

VAPOUR CLOUD EXPLOSION RISK MANAGEMENT IN ONSHORE PLANT USING EXPLOSION EXCEEDANCE TECHNIQUES

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The accidental release and ignition of flammable vapours in refineries, gas and petrochemical plants present potential explosion hazards that can impact the safety of plant personnel. This paper discusses a methodology developed by Shell Global Solutions to determine the explosion risk to people in occupied buildings on the site from knowledge of process conditions and site layout. The methodology, known as "explosion exceedance", draws on recent developments in vapour cloud dispersion and explosion science.

The calculations are designed to satisfy the guidance given in API RP752 [API 1995] and CCPS [1996] on explosion risks. The results are expressed as the risk of fatality for the individual who is most exposed to building damage following an explosion in the plant. Also the group risk is calculated in terms of Potential Loss of Life (PLL)/yr and f(n) for the site employees who may also be exposed to the building explosion risk. These risk markers enable the derivation of guidance to satisfy a site's risk criteria by way of:

1. design overpressures for new buildings or upgrades to existing buildings,
2. the siting of temporary buildings,
3. the siting of new buildings,
4. the siting of new processing units,
5. levels of building occupancy, and
6. identity of the main risk contributors.

The methodology has been implemented in a suite of software risk tools known as Shepherd and is based on a full probabilistic approach to assess explosion hazards. Considerable effort has gone into validation and comparison with historical experience. The software is being used for many Shell sites to ensure consistency of approach and to comply with the Company's commitment to health and safety.

The paper will discuss the methodology, some case studies, and underlying remaining uncertainties.

[1]Shell Global Solutions is a network of independent technology companies in the Royal Dutch Shell Group.

INTRODUCTION

The Health, Safety and Environment Consultancy Group in Shell Global Solutions has developed a methodology to assess the risks posed by vapour cloud explosions in process plant. The methodology has been implemented in a suite of risk tools known as Shepherd and is based on a full probabilistic approach to assess explosion hazards [Puttock 2000].

Originally, a full explosion exceedance study was carried out for the processing units at a UK refinery. This involved a complete count of equipment, flanges, fittings and associated pipe-work with the potential to leak flammable fluids. The methodology then calculates vapour cloud dispersion and explosions to predict the consequences of all foreseeable explosions at occupied buildings on the site. Associated with each scenario is a frequency of individual risk derived from the frequency of the original leak multiplied by the ignition probability, the degree of overlap of the flammable cloud with congested areas of plant and vulnerability to explosion following damage to the building. To repeat this exercise for other sites would not be cost effective so a generic version has been developed and implemented into the Shepherd software and is reported here. In the generic exceedance methodology, the input and processing of data is considerably reduced over the full exceedance and significant effort has been applied to minimise loss of accuracy.

THE RISK ASSESSMENT METHODOLOGY

The full methodology for assessing the tolerability of site personnel in occupied buildings to the risk of process plant explosions is explained in Chamberlain [2004]. Essentially each site under study must supply data on process streams (normal operating pressure, temperature and fluid composition), layout of the main equipment items (vessels, pumps, compressors, heat exchangers, furnaces, etc.), building construction types and occupancy levels. The Shepherd exceedance methodology is a simpler, but more pragmatic, version of this full exceedance methodology, and is described below.

The Shepherd risk tool forms a family of graphical risk integrators, containing *inter alia* the explosion exceedance methodology. The tool has been developed to carry out fit-for-purpose Quantified Risk Assessment (QRA) for a broad range of onshore industrial sites such as refineries, gas plants, chemicals plants, LPG distribution sites, pipeline systems, etc.

The Shepherd exceedance methodology is designed to make use of generic exceedance curves. The gas dispersion scenarios and their associated explosion overpressures and impulses have been collapsed onto two generic exceedance curves, one for flammable releases originating within the process unit comprising the congestion area and one for releases originating in adjacent areas. The derivation of these curves is described subsequently. Note that Shepherd exceedance ends with a prediction of the overall explosion risk per building or site. Application of risk tolerance and effectiveness of safety measures are decisions for the site. Shepherd exceedance is not intended to replace the full risk methodology, but it is a considerably more efficient way of carrying out the calculations.

