass [kg]	Explosion Energy [J]	Centre X co-ordinate [m]	Centre Y co-ordinate [m]	Cloud Equiv. Hemispherical Radius [m]	Index of dominant obstructed region (0=unobstructed explosion)	Peak Overpressure [N/m2]	Capping? Blank for Uncapped or No capping	Net Dhym [m]	Net Flame Path Length [m]	Net Level of Confinement	Net VBR [-]
1_Feed Gas t	346	1	2.07E+02	7.54E+00	1	7.00E+00	1.91E+01	5.29E-01	2.65E+07	1.11E+03	3.28E+02	2.09E+00	1	1.01E+05					
1_Feed Gas t	346	1	2.07E+02	7.54E+00	2	9.89E+00	2.42E+02	1.45E+01	7.25E+08	1.13E+03	3.72E+02	4.87E+00	7	1.31E+06		1.00E-01	4.87E+00	2.00E+00	2.00E-01
1_Feed Gas t	348	1	2.07E+02	1.65E+01	1	7.00E+00	1.90E+01	5.44E-01	2.72E+07	1.11E+03	3.28E+02	2.09E+00	1	1.01E+05					
1_Feed Gas t	348	1	2.07E+02	1.65E+01	2	1.00E+01	4.05E+02	1.99E+01	9.97E+08	1.14E+03	3.75E+02	5.78E+00	7	1.93E+06		1.00E-01	5.78E+00	2.00E+00	2.00E-01
1_Feed Gas t	350	1	2.07E+02	3.47E+01	1	7.00E+00	1.90E+01	5.46E-01	2.73E+07	1.11E+03	3.28E+02	2.09E+00	1	1.01E+05					
1_Feed Gas t	350	1	2.07E+02	3.47E+01	2	1.00E+01	4.12E+02	2.01E+01	1.00E+09	1.14E+03	3.75E+02	5.82E+00	7	1.95E+06		1.00E-01	5.82E+00	2.00E+00	2.00E-01
1_Feed Gas t	352	1	2.07E+02	2.92E+02	1	7.00E+00	1.90E+01	5.46E-01	2.73E+07	1.11E+03	3.28E+02	2.09E+00	1	1.01E+05					
1_Feed Gas t	352	1	2.07E+02	2.92E+02	2	1.00E+01	4.12E+02	2.01E+01	1.00E+09	1.14E+03	3.75E+02	5.82E+00	7	1.95E+06		1.00E-01	5.82E+00	2.00E+00	2.00E-01
1_Feed Gas t	354	1	2.16E+02	1.04E+00	1	7.00E+00	1.09E+01	2.72E-01	1.36E+07	1.11E+03	3.26E+02	1.73E+00	1	1.01E+05					
1_Feed Gas t	354	1	2.16E+02	1.04E+00	2	6.85E+00	6.97E+00	4.59E-01	2.30E+07	1.13E+03	3.52E+02	1.49E+00	7	9.16E+04		1.00E-01	1.49E+00	2.00E+00	2.00E-01
1_Feed Gas t	356	1	2.16E+02	3.18E+00	1	7.00E+00	1.04E+01	2.75E-01	1.37E+07	1.11E+03	3.26E+02	1.71E+00	1	1.01E+05					
1_Feed Gas t	356	1	2.16E+02	3.18E+00	2	9.88E+00	2.63E+02	1.70E+01	8.52E+08	1.14E+03	3.58E+02	5.00E+00	7	1.39E+06		1.00E-01	5.00E+00	2.00E+00	2.00E-01
1_Feed Gas t	358	1	2.16E+02	7.54E+00	1	7.00E+00	1.00E+01	2.76E-01	1.38E+07	1.11E+03	3.26E+02	1.69E+00	1	1.01E+05					
1_Feed Gas t	358	1	2.16E+02	7.54E+00	2	1.00E+01	5.57E+02	3.09E+01	1.55E+09	1.14E+03	3.62E+02	6.43E+00	7	2.45E+06		1.00E-01	6.43E+00	2.00E+00	2.00E-01
1_Feed Gas t	360	1	2.16E+02	1.65E+01	1	7.00E+00	9.64E+00	2.80E-01	1.40E+07	1.11E+03	3.26E+02	1.66E+00	1	1.01E+05					
1_Feed Gas t	360	1	2.16E+02	1.65E+01	2	1.00E+01	7.55E+02	3.64E+01	1.82E+09	1.14E+03	3.65E+02	7.12E+00	7	3.07E+06		1.00E-01	7.12E+00	2.00E+00	2.00E-01
1_Feed Gas t	362	1	2.16E+02	3.47E+01	1	7.00E+00	9.62E+00	2.80E-01	1.40E+07	1.11E+03	3.26E+02	1.66E+00	1	1.01E+05					
1_Feed Gas t	362	1	2.16E+02	3.47E+01	2	1.00E+01	7.63E+02	3.65E+01	1.83E+09	1.14E+03	3.65E+02	7.14E+00	7	3.10E+06		1.00E-01	7.14E+00	2.00E+00	2.00E-01
1_Feed Gas t	364	1	2.16E+02	2.92E+02	1	7.00E+00	9.62E+00	2.80E-01	1.40E+07	1.11E+03	3.26E+02	1.66E+00	1	1.01E+05					
1_Feed Gas t	364	1	2.16E+02	2.92E+02	2	1.00E+01	7.63E+02	3.65E+01	1.83E+09	1.14E+03	3.65E+02	7.14E+00	7	3.10E+06		1.00E-01	7.14E+00	2.00E+00	2.00E-01
1_Feed Gas t	366	1	2.25E+02	1.04E+00	1	7.00E+00	7.21E+00	1.78E-01	8.89E+06	1.11E+03	3.25E+02	1.51E+00	1	1.01E+05					
1_Feed Gas t	366	1	2.25E+02	1.04E+00	2	9.08E+00	7.68E+01	5.05E+00	2.53E+08	1.13E+03	3.46E+02	3.32E+00	7	5.53E+05		1.00E-01	3.32E+00	2.00E+00	2.00E-01
1_Feed Gas t	368	1	2.25E+02	3.18E+00	1	7.00E+00	6.68E+00	1.84E-01	9.22E+06	1.11E+03	3.25E+02	1.47E+00	1	1.01E+05					
1_Feed Gas t	368	1	2.25E+02	3.18E+00	2	1.00E+01	4.15E+02	2.61E+01	1.31E+09	1.14E+03	3.51E+02	5.83E+00	7	1.96E+06		1.00E-01	5.83E+00	2.00E+00	2.00E-01

