CHEMICAL ENGINEERING TRANSACTIONS
VOL. 36, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216
DOI: 10.3303/CET1436090

A Software Model for the Assessment of the Consequences of Explosions in Congested and Confined Spaces on Personnel, Buildings and Process Equipment

Kehinde Shaba*[a], Nic Cavanagh[a]

[a]DNV GL Software Ltd, 200 Great Dover Street, London SE1 9YB, UK
kehinde.shaba@dnvgl.com

Major accidents such as Buncefield, Texas City and, more recently, at the Amuay refinery in Punto Fijo Venezuela, have focused attention on assessing the effects of Vapour Cloud Explosions (VCEs) on assets such as buildings and process equipment, as well as people. Ensuring the safe location and design of occupied buildings is high on the agenda of key stakeholders.
In recent years much research has been undertaken to improve the accuracy and understanding of the mathematical modelling of VCEs. This has resulted in the development of simplified empirical models based on Computational Fluid Dynamics (CFD) calculations and the results of experiments. The two most well-known models to emerge from this research are the TNO Multi Energy Method (ME) and the Baker-Strehlow-Tang Model (BST).
Since the physical phenomena which drive explosions are complex, the nature of the most accurate predictive models available is also necessarily complex. CFD based models are generally considered to give the best approximations of these phenomena. However, such models are largely considered impractical for day-to-day work due to the significant resource and time requirements needed to build, run and analyse such complex models. In most consequence calculations performed in the context of a QRA (Quantitative Risk Analysis) or worst case analysis, this complexity is unnecessary. Additionally, the resource demands of this approach are such that applying it for a plant wide assessment is generally not feasible.
The “simplified” models mentioned above are designed to solve this problem by allowing a reasonable level of characterisation with less geometric and physical complexity, placing emphasis on the key parameters that are known to have a significant influence on the consequences in terms of overpressure and impulse.
This paper describes a more detailed implementation of the two most widely used vapour cloud explosion models mentioned above, namely the ME and BST models, in Phast, the well-known general purpose consequence analysis software package developed by DNV GL Software. The method provides a more detailed analysis of VCE threats without recourse to over simplification which can be detrimental to the accuracy of the results obtained from a risk management perspective. Example results from a hypothetical occupied building siting study are presented and the value of using the tool discussed.

1. Introduction

Major accidents such as Buncefield, Texas City and, more recently, at the Amuay refinery in Punto Fijo Venezuela have focused attention on assessing the effects of Vapour Cloud Explosions (VCEs) on assets such as buildings and process equipment, as well as people. Ensuring the safe location and design of occupied buildings is high on the agenda of key stakeholders, particularly since two of the three accidents mentioned above resulted in multiple fatalities.
Whilst this is high on the agenda, solving this challenge is not a trivial task as there are numerous considerations that need to be taken into account. The potential for a vapour cloud explosion is contingent on the various interactions that occur between a dispersing cloud and its environment such as prevailing weather condition and the dispersing terrain. The discharge conditions such as the release momentum

Please cite this article as: Shaba K., Cavanagh N., 2014, A software model for the assessment of the consequences of explosions in congested and confined spaces on personnel, buildings and process equipment, Chemical Engineering Transactions, 36, 535-540
DOI: 10.3303/CET1436090