It is recommended that the full methodology should be carried out when making critical decisions, such as ones that involve severe consequences with borderline risks.

A flow chart outlining the methodology is shown in Figure 1. The information in the numbered boxes is further described below:

1. The dispersion distance to the lower flammable limit is calculated, to examine whether a flammable cloud released in one unit extends to adjacent congested areas. The release rate is determined by the fluid properties and hole size. A release frequency must also be assigned using, for example, EP Forum [1992]. An ignition probability must be assigned to each release. The data recommended by Cox et al. [1990] is one such source.
2. An explosion calculation is performed to determine the source size, pulse duration and overpressure of the worst-case vapour-cloud explosion. The rule sets used are the Congestion Assessment Method, CAM, [Puttock 1995, 1999, 2001]

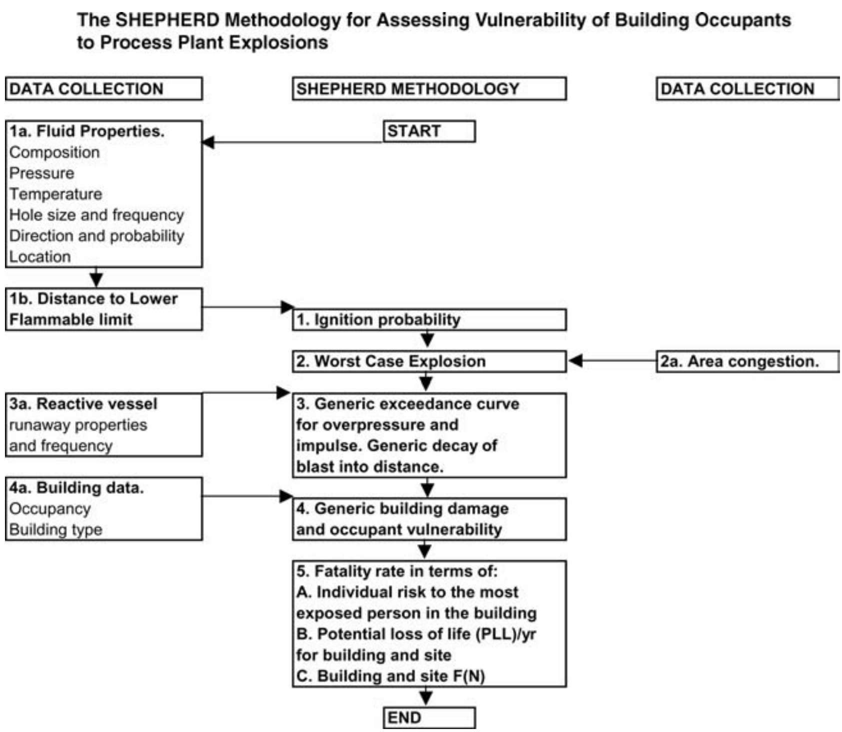

Figure 1. The simplified explosion exceedance methodology implemented in SHEPHERD

3. for vapour cloud explosions (using data from box 2a) and a modified BLEVE (Boiling Liquid Expanding Vapour Explosion) model [Shield 1993, Baker et al. 1983, Lees 1996] for vessel runaway explosions (using data from Box 3a). For enclosed process areas we assumed that all flammable leaks within the enclosures are capable of filling with a flammable mixture, that leaks within the enclosures will not migrate to neighbouring congested areas and that leaks from neighbouring process areas will not migrate into the enclosures. An explosion exceedance curve was produced for each process enclosure by varying the stoichiometry of the fuel/air mixture in CAM. Point sources were then used in Shepherd to represent an exceedance curve for each enclosure.
4. The total frequency of releases and worst case explosions are mapped onto generic exceedance curves for each congested area, one for internal vapour cloud hits and one for vapour cloud hits from external sources. The blast decay as pressure pulses move away from the source into the surroundings is also calculated at this stage following the procedure in Section 3.
5. The structural response of the building and building damage is coupled to the blast loading calculated in Box 3 by using the generic data contained in the 1995 Technology Co-Operative report prepared by Barker et al. [1996]. Clearly more sophisticated building response calculations could be carried out if necessary. The vulnerability of occupants to building damage has been derived from studies by Oswald et al. [2000], and by Jeffries et al. [1997]. There are three vulnerability models programmed into Shepherd: the model published in API RP752 [1995], a pressure-only method based on 100 ms pulse durations and a Pressure-Impulse (PI) method. The last two methods are based on the generic building types of Barker et al. [1996].
6. The fatality rates are derived from the time each individual spends in that building and the total amount of time that all occupants spend in the building. All fatality rates are summed and can be expressed in terms of risk markers such as Individual Risk, risk contours, Potential Loss of Life per annum, or F(N) (group risk) plots.