9.6 Explosion results at points of interest (Phast) or risk ranking points (Safeti)

An example of the diagnostic data at points of interest of a ME study

Case name	Weather index	Wind angle (deg)	Ignition time (s)	Outcome ID	Index of the point	Type of explosion results	Index of dominant obstructed region (0=unobstructed explosion)	Mass of explosion (kg)	Explosion centre X	Explosion centre Y	Side_on overpressure (Pa)	Dynamic overpressure (Pa)	Duration of positive overpressure (s)	Impulse (side-on overpressure) (Pa s))	Stagnation overpressure (Pa)	Reflected overpressure (Pa)
1_Feed Ga	1	-18	1.044	42	1	Side-on overpr	1	1.208	1110.791	315.971	948.312124	101.325	0.012899	6.116167	1049.637124	1904.221542
1_Feed Ga	1	-18	1.044	42	1	Dynamic overp	0	21.404	1115.572	302.795	153.545644	101.325	0.195223	14.987793	254.870644	307.290685
1_Feed Ga	1	-18	1.044	42	1	Duration of po	0	21.404	1115.572	302.795	153.545644	101.325	0.195223	14.987793	254.870644	307.290685
1_Feed Ga	1	-18	1.044	42	1	Impulse (side-c	0	21.404	1115.572	302.795	153.545644	101.325	0.195223	14.987793	254.870644	307.290685
1_Feed Ga	1	-18	1.044	42	1	Stagnation ove	1	1.208	1110.791	315.971	948.312124	101.325	0.012899	6.116167	1049.637124	1904.221542
1_Feed Ga	1	-18	1.044	42	1	Reflected over	1	1.208	1110.791	315.971	948.312124	101.325	0.012899	6.116167	1049.637124	1904.221542
1_Feed Ga	1	-18	1.044	42	2	Side-on overpr	1	1.208	1110.791	315.971	229.48838	101.325	0.014141	1.622581	330.81338	459.422126
1_Feed Ga	1	-18	1.044	42	2	Dynamic overp	0	21.404	1115.572	302.795	43.68216	101.325	0.195223	4.263873	145.00716	87.38046
1_Feed Ga	1	-18	1.044	42	2	Duration of po	0	21.404	1115.572	302.795	43.68216	101.325	0.195223	4.263873	145.00716	87.38046
1_Feed Ga	1	-18	1.044	42	2	Impulse (side-c	0	21.404	1115.572	302.795	43.68216	101.325	0.195223	4.263873	145.00716	87.38046
1_Feed Ga	1	-18	1.044	42	2	Stagnation ove	1	1.208	1110.791	315.971	229.48838	101.325	0.014141	1.622581	330.81338	459.422126
1_Feed Ga	1	-18	1.044	42	2	Reflected over	1	1.208	1110.791	315.971	229.48838	101.325	0.014141	1.622581	330.81338	459.422126
1_Feed Ga	1	-18	1.044	42	3	Side-on overpr	1	1.208	1110.791	315.971	1402.799745	101.325	0.012434	8.721322	1504.124745	2822.213323
1_Feed Ga	1	-18	1.044	42	3	Dynamic overp	0	21.404	1115.572	302.795	250.269261	101.325	0.195223	24.429112	351.594261	501.068183
