FUEL GAS EXPLOSION GUIDELINES - PRACTICAL APPLICATION

R.F. Barton
Sedgwick Energy Ltd, London, E1 8DX

Prediction of blast and fire damage to process plant and buildings arising from a catastrophic vapour cloud explosion is important for the insurance industry in order to assess underwriting exposures. Based on fundamental research insights, a new financial consequence model has been developed. This paper describes the model basis and its practical application. Comparison with recent industry losses is presented.

INTRODUCTION

The accidental release of a combustible gas or vapour into the atmosphere can lead to the formation of a flammable cloud. Under particular conditions, the combustion of such clouds can produce damaging overpressures. These events are known as vapour cloud explosions. Probably the most well known occurred at Flixborough, United Kingdom in 1974 following the release of cyclohexane and, more recently, at Pasadena, USA in 1989 when a breakdown in operating and maintenance procedures resulted in the release of the contents of a high density polyethylene loop reactor. Such explosions have led to extensive property damage and, in many cases, injuries and loss of life. In addition, a company's business can be severely disrupted causing loss of revenues. The total financial loss associated with the Pasadena explosion approached US$ 1.7 billion.

Although these catastrophic explosion events are considered remote and of low probability, there have been over 200 such incidents in the last 50 years [1]. Some of the more significant events are listed in Table 1 with property losses updated to reflect 1995 values. The table also highlights the diversity of operation and materials involved in the initial hydrocarbon release.

The significant financial consequences reflect the large amounts of capital tied up in the refining, petrochemical and chemical industries in what are often complex, high technology facilities.

VAPOUR CLOUD EXPLOSION AND INSURANCE CONSIDERATIONS

Vapour cloud explosions, or VCEs, are of key interest to the insurance industry since, along with jet fires and natural perils such as earthquakes and hurricanes, they can represent the estimated maximum loss (EML) to which an insurance underwriter is exposed.

For the operator, knowledge of the EML ensures that optimum levels of insurance are purchased as part of any risk management programme. Confidence in EML prediction is, therefore, of prime concern to operators and insurers alike.

In predicting financial property damage, the insurance industry has relied on two types of approach in recent years. The first involves empirical prediction tools based on insurance loss history, while the second is calculation of overpressure and hence, fire and blast damage by equating the amount of hydrocarbon released to an equivalent mass of TNT explosive. Review of these modelling approaches revealed a number of weaknesses which, coupled to the insights from industrial research by organisations such as Shell Research [2], British Gas [3] and TNO [4], prompted development of the Cates approach [5] into an insurance model for predicting catastrophic property damage loss.

LOSS ASSESSMENT MODEL BASIS

The basis for the Sedgwick model reflects current understanding of vapour cloud explosions, i.e. under practical plant conditions, fast flame speeds are only generated by regions of high congestion or semi-confinement, thereby giving rise to damaging overpressure. The model at this time is applicable to methane, LPG and most refinery and petrochemical materials. More reactive systems, including propylene oxide, ethylene oxide or acetylene, fall outside the scope of the model.

The extent of flame acceleration, and hence overpressure potential, is a function of gas concentration, the degree of congestion or confinement within a plant structure, and material type. Overpressure from the explosion epicentre, which is centred on a plant structure, decays acoustically according to the relationship published by Cates, i.e.

$$P = (R_o/r)\, P_{max} \qquad \text{and } r = R_o + r'$$

where P is the overpressure at a distance r' from the edge of an effective source volume V of radius R_o, defined as $R_o = \sqrt[3]{(3V/2\pi)}$.

The volume term reflects not only the volume of the process structure, but also includes allowance for the fact that a part of the explosion will take place in the turbulent gas driven outside of the confined or congested area. A typical industry plant structure is of the order of 40,000 m^3. P_{max} is the maximum pressure assumed uniform throughout the source volume where the vapour cloud explosion is centred.

The gas concentration within the cloud is assumed to be stoichiometric, i.e. conditions whereby maximum flame temperatures and, therefore, overpressure will result.

P_{max} is material-dependent and values for different hydrocarbon types for an industry typical plant structure in terms of layout is shown in Table 2. For more highly congested structures P_{max} will be higher, and similarly for more open structures flame speed, and hence overpressure, will be lower. Within the Sedgwick model, four types of plant congestion are defined: Minimal, Low, Typical and Severe. The choice of congestion category follows the guidelines within Cates in terms of equivalent layers and separation as a function of equipment diameter.