At this stage decisions have to be made regarding the tolerability to the explosion risk to occupied buildings. Then the calculated risk values can be compared to the tolerability criteria. At low frequencies, the risk can be regarded as tolerable. At higher frequencies, protection, control and mitigation measures must be assessed to reduce the risks to tolerable or to as low as reasonably practicable (ALARP).

DERIVATION OF GENERIC EXCEEDANCE CURVES

THE FULL EXCEEDANCE RUNSF

The generic exceedance curves were derived from the results of a full set of specific exceedance calculations for the processing units at a UK refinery. This involved 16 processing units comprising 42 congested plant areas, 1218 base release scenarios, approximately 40,000 gas dispersion simulations and approximately 60,000 explosion calculations. The method is an adaptation of the procedure described for offshore risk assessment by Puttock (2000).

1. A complete count of equipment, flanges, fittings and associated pipe-work with the potential to leak flammable fluids was performed for each unit.
2. The frequency of releases of various sizes was derived from the equipment count using data from EP Forum [1992]. An ignition probability was assigned to each release scenario as recommended by Cox et al. [1990].
3. Dispersion calculations were performed for each release scenario, for each wind direction and two wind speeds, using DICE [Chynoweth 2001]. DICE calculated the intersection of the flammable cloud with any congested areas in its path. It also calculated the effect of expansion during combustion on this intersection volume.
4. A very large number of explosion simulations was performed for each congested area, based on the flammable volumes already calculated. The explosion model was CAM [Puttock, 1995, 1999, 2001]; an extended version of the model was run that can make use of the cloud expansion data saved by DICE. (In the absence of such information the CAM model would have to assume, conservatively, that all expansion of the gas takes place within the congested area.) A Monte-Carlo approach was used so that all relevant parameters, such as stoichiometry at ignition, were varied randomly. The selection of gas cloud scenarios was weighted by their frequencies, which were derived from the frequency of each leak and probabilities associated with release direction, wind speed and direction, and ignition. Sufficient repeats were performed to ensure statistical significance of the results.
5. Every CAM run included the calculation of the overpressure at each of the 32 receptors. These were normally the locations of occupied buildings. The results were accumulated at each receptor to give the exceedance curves for pressure and impulse at that location.

This comprehensive approach to the calculation required large computational resources, particularly for the dispersion runs. It was achieved by using "task farming", using unused CPU time on every PC in our group.

THE GENERIC CURVES

For the purposes of the simplified exceedance in Shepherd, generic explosion overpressure exceedance curves need to be fitted for the internal overpressure in a congested region for a specific fuel. It can be expected that the shape of the exceedance curves would be different when considering releases occurring within the congested area as contrasted to releases occurring elsewhere, with the gas clouds drifting into the area. The latter would have a higher probability of generating clouds that fill a large proportion of the congested volume, as they have some distance to disperse and spread. Plumes from the internal releases would typically still be quite narrow as they leave the area. For this reason, two generic exceedance curves, one for internal releases and one for external releases, should be fitted.

The final results from the specific exceedance calculation described above could not be used directly, because the calculated overpressures in each unit were derived from summing the influence of the various fuels present in that unit. In deriving the generic curves, we need to relate the results for one fuel to "worst-case" overpressure for that fuel. Also those calculations involved a mixture of "internal" and "external" releases.