and temperature are also important. Environmental considerations include the presence of areas of congestion and confinement (obstructed regions).
The proximity between release sources and obstructed regions and the direction of these objects relative to the release location are key factors. Understanding this influence will significantly enhance the ability to minimise the potential VCE hazards and better prepare for them. For example is there a particular site layout that results in higher interactions and thus increased explosion potential?
Process plants typically handle a range of flammable materials in various physical states (gas, liquid, two-phase); hence there is a need to evaluate a wide range of loss of containment events. This requirement adds further complexity to the task due to the large number of events and outcomes that need to be considered.
A range of solutions have been developed to address this problem and these lie on a spectrum from basic to complex. The basic end of the spectrum involves the use of standards, spacing tables and related approaches whose appeal largely lies in their relative simplicity and the almost negligible effort required for use. This simplicity is achieved at the expense of specificity such that using this method can result in inappropriate outcomes if applied in a dissimilar context - conservative in some areas, under predicting in others. Computational Fluid Dynamics (CFD) based tools occupy the opposite end of the spectrum. These are generally considered to offer the most accurate VCE characterisation potential, but are complex to use and time consuming to deploy. These factors mean that CFD does not readily lend itself to application at scale. The application of CFD is still warranted in highly uncertain situations or those not readily evaluated using other approaches. One such area is the prediction of near-field effects, for which other approaches are known to be less accurate. The practical limitations of the technology are well recognized and diverse initiatives are being undertaken to address them (See for example (Haidairi and Matthews, 2003)).
Some would argue that the technical superiority of CFD is of utmost importance and are consequently willing to manage the limitations of scale by modelling a limited number of scenarios to be considered representative of a wider set. This approach is justified by using logical and largely theoretical arguments, based on engineering judgement, which can be subjective.
The middle belt is occupied by what is generally referred to as “simplified” models. These have been developed as an effective response to the limitations in the solutions outlined above and are underpinned by both theoretical (CFD simulations) and empirical research. Here, the most widely used are the Multi-Energy (ME) (Van den Berg, 1985) and Baker Strehlow Tang (BST) (Baker, et al., 1996) models. Whilst these models can be categorised as “simplified” relative to CFD, such a characterisation could not be further from the truth from a practical perspective.

Rather than consider all parameters that have an influence on the explosion outcome, it is common to place emphasis on a few parameters that are thought to have a significant influence. An example is the implementation of the ME model into the base configurations of Phast (versions 7.01 and below) which utilises the size of the confinement and blast curve number as the key governing parameters. Such implementations tend to be conservative in their outlook and focus solely on the worst case outcome, a basis not always suitable for risk management.
This paper describes a more detailed implementation of the two most widely used vapour cloud explosion models mentioned above, namely the TNO Multi Energy (ME) Method and the Baker-Strehlow-Tang (BST) model, in Phast, the well-known general purpose consequence analysis software package developed by DNV GL Software. This is in direct response to the aforementioned challenges and the intention is to provide a robust platform by which a more detailed analysis of the VCE threats posed by process plant can be evaluated - without recourse to over simplification which can be detrimental to the accuracy of the results obtained from a risk management perspective. The implementation of both models is quite detailed and includes all the key parameters that have a bearing on the magnitude of a vapour cloud explosion. Simple example results from a hypothetical occupied building siting challenge are presented and the value of using the tool discussed.

2. The Phast Software Package and Recent Updates

Phast is an integrated consequence analysis package that models all stages of an accidental release from:

- Discharge: including rainout, pool evaporation and spreading
- Dispersion: from the pool and the discharge orifice
- Effects including toxicity, jet fires, fireballs, pool fires, flash fires and explosions

In terms of VCE modelling, Phast enables the key requirement namely the size and dimensions of the dispersing vapour cloud to be determined.

The modelling takes into account various contextual factors that can influence the development of the hazard. More details of the technical capabilities of the Phast Software package can be found in the body of technical reference documentation available with the tool as well as in papers by (Witlox, 2010) and (Witlox and Oke, 2008) amongst others.

The current base configurations of Phast (versions 7.01 and below) include what can be referred to as a narrow implementation of both the ME and BST models. In the ME implementation, the blast curve number and a single fixed congested volume are considered to the exclusion of other parameters such as degree of confinement. In the BST implementation, the flame speed and confined volume are given primacy. Also, in both implementations, the time varying interaction between the dispersing cloud and the region of obstruction are defined in an ambiguous manner. Additionally, whilst the tool had the capability to evaluate numerous scenarios simultaneously and display the hazard range as contours on a location map, evaluating the impact to any one target was generally a resource intensive exercise as this had to be done on an individual outcome-by-outcome basis.

2.1 Recent Updates

The software package has now been updated to address the limitations highlighted above. Key innovations with regards to VCE modelling include: a fully featured implementation of the ME and BST explosion models as well as the inclusion of a multi-scenario contouring capability. These updates are available in the Phast 3D Explosions add-on to version 7.1 onwards. The implementation of both models into Phast is executed as part of the Obstructed Region Explosion Model (OREM). The theory and validation of the OREM model is discussed in (Xu, 2010a) and (Xu, 2010b) respectively.