1_Feed Ga	1	-18	1.044	42	3	Duration of po	0	21.404	1115.572	302.795	250.269261	101.325	0.195223	24.429112	351.594261	501.068183
1_Feed Ga	1	-18	1.044	42	3	Impulse (side-c	0	21.404	1115.572	302.795	250.269261	101.325	0.195223	24.429112	351.594261	501.068183
1_Feed Ga	1	-18	1.044	42	3	Stagnation ove	1	1.208	1110.791	315.971	1402.799745	101.325	0.012434	8.721322	1504.124745	2822.213323
1_Feed Ga	1	-18	1.044	42	3	Reflected over	1	1.208	1110.791	315.971	1402.799745	101.325	0.012434	8.721322	1504.124745	2822.213323
1_Feed Ga	1	-18	1.044	42	4	Side-on overpr	1	1.208	1110.791	315.971	261.574511	101.325	0.014051	1.837645	362.899511	523.727608
1_Feed Ga	1	-18	1.044	42	4	Dynamic overp	0	21.404	1115.572	302.795	48.15047	101.325	0.195223	4.700031	149.47547	96.320551
1_Feed Ga	1	-18	1.044	42	4	Duration of po	0	21.404	1115.572	302.795	48.15047	101.325	0.195223	4.700031	149.47547	96.320551
1_Feed Ga	1	-18	1.044	42	4	Impulse (side-c	0	21.404	1115.572	302.795	48.15047	101.325	0.195223	4.700031	149.47547	96.320551
1_Feed Ga	1	-18	1.044	42	4	Stagnation ove	1	1.208	1110.791	315.971	261.574511	101.325	0.014051	1.837645	362.899511	523.727608
1_Feed Ga	1	-18	1.044	42	4	Reflected over	1	1.208	1110.791	315.971	261.574511	101.325	0.014051	1.837645	362.899511	523.727608
1_Feed Ga	1	-18	3.177	44	1	Side-on overpr	1	1.232	1110.803	315.802	955.178172	101.325	0.012977	6.197773	1056.503172	1918.063974
1_Feed Ga	1	-18	3.177	44	1	Dynamic overp	0	44.628	1118.394	294.052	192.454288	101.325	0.249403	23.999372	293.779288	385.221814
1_Feed Ga	1	-18	3.177	44	1	Duration of po	0	44.628	1118.394	294.052	192.454288	101.325	0.249403	23.999372	293.779288	385.221814
1_Feed Ga	1	-18	3.177	44	1	Impulse (side-c	0	44.628	1118.394	294.052	192.454288	101.325	0.249403	23.999372	293.779288	385.221814
1_Feed Ga	1	-18	3.177	44	1	Stagnation ove	1	1.232	1110.803	315.802	955.178172	101.325	0.012977	6.197773	1056.503172	1918.063974
1_Feed Ga	1	-18	3.177	44	1	Reflected over	1	1.232	1110.803	315.802	955.178172	101.325	0.012977	6.197773	1056.503172	1918.063974
1_Feed Ga	1	-18	3.177	44	2	Side-on overpr	1	1.232	1110.803	315.802	231.297026	101.325	0.01423	1.645689	332.622026	463.046465
1_Feed Ga	1	-18	3.177	44	2	Dynamic overp	0	44.628	1118.394	294.052	55.868044	101.325	0.249403	6.966839	157.193044	111.76249
1_Feed Ga	1	-18	3.177	44	2	Duration of po	0	44.628	1118.394	294.052	55.868044	101.325	0.249403	6.966839	157.193044	111.76249