Thus a major part of the full exceedance calculation had to be re-run. The procedure was as follows:

1. The results of the gas cloud calculations (>40,000), from steps 1 to 3 in the full exceedance, were used.
2. The same number of explosion simulations were performed as before, but in each case the *ratio* of the overpressure to the "full fill" value for that fuel in that congested region was recorded.
3. The results were accumulated per congested area, and separately for internal and external releases.
4. Overpressure exceedance curves were then plotted for each of these cases.

For each congested area, exceedance curves for external and internal releases were obtained, plotting *probability* of exceedance against *relative* overpressure. In this form, with both variables normalized to a maximum value of one, some collapse of the data could be expected. The curves for external releases are shown in Figure 2. The use of logarithmic axes obscures the fact that all the curves have end points at (0.1) and (1,0).

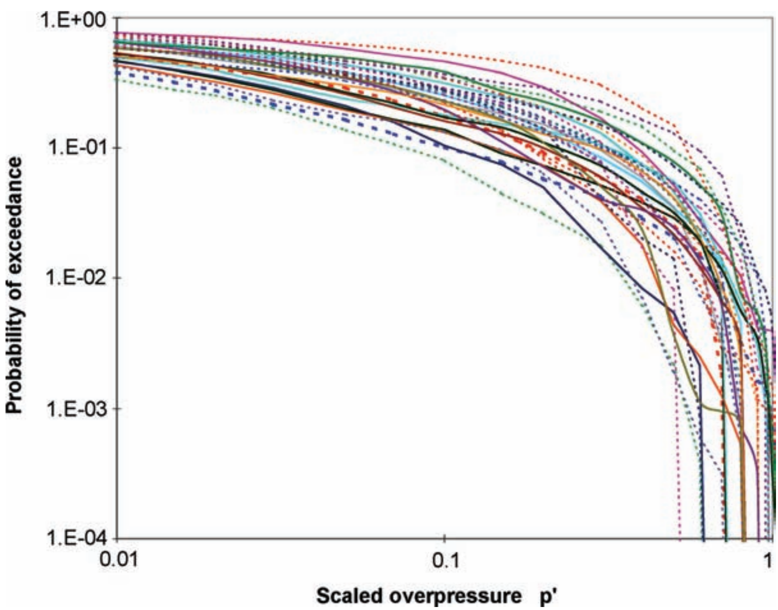

Figure 2. Normalised exceedance plot of UK refinery data for external releases

It was expected that the size of the congested regions could be shown to influence the position of the curves. For example, if the distribution of release sizes and thus gas-cloud sizes is fairly similar for different areas, then a large area will be *filled* with gas less often than a small area. This would lead to less frequent overpressures near the full-fill overpressure tending to lower the curve. Similarly, it is difficult to fully fill a long narrow area with gas, because this can only occur when the release direction and wind are closely aligned with the long axis; thus the curve for such an area would be different from that for a roughly square area.

To improve the collapse of the data, transformations were applied to the curves depending on the congested area volume, length/width ratio and height/width ratio. It was important that the transformations should not change the asymptotic behaviour of the curves at zero and one, so the form used was:

$$(1 - p'_s) = (1 - p')^n$$

where n is a function of the volume and aspect ratios of the congested area, and p' is the relative overpressure $P/P_{\text{full-fill}}$. This has the effect of shifting a curve left and down (except at the ends) if $n < 1$, or right and up if $n > 1$. The effect of applying this transformation was to reduce the variation at, say, $p' = 0.3$ by a factor of three (Figure 3).

It was then necessary to fit a curve to these results. In this, the aim was to obtain a good representation of the data, with a tendency to conservatism, i.e. a curve towards the upper end of the main group of curves. The result is also shown in Figure 3 as a heavy curve.

The fit for releases inside the congested area followed the same process.

PRESSURE DECAY

The results give expressions for the probability of exceeding various levels of source overpressure in a plant. If this is to be used to determine the effect on distant receptors, e.g. buildings, further assumptions have to be made about the pressure decay away from the source. The simplest way to do this is to assign an "effective radius" R_0 to each pressure level (or probability level) on the exceedance curve. Then the standard CAM pressure decay relation can be used to give pressure at any distance for that probability level. The issue is what to take for the effective radius.