In determining the degree of congestion, a logic chart is followed, which is attached at the end of the paper. Should the hazard area be enclosed by solid walls or large obstacles such as vessels to the extent of 60% confinement or greater, then a Severe categorisation is automatically selected.

The different P_{max} potential for various hydrocarbon types is related to the different combustion kinetics of the burning processes involved. Using the fractal scaling theory of Taylor and Hirst [6], turbulent burning velocity for a given plant geometry will be proportional to the product of the laminar burning velocity and expansion ratio of the gas raised to the power of 1.36. Since overpressure is proportional to the turbulent burning velocity squared, overpressures for different materials can be computed relative to some reference molecule. Within the Sedgwick model, this corresponds to a standard saturated light aliphatic hydrocarbon mixture (ethane, propane, butane), which, for a typical industry structure, yields a $P_{max} = 0.7$ bar. A review of historical VCEs where there was some knowledge of the maximum overpressure allowed fine-tuning of the estimated P_{max} for a range of materials.

The variation in P_{max} for different levels of plant congestion is shown in Table 3 for a range of material types.

Once the overpressure-distance profile has been calculated, fire and blast damage factors are applied depending on the overpressure. For practical purposes, a series of isobars are drawn overlaid on a plot plan which, if the distribution of the asset values is known, allows for computation of the EML. The fire and blast damage factors are based on analysis of actual insurance loss events, and data published by the US Department of the Interior [7]. The ability of different plant type to withstand overpressure is duly recognised, i.e. in reality, heat exchangers, pipes and vessels are inherently stronger than non-blast resistant buildings. The critical overpressure isobar is 0.35 bar, the point at which pipes can damage or flanges separate. This causes subsequent release of hydrocarbons and knock-on fires with devastating consequences in terms of financial loss.

PRACTICAL APPLICATION

On visiting a refinery or petrochemical site, the surveying engineer follows a number of steps in estimating the potential for damage arising from a vapour cloud explosion. The catastrophic EML reflects the loss that could be sustained under abnormal conditions with the failure of multiple protection systems. These steps, which involve detailed discussion with the operator, include:

(i) Allocation of asset values on to a plot plan of the site.

(ii) Identification of large hydrocarbon sources, gas or liquid phase, capable of generating a gas cloud together with operating conditions.

(iii) Identification of plant structures capable of generating fast flame speeds and hence overpressures.

(iv) Gas cloud dispersion analysis using local average wind speed conditions.

(v) Generation of an overpressure-distance profile.

(vi) Estimation of the degree of fire and blast damage arising from the explosion.

(vii) Adjustment of the EML for additional costs likely to arise from investigation, site clearance, engineering, commissioning, start-up and, where relevant, inflation effects.

The calculation of the financial EML is greatly speeded up by use of a computerised version of the model, the Sedgwick Loss Assessment Model (SLAM), which runs in an IBM windows compatible computing environment.

The potential for gas cloud drift is important since more than one structure can be engulfed, i.e. there is the possibility of multiple explosions which is in fact what has happened in some of the major insurance losses involving sizeable vapour clouds. Explosion epicentres are centred on plant structures since fast flame speeds cannot be developed in large open spaces for the materials of interest.

MODEL PERFORMANCE VERSUS INSURANCE LOSSES

To demonstrate the applicability of the model, two recent insurance losses are discussed involving different materials and types of plant. These losses represented tests for the model since neither was used in its development. These losses also demonstrate the significant damage that can arise from only small releases of hydrocarbon if conditions are such that fast flame speeds can be generated.

La Mede Refinery, 1992

A vapour cloud of less than 10 tonnes formed following the suspected failure of a bypass around a cooling exchanger associated with an absorber deethaniser column within a gas plant. The vapour cloud drifted towards the furnaces associated with a nearby catalytic cracker unit and ignited. The subsequent vapour cloud explosion and ensuing fires caused US$ 225 million of property damage to the refinery and disrupted the operator's business. Six plant personnel died in the collapse of a control room which was non-blast resistant. Windows were damaged in the surrounding villages at distances up to 5 km from the blast epicentre.

Analysis of this loss, relying on a knowledge of the plant design, and comparison of predicted overpressure against observed damage within both plant areas and the local community, is shown in Figure 1.