9.7 Explosion transect results of Safeti

An example of the diagnostic data along a transect of a ME study

	Case Name	Outcome Key	Weather Index	Wind Angle (deg)	Ignition Time (s)	
	1_Feed Gas to Absc	42	1	-1.80E+01	1.04E+00	
	Point No	Transect X co-ordinate	Transect Y co-ordinate	Side-On Overpressure	Impulse	Dynamic Overpressure
	1	1.28E+03	5.02E+02	7.16E+02	4.73E+00	1.01E+02
	2	1.27E+03	4.87E+02	7.77E+02	5.10E+00	1.01E+02
	3	1.26E+03	4.72E+02	8.48E+02	5.52E+00	1.01E+02
	4	1.25E+03	4.56E+02	9.33E+02	6.02E+00	1.01E+02
	5	1.24E+03	4.41E+02	1.03E+03	6.62E+00	1.01E+02
	6	1.23E+03	4.26E+02	1.16E+03	7.34E+00	1.01E+02
	7	1.22E+03	4.10E+02	1.32E+03	8.23E+00	1.01E+02
	8	1.21E+03	3.95E+02	1.51E+03	9.34E+00	1.01E+02
	9	1.20E+03	3.80E+02	1.78E+03	1.08E+01	1.01E+02
	10	1.19E+03	3.65E+02	2.13E+03	1.27E+01	1.01E+02
	11	1.18E+03	3.49E+02	2.61E+03	1.52E+01	1.01E+02
	12	1.17E+03	3.34E+02	3.30E+03	1.86E+01	1.01E+02
	13	1.16E+03	3.19E+02	4.20E+03	2.32E+01	1.01E+02
	14	1.15E+03	3.04E+02	5.11E+03	2.77E+01	1.01E+02
	15	1.14E+03	2.88E+02	5.24E+03	2.83E+01	1.01E+02
	16	1.13E+03	2.73E+02	4.46E+03	2.44E+01	1.01E+02
	17	1.12E+03	2.58E+02	3.51E+03	1.97E+01	1.01E+02
	18	1.11E+03	2.42E+02	2.76E+03	1.60E+01	1.01E+02
	19	1.10E+03	2.27E+02	2.23E+03	1.32E+01	1.01E+02
	20	1.09E+03	2.12E+02	1.85E+03	1.12E+01	1.01E+02
	21	1.08E+03	1.97E+02	1.57E+03	9.67E+00	1.01E+02
	22	1.07E+03	1.81E+02	1.36E+03	8.49E+00	1.01E+02
	23	1.06E+03	1.66E+02	1.20E+03	7.55E+00	1.01E+02
	24	1.05E+03	1.51E+02	1.06E+03	6.79E+00	1.01E+02
	25	1.04E+03	1.36E+02	9.56E+02	6.16E+00	1.01E+02

9.8 Explosion contour results of Phast & Safeti

An example of the diagnostic data for a contour of side-on overpressure of 2068 Pa of a ME study

Case Name	Outcome Key	Weather Index	Wind Angle (deg)	Ignition Time(s)
1_Feed Gas to Absorber\1_100mm	42	1	-1.80E+01	1.04E+00
Number of Active Explsn Sources	Explosion Effect Type	Explosion Effect Value	Number of Contour Points	
2	Ps [N/m2]	2.07E+03	50	
Explosion Source Identifier	Absolute X co-ordinate	Absolute Y co-ordinate		
1	1206.446022	315.9706817		
1	1205.660698	328.2027257		
1	1203.317623	340.2339199		
1	1199.45527	351.8667123		
1	1194.137058	362.910093		
1	1187.450313	373.1827298		
1	1179.50483	382.5159463		
1	1170.431074	390.7564915		
1	1160.378036	397.7690557		
1	1149.510786	403.4384929		
1	1138.007765	407.671711		
1	1126.057851	410.3992008		
1	1113.857263	411.5761769		
1	1101.606333	411.1833134		
1	1089.506221	409.2270611		
1	1077.75561	405.7395417		
1	1066.547447	400.77802		
1	1056.065767	394.4239643		
1	1046.48268	386.7817077		
1	1037.955541	377.9767361		
1	1030.624364	368.1536268		
1	1024.609527	357.473675		
1	1020.009794	346.1122452		
1	1016.900692	334.2558917		
1	1015.333272	322.0992956		
1	1015.333272	309.8420678		
1	1016.900692	297.6854717		
1	1020.009794	285.8291182		
1	1024.609527	274.4676884		
1	1030.624364	263.7877366		
1	1037.955541	253.9646273		
1	1046.48268	245.1596557		
1	1056.065767	237.5173992		
1	1066.547447	231.1633434		
1	1077.75561	226.2018217		
1	1089.506221	222.7143023		
1	1101.606333	220.75805		
1	1113.857263	220.3651865		
1	1126.057851	221.5421626		
1	1138.007765	224.2696524		
1	1149.510786	228.5028706		
1	1160.378036	234.1723077		
1	1170.431074	241.184872		
1	1179.50483	249.4254171		
1	1187.450313	258.7586337		
1	1194.137058	269.0312705		
1	1199.45527	280.0746511		
1	1203.317623	291.7074436		
1	1205.660698	303.7386377		