There are two reasons why the calculated overpressure in a congested region can be lower than the maximum overpressure. One is that the gas cloud might be small; the other is that the gas cloud might not all be at stoichiometric concentration. If all the gas clouds are stoichiometric, but of varying sizes, then we can relate the overpressure to the cloud size, and hence effective source size, by running CAM for a number of different gas cloud sizes. At the other extreme, if all the gas clouds are larger than the congested volume, but of varying stoichiometry, then the effective source size is always determined by the congested volume (full-fill effective radius $R_{\max}$), and $R_0/R_{\max}$ is always 1.

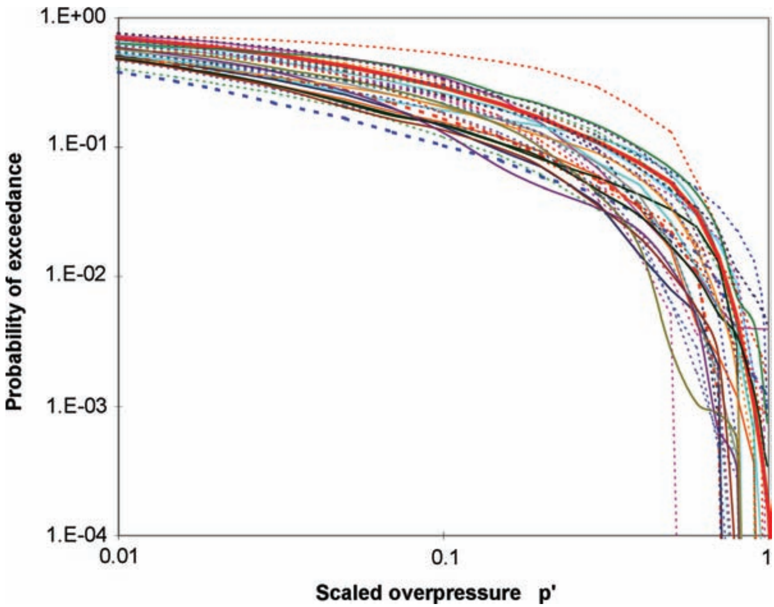

Figure 3. Transformed exceedance plot of UK refinery data for external releases. The heavy curve is the generic curve

The reality is that the low overpressures are caused by a combination of smaller cloud sizes and variations in stoichiometry. It can be assumed that there is an effective source radius associated with every point on the source overpressure exceedance curve. Exceedance curves were produced both for the source overpressure and for a number of receptors at distances from 10 m to 400 m from the congested area. The fit was performed by taking successive points on the source curves and the points with the *same probability* on the receptor curves. Each time, a value for source overpressure and a series of overpressures at various distances was obtained. If a source radius is chosen, the overpressures at the receptors predicted by the CAM correlation can be calculated. These can be compared with the series of values obtained from the exceedance runs. This was done, and the radius was varied to determine a best fit.

For the full range of overpressures, the resulting best fits are shown in Figure 4. The plotted values are normalised by the full-fill source radius, and the full-fill stoichiometric overpressure. The exercise was performed for three different congested areas. The fitted line is also shown in Figure 4(a).

To determine the effects of an explosion on a structure, it is often necessary to know the impulse received, as well as the overpressure. The Congestion Assessment Method

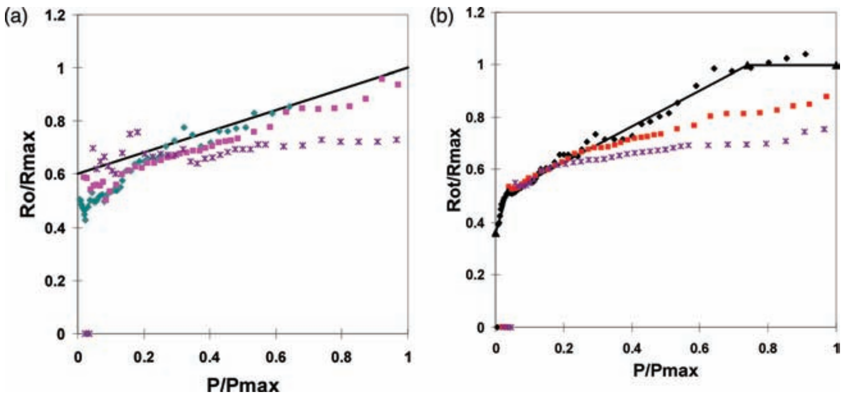

Figure 4. Best fit of the effective source size (effective radius R_o and R_{ot}) for (a) overpressure exceedance and (b) impulse exceedance, derived from the UK refinery data