Key aspects of the update include:

- The definition of 3D obstructed regions in the Geographical Information System (GIS)
- Consideration of the degree of overlap between the flammable cloud and the obstructed region to accurately determine the explosive mass and location
- Consideration of critical separation distance between defined obstructed regions. The separation distance is important as it aids in the determination of how many explosion sources can be reasonably expected where a vapour cloud envelopes more than one region of obstruction.
- The ability to consider multiple and singular wind directions of interest
- The software has been updated to allow for multi-scenario contouring - an efficient way of organizing and communicating the resulting hazard ranges especially when used to inform facility siting considerations as outlined in (CIA, 2010), (API, 2009) and (API, 2007).

2.2 Definition of Obstructed Regions

Obstructed regions are central to the potential for high strength VCE's and are thus a key element of both the ME and BST models. They are typically defined based on a review of the site layout diagrams/plot plans and the external boundaries of these areas are typically defined via "perimeter bounding boxes".
Whilst there are guidelines to facilitate this activity, see for example (Van den Berg and Mos, 2005) and (API, 2007), there remains a degree of subjectivity which can lead to some variation in the definition depending on the perspective of the person undertaking the task. Once defined, they are then approximated to distinct cuboid shaped volumes and input to the Phast model using the GIS.
Beyond the geometrical similarities in obstructed regions for both explosion models they each require a different set of parameters for their complete definition. As a consequence they are created differently within the Phast software package. Additionally, for each explosion model, two types of obstructed regions can be created: "Defined Strength" or "Calculated Strength" in the case of the ME model and "Defined Flame Speed" or "Calculated Flame Speed" in the case of the BST model. For the ME model, key parameters for the Calculated Strength option include degree of expansion (or confinement), flame path length and volume blockage ratio. For the "Defined strength" option, the only inputs required are the curve number and the volume blockage ratio. For the BST model, the Calculated Flame Speed option requires degree of confinement, congestion level and flame reactivity. The flame speed and the blockage ratio are the only inputs required by the Defined Flame Speed option.

2.3 Consideration of Flammable Cloud/Obstructed Region overlap

It is important to evaluate the extent to which overlap of flammable cloud and obstructed regions occurs for the range of scenarios to be considered and for the various obstructed regions on a facility.
A range of factors have an influence on this possibility. The relative distance between the release event and the obstructed region, the size of the resulting flammable cloud as it develops and disperses and the direction of travel of the cloud are key aspects to consider. This is performed for multiple release

scenarios, multiple time steps during dispersion, multiple obstructed regions and multiple wind directions. Phast examines in detail the degree of interaction between the resulting flammable cloud and the obstructed regions and thus determines the degree of fill to be used within the explosion calculations. It does so for all wind directions specified.

2.4 Critical Separation Distance

In the presence of a flammable cloud, each identified obstructed region has the potential to act as an explosion source. However, where a flammable cloud overlaps more than one obstructed region there is the prospect for multiple explosion sources. The potential is governed by the "separation distance" between the regions. A large gap between multiple regions will mean that the flame front will decelerate resulting in multiple independent explosions. On the other hand, a small gap will result in a single explosion with the combined energy of all the sub-sources. The "critical separation distance" is the threshold criterion used to establish whether an explosion source should be considered as independent or part of a larger group.

There are divergent views on the specification of the critical separation distance. TNO (TNO, 1997) suggests a critical separation distance equal to 10 obstacle diameters with an upper bound of 25m. Alternatively, work by Van den Berg and Mos (2005) has indicated that this approach might not always be conservative particularly where the resulting overpressures are high. The report recommends the critical separation distance should be a function of the size of the maximum overpressure from the source explosion, referred to as a "critical separation ratio". In addition, Baker et al., (1998) suggests than 5m should be adopted as the upper limit for defining when obstructed regions are separate explosion sources. The Phast model allows for the critical separation distance to be specified as a ratio or fixed value to account for these views.

2.5 Directional Modelling

The potential for explosions depends heavily on the spatial distribution of release sources and obstructed regions and their ability to interact. For example, a dispersing cloud might interact with an obstructed region in one direction and not in other directions, leading to the potential for explosions in one path only.