NOMENCLATURE

Symbol	*Description*	*Units*
a	Major ellipse radius	m
a_0	Given height/radius ration for the cylinder cloud for releases inside obstructed regions	
A_{cloud}	Cross-sectional area of the vapour cloud above the lower flammable limit	m^2
A_i	External surface area of obstacles within the *i-th* obstructed region	m^2
$A_{i,o}$	The overlapped cross-sectional area between a cloud and the *o-th* obstructed region at midway downwind distances x_i and x_{i+1}	m^2
$A_{obst,i}$	Surface area of the obstacles inside the *i-th* obstructed region	m^2
A_t	Area between ellipse centre and truncating line	m^2
$A_{ttl,i}$	The total overlapped cross-sectional area between a cloud and obstructed regions at midway downwind distances x_i and x_{i+1}	m^2
b	minor ellipse radius	m
b_1, b_2, b_3	Dimensions of a rectangular object	m
Cf	Correction factor of the ground correction method	
C_{ST}	Stoichiometric concentration of fuel	fraction
$C_{x,y}$	Fuel concentration in the vapour cloud at position x, y and position i	fraction
D	Typical diameter of obstacles	m
D_i	Typical diameter of obstacles of the i-th obstructed region	m
$\overline{D}$	Typical diameter of obstacles within an explosion source	m
D_1	Smallest dimension of an object perpendicular to the flame propagation direction	m
D_2	Obstacle dimension parallel to the flame propagation direction	m
d_c	Diameter of a cylinder	m
D_{hym}	Hydraulic diameter of the obstacles in an obstructed region	m
DPR	Diameter-to-Pitch ratio of the obstacles inside obstructed regions	
d_s	Diameter of a sphere	m
E	Combustion energy of an explosion source	J/kg
f_e	Efficient factor of the vapour cloud in an explosion	
f_j	Fraction of cloud within the obstructed region j	fraction
h	Half-height of the vapour cloud to the lower flammable limit	m
h_c	Half-height of the cylinder cloud	m
H_{comb}	Specific heat of combustion of fuel	J /kg
H'_{comb}	Modified specific heat of combustion of fuel to use the typical specific heat of 3.5e^5 MJ/m^3 as adopted by GAME and GAMES	J/m^3
I	Impulse produced a vapour cloud explosion	Pa s
I'	Scaled impulse	
l_c	Length of a cylinder	m
L_p	Flame path length within the obstructed region	m
$m_{cloud,i}$	Flammable mass of a cloud section between x_i and x_{i+1}	kg
M_c	Total flammable mass of a cloud	kg
M_{gr}	Total combustion mass in obstructed region	kg
$M_{i,o}$	Flammable mass flux between LFL and stoichiometric concentration in obstructed region o at position i	kg/m^2
M_j	Mass of fuel within obstructed region j	kg
$M_{Unobstructed}$	Mass of fuel in unobstructed region of the cloud	kg
$n_{c,i}$	Number of the blast curve specified for the *i-th* 'Defined Strength' obstruction	
$\overline{n}_c$	Blast curve for an explosion including multiple obstructed regions	
$n_{dx,i}$	Degree of expansion specified for the *i-th* obstructed region	
N_{obstr}	Number of obstructed regions	
N_x	Number of step to integrate downwind	-
P_a	Atmospheric pressure	Nm^{-2}
P_{dyn}	Dynamic pressure	Nm^{-2}
PR_{ij}	Ratio of the pitches in *i* & *j* directions	
$P_{ref,\tau}$	Reflected overpressure at a reflect angle π	Nm^{-2}
$Prob_{ff}$	Probability of flash fire for a building	
P_S	Peak side-on overpressure	Nm^{-2}
P_S'	Scaled peak side-on overpressure	fraction
P_0	Initial Peak side-on overpressure within an explosion source	fraction