The data fit is remarkably good. Interestingly, the shape of the overpressure-distance profile is in line with the Cates acoustic pressure wave decay hypothesis, i.e. very different from the approximate $^1/_r{}^2$ decay TNT prediction. The relationship holds both in on-site ("near field") areas, which are of interest to the property damage insurance underwriter, and outside the refinery, which is the concern of the liability insurance market. The predicted overpressure in the near field is consistent with observed plant damage in the gas plant, which was totally destroyed, and adjacent processing and tank farm areas where only partial losses of equipment occurred.

Lake Maracaibo, 1993

The failure of a propane refrigeration exchanger within a multiple production platform complex in shallow water led to a release of 3 tonnes of liquid propane. A vapour cloud developed and following subsequent ignition, an explosion occurred with the loss of 11 lives, and extensive facilities damage.

The model is applicable to this type of facility since, in reality, it is simply a plant structure, but located above water. Unlike the confined structures of the North Sea, there is an absence of highly enclosed modules or blow-out design panel features. The main production platform, which is where the explosion was centred, separates liquefied petroleum gases from natural gas. It is connected to associated pipeline riser, control room and utility platforms by walkways above the water over an area 500 metres by 250 metres. Outlying platforms suffered only blast-related effects, while the damage to the processing platform was exacerbated by fire.

The predicted blast overpressure isobars are shown in Figure 2. These are based on a 1.5 tonne vapour cloud following flashing of the liquid propane released within the congested processing structure. The model predicts a damage level of US$ 100 million, which is within a few million dollars of the insurance claim. "Far field" blast damage to control rooms and power generation equipment is consistent with the low overpressures predicted.

RECENT EXPLOSION UNDERSTANDING DEVELOPMENTS

A sister paper presented by Puttock [8] highlights important advances in the understanding of explosions arising out of the CEC sponsored MERGE project. The changes proposed to the original Cates methodology are likely to impact on the insurance model to a minor extent, and only for those scenarios where a maximum overpressure of greater than 0.9 bar is anticipated. Loss history shows that such events are few and far between. In such instances, the rate of pressure decay can be anticipated to be greater than the acoustic approximation in the "far field". From an insurance perspective, this is a third party liability issue.

Review of the 1974 Flixborough loss using the modified equations presented by Puttock is presented in Figure 3. Here, the predicted overpressure profile from the epicentre is compared with Sadee's data [9]. The original overpressure-distance profile has been modified to reflect an epicentre based on the Cates approach in which structure volume location is all important. The original epicentre proposed by Sadee was based on an aerial blast of 16 tonnes TNT equivalent of cyclohexane. The complexity of the Flixborough explosion in terms of a number of hydrocarbon- engulfed structures and actual epicentre is well described by Roberts and Pritchard [10].

Figure 4 reveals that the distances at which window damage was observed in the villages of Burton upon Stather and Amcotts fall below that predicted by a purely acoustic pressure wave decay format. Such effects may well be due to the changing nature of the overpressure decay relationship in the far field for very high pressures close to the epicentre. Indeed, the predicted relationship based on the equations in Reference 8 would indicate that the findings of the small-scale MERGE experiment can indeed be extrapolated to large plant installations.

INHERENT RISK & EML MAGNITUDE

The Sedgwick insurance model is highly sensitive to the type of operating risk. In the past, models for estimated maximum loss evaluation have tended to rely solely on a mass input term and were almost independent of hydrocarbon type or plant design layout features. Using the Sedgwick approach, higher EMLs are to be anticipated for those facilities which are petrochemical-based, for example, steam crackers, or highly congested plant with poor inter-unit separation. Relatively lower EMLs can be expected for LPG or NGL processing plant which is well laid out in terms of both intra- and inter-unit spacing. This is borne out by Table 5 in which predicted average EMLs are presented by industry sector.

In predicting an overpressure-distance profile, the model can also be used by designers, safety specialists and risk managers to assist in studies relating to:

i New plant design layout and inter-unit separation.

ii Control room location and decision as to the need for blast-resistant construction.

iii Location of high occupation level administration and maintenance facilities relative to process plant.

iv Liquid hydrocarbon inventory minimisation to reduce potential gas cloud size.

v Location of tank farm and cooling units relative to process areas.

vi Liability evaluation where blast effects could impact on communities and industrial neighbours outside of a company's boundary fence.

vii Support in safety case preparation.

Such studies have already been carried out for a number of companies throughout the world where existing TNT-based modelling approaches have been found to be wanting.