The latest addition to Phast allows wind directions of interest to be selected. By doing so, it allows for a greater level of detail to be taken into account and thus, enabling more accurate analysis. It also facilitates increased transparency in the results – namely by allowing a greater understanding of how a particular site layout influences the resulting hazard profile.

2.6 Multi-Scenario Hazard Contouring

Another key update is the capability to plot combined hazard contours to a defined threat level (e.g. as overpressure or impulse) for a range of scenarios on a facility layout diagram. This feature allows for clearer understanding and communication of hazards ranges and their impact footprint as well as makes for more efficient and comprehensive analysis - the full range of flammable release scenarios (as opposed to a limited subset) can be modelled simultaneously.

This feature is not limited to explosion hazards only but can also be used to develop aggregate hazard contours for dispersing clouds (e.g. flammable concentration or toxic lethality) and thermal radiation from fires (jet fires, fireballs and pool fires).

3. Example Results

Example results are presented here from a case used to evaluate the side on overpressure loads to three existing buildings of interest arising from a number of release events associated with a proposed installation of a gas compression facility. The loads are to be used as basis for consideration of possible mitigation strategies. A range of pressurised ethane release scenarios associated with the proposed facility has been identified. These are located in and around the congested regions. For each scenario, three hole sizes have been considered – Small, Medium and Large. A single weather condition has been assumed. 8 weather directions are considered. The resulting side on overpressure contours derived for the hypothetical study are as shown in Figure 1. These show the combined hazard ranges from all explosion scenarios to specific levels of interest – in this case side-on overpressure levels ranging from 0.1 bar to 2 bar.

A detailed evaluation of explosion hazard potential to buildings requires a consideration of both the overpressure level experienced as well as the duration of the blast wave. Though not shown, the software model includes the capability to plot impulse contours.

These example results indicate:

- The explosion sources occur within the obstructed regions, indicated as pink boxes on the map.

- The peak overpressure potentially experienced by the three buildings of interest will be of the order of 0.3 bar, as this contour just marginally touches the periphery of these buildings.
- The 0.2 bar overpressure contour overlaps most of the buildings suggesting that this is a more representative pressure loading.
- Due to the fact that the 0.3 bar contour just skirts the borders of the buildings, some further investigation of the results will be required to evaluate how sensitive this overpressure level is to key assumptions (e.g. size/degree of congestion of the obstructed region).
- Additionally, it is evident the blast loads to these buildings are driven by the obstructed region to the north. Reducing the potential for obstruction in this area represents a potential solution to mitigating the blast loads to the buildings of interest.

The insights gained above can serve as input to the development of prevention and protection strategies, ultimately resulting in better control and management of explosion hazards. The calculation time for this study is less than five minutes.