R	Distance from centre of explosion	m
R'	Scaled distance from centre of explosion	fraction
R_c	Radius of the cylinder cloud for releases inside obstructed regions	m
r_0	Radius of equivalent hemispherical shaped fuel-air charge	m
r_0'	Scaled radius of equivalent hemispherical shaped fuel-air charge	fraction
S	Scaling factor	-
S_L	Laminar burning velocity of the fuel in air	m/s
t_p	Positive phase duration of blast wave	s
t_p'	Scaled positive phase duration of blast wave	fraction
VBR	Volume blockage ratio	fraction
V_F	Specific volume of the fuel	m^3/kg
V_{cld}	Volume of cloud view	m^3
V_{gr}	Volume of cloud in obstructed region	m^3
V^b_i	Volume of the i-th building for flash fire calculation	m^3
$V^b_{gr,i}$	Volume of the i-th building within a flammable cloud for flash fire calculation	m^3
$V_{rd\text{-}loud}$	Volume of the cloud redistributed into obstructed regions when released inside an obstructed region	m^3
V_{obst}	Volume of the obstacles in an obstructed region	m^3
V_{or}	Overall volume of an obstructed region (ie the bounding box(es))	m^3
V_{void}	Free volume of the obstructed region (ie subtracting the volume of objects)	m^3
v_a	Speed of sound	m/s
V_{Total}	Total volume of the flammable vapour cloud	m^3
W	Half-width of the vapour cloud to the lower flammable limit	m
X	Used generally to indicate coordinate position, usually downwind position	m
x_{ex}	Calculated centre of the explosion source in the downwind x direction	m
$x_{h,c}$	Extreme downwind coordinate (high) of a given vapour cloud, c	m
$x_{h,o}$	Extreme downwind coordinate (high) of a given obstructed region, o	m
x_i	Downwind distance of position i	m
x_{i+1}	Downwind distance of position i+1	m
$x_{l,c}$	Extreme upwind coordinate (low) of a given vapour cloud, c	m
$x_{l,o}$	Extreme upwind coordinate (low) of a given obstructed region, o	m
x_{rp}	Downwind location of the release point	m
Y	Used generally to indicate coordinate position, usually crosswind position	m
yex	Calculated centre of the explosion source in the crosswind y direction	m
$y_{i,h,c}$	Extreme crosswind coordinate (high) of a given vapour cloud, c, on a plane i	m
$y_{i,h,o}$	Extreme crosswind coordinate (high) of a given obstructed region, o, on a plane i	m
$y_{i,l,c}$	Extreme crosswind coordinate (low) of a given vapour cloud, c, on a plane i	m
$y_{i,l,o}$	Extreme crosswind coordinate (low) of a given obstructed region, o, on a plane i	m
y_t	Distance of truncation line from centre of the ellipse	m
z	Used generally to indicate coordinate height above ground	m
z_c	Height of cloud centreline above the ground	m
z_{ex}	Calculated centre of the explosion source in the vertical direction direction	m
$z_{i,h,c}$	Extreme vertical coordinate (high) of a given vapour cloud, c, on a plane i	m
$z_{i,h,o}$	Extreme vertical coordinate (high) of a given obstructed region, o, on a plane i	m
$z_{i,l,c}$	Extreme vertical coordinate (low) of a given vapour cloud, c, on a plane i	m
$z_{i,l,o}$	Extreme vertical coordinate (low) of a given obstructed region, o, on a plane i	m
α	Interpolating constant	
β	User specified height/radius ratio of a cylinder cloud	
ρ_1	Selected cloud density to fill the obstructed regions or the cylinder cloud when the cloud is released from an obstructed region	kg/m^3
ρ_v	Density of a flammable material without mixing with air	kg/m^3
ρ_v'	Density of a flammable material without mixing with air at atmospheric temperature	kg/m^3

GLOSSARY

"1/3 Rule"

A simple rule which states that, for explosions from flammable cloud filling a compartment, the explosion overpressure of a filling ratio 1/3 (i.e. one third of the compartment is filled with flammable cloud) is the same as that when the compartment is fully filled.

ABR

Area blockage ratio in the flame path

AutoReaGas

A CFD model developed by Century Dynamics and TNO for explosion modelling

BFETS

Acronym for a joint industry project on Blast and Fire Engineering for Topside Structures.

Blast curve

The normalised curves describing the change of peak overpressure, duration or impulse against distance for idealised explosion scenarios. The Multi-energy and the BST models come with a set of its own blast curves.