CONCLUSIONS

The findings of large and small-scale research into deflagration type processes involving hydrocarbons has been developed into a practical approach for assessing insurance exposures arising from vapour cloud explosions. Estimation of overpressure and consequential financial loss is based on specific risk type and, in particular, the type of plant process technology, equipment design layout features and overall site layout.

This approach realistically models the major energy insurance industry losses of recent years, giving greater confidence in EML prediction for insurance purposes. This will be to the benefit of operators, insurers and plant designers.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the valuable contributions made in developing the model from insurance companies, operators, the Shell organisation and, in particular, Dr. J.S. Puttock, Mr. M.S.P. de Groot, and Dr. M.J. Pikaar.

REFERENCES

1. E.M. Lenoir & J.A. Davenport, 1992
   A Survey of Vapour Cloud Explosions, Second Update
   26th Annual Loss Prevention Symposium, AIChE, New Orleans

2. A.J. Harrison & J.A. Eyre, 1987
   The effect of obstacle arrays on the combustion of large pre-mixed gas/air clouds.
   Combustion Science & Technology, 52, 121-137

3. R.J. Harris & M.J. Wickens, 1989
   Understanding Vapour Cloud Explosions - an experimental study
   Institution of Gas Engineers, Communication 1408

4. W.P.M. Mercx, R.M.M. van Wees & G. Opschoor, 1993
   Current research at TNO on Vapour Cloud Explosion modelling
   27th Annual Loss Prevention Symposium, AIChE

5. A.T. Cates, 1991
   Fuel gas explosion guidelines
   International Conference on Fire and Explosion Hazards,
   Institute of Energy

6. P.H. Taylor & W.J.S. Hirst, 1988
   The Scaling of Vapour Cloud Explosions: a fractal model for size and fuel type
   22nd International Symposium on Combustion

7. M.M. Stephens, 1970
   Minimising Damage to Refineries
   Office of Oil & Gas, The Department of The Interior

8. J.S. Puttock, 1995
   Fuel gas explosion guidelines & further development
   Second European Conference on Major Hazards, Manchester

9. C. Sadee et al, 1976
   The characteristics of the explosion of cyclohexane at the Nypro (UK) Flixborough plant on 1st June 1974
   Journal of Occupational Accidents, 1

10. A.F. Roberts & D.K. Pritchard, 1982
    Blast effect from unconfined vapour cloud explosions
    Journal of Occupational Accidents, 3

Table 1 **Recent large insurance losses arising from vapour cloud explosions (US$ millions)**

Year	Plant Type	Material	Fatalities	Property Loss
1987	Acetic Acid	Butane, oxygenates	3	265
1988	Refinery	Propylene, propane	7	356
1989	HDPE Polymer	Isobutane, ethylene	23	779
1992	Refinery	Unsaturated LPG	6	243
1993	Offshore Processing	Propane	11	105
1994	Refinery	Cracked gases	-	101

Table 2 P_{max} **for different materials and typical plant structure congestion (bar)**

Material Type	Overpressure
Methane, toluene	0.6
LPG, gasoline	0.7
Unsaturated LPG	1.1
Butadiene	1.5
Ethylene	1.8

Table 3 P_{max} potential for different structure congestion (bar)

Material Type	Minimal	Low	Typical	Severe
Methane	-	0.3	0.6	0.8
LPG	0.2	0.4	0.7	1.0
Propylene	0.3	0.5	1.1	1.5
Ethylene	0.4	0.9	1.8	2.0

Table 4 Fire & blast damage allocation (% of asset damaged)

Overpressure (bar)	Process Plant	Heavy Machinery	Non-blast resistant buildings	Atmospheric Tankage
>0.7	100	80	100	100
0.7-0.35	80	40	100	100
0.35-0.2	20	-	100	100
0.2-0.1	5	-	100	50
0.1-0.05	-	-	50	-

Table 5 EML & risk type (US$ millions)

Risk Type	No. of Sites	Average EML
Gas Processing	7	180
Refining	11	230
Petrochemical	12	340