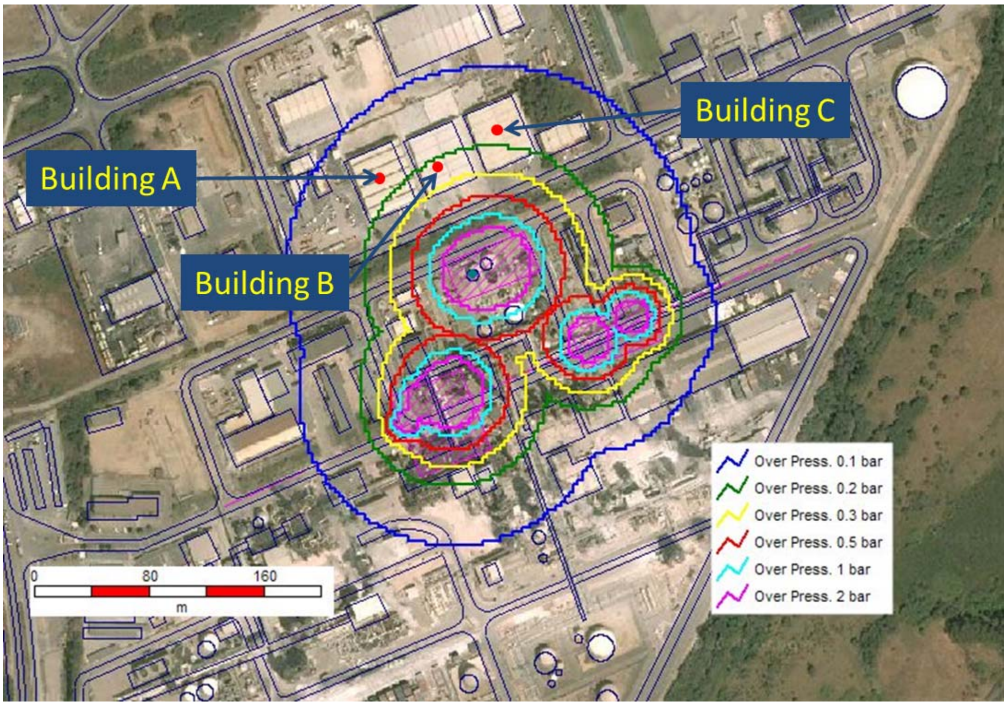

Figure 1 – Obstructed regions (pink boxes) and side-on overpressure contour envelope

4. Conclusions

Ensuring the safe location and design of occupied buildings on process facilities is high on the agenda of key stakeholders. However, effectively solving this challenge is not a trivial task. Due to the complexity of the VCE accident sequence and the scale of the analytical work involved, software tools are necessary. Such tools must provide a good level of characterisation potential, and provide results in a reasonable time frame. It is therefore desirable to have a software tool which allows for a comprehensive analysis to be undertaken in a rigorous, and resource efficient manner.

This paper has described and examined the recent advances in the Phast consequence model designed to address this challenge. The advancements to the Phast software platform are a welcome addition to the range of software tools available to facilitate the evaluation of explosion risks and will help improve the robustness and overall quality of such evaluations resulting ultimately in more effective assessment of the consequences of explosions in congested and confined spaces on personnel, buildings and process equipment.

References

API (American Petroleum Institute), 2007, Management of Hazards Associated with Location of Process Plant Portable Buildings, API Recommended Practice RP753, 1st Ed (Reaffirmed January 2012). American Petroleum Institute: Washington, USA.

API (American Petroleum Institute), 2009, Management of Hazards Associated with Location of Process Plant Buildings, API Recommended Practice RP752, 3rd Ed. American Petroleum Institute: Washington, USA.

Baker, Q., Doolittle, C., Fitzgerald, G., & Tang, M., 1998, Recent development in the Baker-Strehlow VCE analysis methodology. Process Safety Progress, 17(4), 297-301.

Baker, Q., Tang, M., Scheier, E., & Silva, G., 1996, Vapor cloud explosion analysis. Process Safety Progress, 15(2), 106-109.

CIA (Chemical Industries Association), 2010, Guidance for the location and design of occupied buildings on chemical manufacturing sites 3rd Edition. Chemical Industries Association: London, United Kingdom.

Haidari, H. Ahmad, Matthews, B., 2003, Future Trends for Computational Fluid Dynamics in the Process Industry. Third International Conference on CFD in the Minerals and Process Industries CSIRO, Melbourne, Australia 10-12 December 2003.

TNO (The Netherlands Organization of Applied Scientific Research), 1997, Methods for the calculation of Physical effects due to releases of hazardous materials "Yellow Book" CPR 14E. The Netherlands Organization of Applied Scientific Research: The Hague, The Netherlands.

Van den Berg, A., 1985, The multi-energy method: a framework for vapor cloud explosion blast prediction. Journal of Hazardous Materials, 12, 1-10.

Van den Berg, A., & Mos, A., 2005, Research to improve guidance on separation distance for the multi-energy method (RIGOS) (TNO Report PML 2002-C50 Prepared for the UK Health and Safety Executive: Research Report 369). TNO Prins Maurits Laboratory: Rijswijk, The Netherlands.

Witlox, H. W., 2010, Overview of consequence modelling in the hazard assessment package Phast. In 6th AMS conference on applications of air pollution meteorology, Atlanta, USA, 17-21 January 2010.

Witlox, H. W., & Oke, A., 2008, Verification and validation of consequence models for accidental releases of hazardous chemicals to the atmosphere. IChemE Hazards XX Symposium & Workshop, Manchester, UK, 15-17 April 2008.

Xu, Y., 2010a, Obstructed Region Explosion Model (OREM): Theory. London: DNV Software.

Xu, Y., 2010b, Obstructed Region Explosion Model (OREM): Validation. London: DNV Software.