BST methodology

The Baker-Strehlow-Tang model as developed by Baker et al for vapour cloud explosions

BST

The Baker-Strehlow-Tang model implemented in OREM of Safeti. It applies the Baker-Strehlow-Tang methodology with enhanced functionality and GUI for QRA studies

Calculated Flame Speed Obstruction

Obstructed region with a given set of parameters which are used to determined the blast curve for confined explosions formed by it using the flame speed table for the BST model.

Calculated Strength obstruction

Obstructed region with a given set of parameters which are used to determined the blast curve for confined explosions formed in it using the GAME correlations.

CFD

Computational Fluid Dynamics

Cloud View

The geometry of a cloud at a particular time

Confined explosion

Explosion occurred inside obstructed regions

Congestion level

A measure of the congestion to flame propagation in an obstructed region in the BST methodology. It is classified as low, medium and high depending on area blockage ratio (ABR) and pitch (i.e. the distance between successive rows of obstacles) in the flame path

Critical separation distance

The maximum separation distance at which the blast waves from donor and acceptor were found to coincide

Cylinder Cloud

A simple model implemented in Safeti for flammable clouds released inside obstructed regions. It assumed a cylinder shape for the flammable cloud around the release point for more conservative consequence and risk predictions and is particularly suitable for low-moment releases in densely congested area

Defined strength obstructed

Obstructed region with a given blast curve for confined explosions formed in it.

Degree of confinement

The degree to which the flammable cloud is constrained from expanding in an explosion. It is 3D if the expanding vapour cloud can move in 3 dimensions, 2D if the cloud is constrained to expand in only 2 dimensions as beneath an elevated storage tank or 1 dimension as in a road tunnel.

DDT

Deflagration to Detonation transition

Defined Flame Speed Obstruction

Obstructed region with a given flame Mach number for confined explosions formed by it for the BST model.

Defined Strength obstruction

Obstructed region with a given blast curve number which are used to determined the blast curve for confined explosions formed by it for the Multi-energy model.

Deflagration

A chemical reaction of vapour cloud explosions in which the flame front is propagating at a speed determined by heat conduction and diffusion at the front.

Detonation

A chemical reaction of vapour cloud explosions in which the flame front is propagating as a shock wave which compresses the flammable material immediately ahead of it beyond its auto-ignition temperature

Dynamic pressure

Blast wave is also accompanied by an air displacement in the same direction as the wave. The dynamic pressure is the load on a reflective surface by this air displacement.

EMERGE

Acronym for the joint industry project of Extended Modelling and Extended Research into Gas Explosions

Explosion efficiency

A ratio between the energy actually contributing to an explosion and the total combustion energy of an explosion

Fill-Obstructed-Region-First

A simple model implemented in Safeti for flammable clouds released inside obstructed regions. It redistributes the flammable mass of a cloud view inside the obstructed region for more conservative consequence and risk predictions.

Flame Mach number

The ratio between the flame propagating velocity of an explosion and the sonic velocity.

Flame path length

Distance travelled by the flame from ignition inside obstructed regions. It depends on the location of ignition and geometry of the obstructed regions.

Ground reflection factor

A factor which increases the explosion energy to correct the consequence predictions by the BST model for the ground effect on vapour cloud explosions. It equals one for free air explosions and 2 for ground explosions.

Ground correction method

A method developed specially for the BST model in Safeti v6.6 which increases both explosion energy and the initial peak overpressure to correct the consequence predictions by the BST model for the ground effect on vapour cloud explosions.

GAME

Acronym for a joint research project for Guidance on the Application of the Multi-Energy model.

GAMES

Acronym for a joint research project for Guidance on the Application of the Multi-Energy model: Second Phase.

GUI

Graphic user interface.

Hydraulic diameter

A terminology adopted from Hydrodynamics to estimate the typical diameter of an obstructed region. It is defined as 4V/A where V is the volume of an obstacle and A is its surface area

IL

Ig*nition location*

Impulse

An integration of pressure-time history of a short duration pressure pulse

Initial peak overpressure

The peak overpressure inside the obstructed region of a confined explosion, i.e. $r<r_o$.

Laminar burning velocity

The velocity of the region of combustion reaction relative to nonturbulent unburned gas in the combustion of a flammable material

ME

The Multi-energy model implemented in Safeti.. It applies the TNO Multi-energy methodology with enhanced functionality and GUI for QRA studies

Obstructed cloud

Part of the flammable cloud which overlap with obstructed regions to form a confined explosion source.