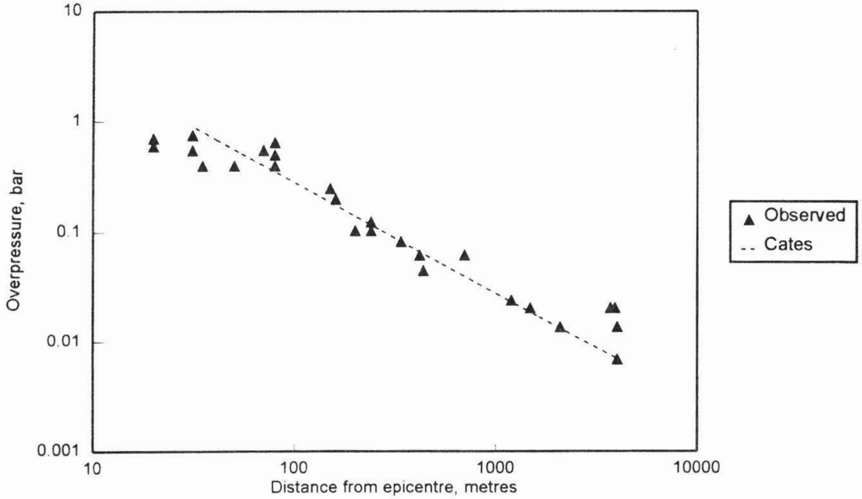

Figure 1 La Mede overpressure versus distance profile (actual versus predicted)

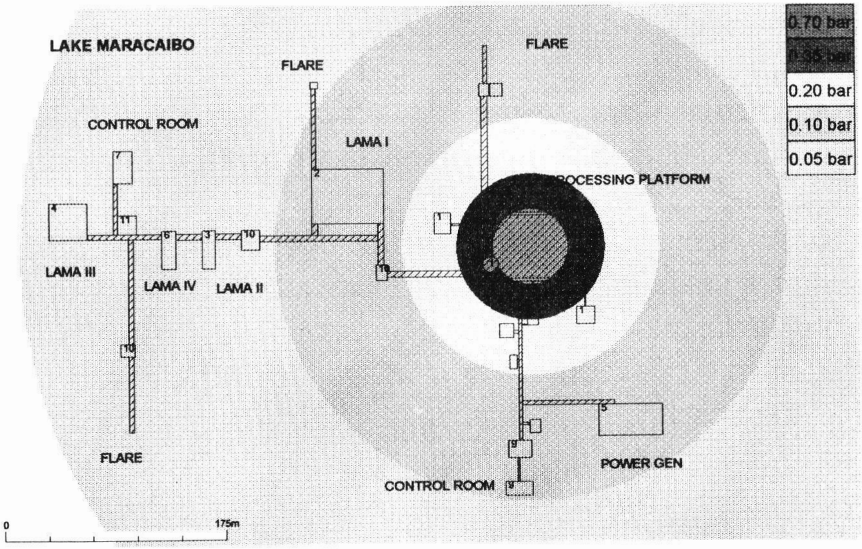

Figure 2 Predicted Lake Maracaibo overpressure isobars

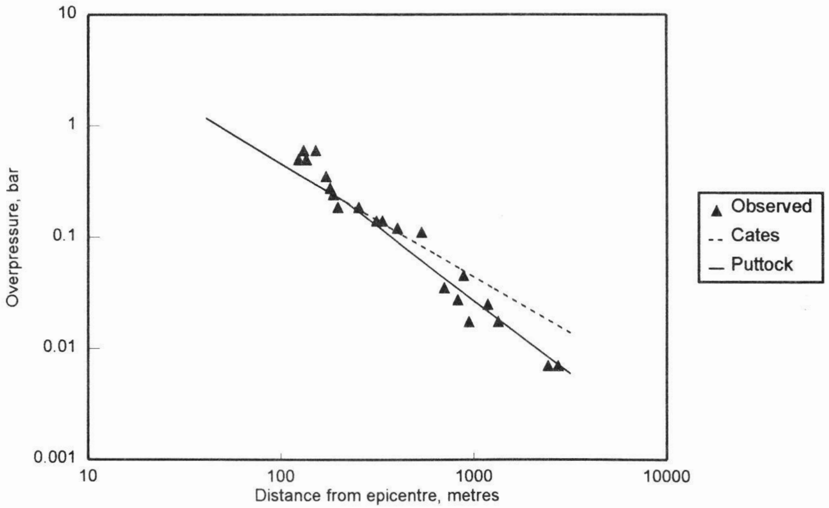

Figure 3 Flixborough overpressure versus distance profile (actual versus predicted)

Guidelines for estimating degree of plant congestion