Obstructed region

Obstructed region is an area where obstacles are present in a configuration which will accelerate a flame if a flammable cloud is ignited inside it

OREM

Obstructed region explosion model for Safeti . It includes the TNO Multi-energy model and the Baker_Strehlow-Tang model for vapour cloud explosions in obstructed regions of process plants.

Pitch distance

The distance between successive rows of obstacles in obstructed regions

Positive phase duration

A blast wave of a vapour cloud explosion is experienced in the surrounding area as a transient change in pressure, density and velocity. The positive phase duration is normally the duration of positive overpressure experienced of the first cycle.

Reactivity

A term used to describe the propensity of a flame to accelerate in a vapour cloud explosion for a flammable material. It is rates as low, medium and high in the BST methodology

Reflected overpressure

The load exerted on a surface when a blast wave is reflected it

RIGOS

Acronym for a joint industry project on Research to improve guidance on separation distance for the multi-energy method (RIGOS)

Separation distance

The shortest distance between two obstructed regions

Side-on overpressure

Pressure experienced by an object as a blast wave passes by without being disturbed

Typical diameter

The average cross-sectional dimension of obstacles in an obstructed region

Unconfined explosion

An explosion formed by flammable cloud outside obstructed regions

VBR

Volume blockage ratio. VBR of an obstructed region is the ratio between the volume of all obstacles and its total volume.

VCE

Vapour cloud explosion resulted from an ignited flammable cloud

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REFERENCES

[i] TNO, "Methods for the calculation of physical effects, (The Yellow Book), CPR14E", Parts 1-2, 3rd Ed., Sdu Uitgevers, The Hague, 1997

[ii] Eggen, J.B.M.M., "GAME: development of guidance for the application of the Multi-Energy Method". TNO Report PML 1995-C44, August 1995

[iii] Mercx, W.P.M.,van den Berg, A.C. and van Leeuwen, D., "Application of correlations to quantify the source strength of vapour cloud explosions in realistic situations. Final report for the project: 'GAMES'", TNO Report PML 1998-C53, October 1998, NL

[iv] Pierorazio, A.J., Thomas, J.K, Baker, Q.A. and Ketchum, D.E, 2005, An update to the Baker-Strehlow-Tang vapour cloud explosion prediction methodology flame speed table, Process Safety Progress, 24, 59-65.

[v] Tang, M.J. and Baker, Q.A., 1999, A new set of blast curves from Vapour Cloud Explosions, Process Safety Progress, 18, 235-240.

[vi] Baker, Q.A., Doolittle, C.M., Fitzgerald, G.A. and Tang, M.J., 1997, Recent development in the Baker-Strehlow VCE analysis Methodology, 31st Loss Prevention Symposium, American Institute of Chemical Engineers, Houston, TX.

[vii] Zeeuwen, J.P. & Wiekema, B.J., The measurement of relative reactivities of combustible gases, Conference on mechanisms of explosions in dispersed energetic material, 1978.

[viii] TNO, "Methods for the calculation of physical effects, (The Yellow Book), CPR14E", Parts 1-2, 3rd Ed., Sdu Uitgevers, The Hague, 1997

[ix] Witlox, H. and Holt, A., "UDM Theory Manual". Risk Management Solutions, DNV, 2004

[x] ven den Ber, A.C & Mos, A.L, "Research to improve guidance on separation distance for the multi-energy method (RIGOS)", A TNO report for Health and Safety Executive. Research Report 369, 2005.

[xi] Baker, Q.A., Doolittle, C.M., Fitzgerald, G.A. and Tang, M.J., 1997, Recent development in the Baker-Strehlow VCE analysis Methodology, 31st Loss Prevention Symposium, American Institute of Chemical Engineers, Houston, TX.

[xii] Fitzgerald, G., A Comparison of Simple Vapor Cloud Explosion Prediction methodologies. Second Annual Symposium, Mary Kay O'Connor Process Safety Center, Texas A&M University, October, 2001.

[xiii] TNO, "Methods for the determination of possible damage, (The Green Book), CPR16E". Voorburg, December, 1989

[xiv] Pappas, J.A., Venting of large-scale volumes. Proceedings from the Control and Prevention of Gas Explosions, Oyez/IBC, December 1983.

[xv] Bjerketvedt, D., Bakke, J.R. & van Wingerde, K., Gas Explosion Handbook, GexCon, CMR

[xvi] Worthington, D. and Xu, Y., "Obstructed Region Explosion Model Validation". DNV Software, DNV, 2010