includes correlations for pulse duration as a function of distance from the source, so for any source overpressure and effective radius, a pulse duration at any receptor can be calculated. The pulse shape is assumed to be triangular, so the impulse is half the product of the peak overpressure and the duration. However, for calculating the duration at the receptors, we typically found that a different effective radius R_{0t} gave a better fit Figure 4(b).

To obtain the impulse at a receptor for any given probability level on the exceedance curve, the overpressure at the receptor should be calculated using R_0, the duration using R_{0t}, and the results combined to give the corresponding impulse.

CORRESPONDING PRESSURE AND IMPULSE VALUES FOR DAMAGE CALCULATION

To calculate potential damage to a building, it is normally necessary to use both the overpressure and the impulse received at the building. For calculation of damage level at a given frequency of occurrence, we take the values of overpressure and impulse at that frequency from the respective exceedance curves. The damage is then calculated, based on these two values.

This is a convenient way to perform the calculation, but it involves an approximation. In reality, over the many possible scenarios, there is a range of impulses for any given overpressure, not just one. We have studied the effect of making this approximation.

The building damage correlations used in Shepherd give a numeric value that indicates the level of damage. Thus exceedance curves can be produced for this parameter. A computer program was written to take data from the full exceedance runs and calculate

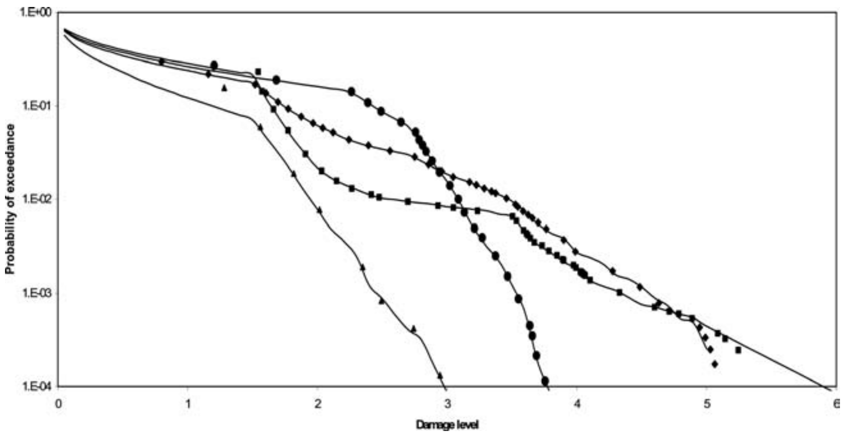

Figure 5. Damage exceedance curves from full explosion exceedance calculations for one unit and four nearby buildings. The points show the results of using the simplified method of calculation. These lie very close to the corresponding curves

the damage exceedance the detailed way; i.e. for each of the (10,000 or more) simulations for a particular plant unit, the pressure and impulse at the building was determined. Then, for each of these pairs, the damage to the building was determined. From these (10,000 or more) results, a damage exceedance curve was drawn.

Another program performed the calculations the simple way, starting from the pressure and impulse exceedance curves, and taking one impulse (duration) for each pressure.

These programs were run for one plant area, and the four nearest receptors. Arbitrarily chosen building types were placed at each receptor. In Figure 5 the results of the full calculations are shown as curves, and the simplified approach as points. It can be seen that there is close agreement between each set of points and the corresponding curve. It did not seem necessary to indicate which curve goes with which set of points.

APPLICATION TO A REFINERY

The exceedance methodology has been applied to many Shell chemical plants and refineries around the world. Here we examine one such study to demonstrate its practicality.

Contour plots over the site for the explosion risk to individuals occupying trailers (40 hours per week) are shown in Figure 6, to assist the site in decisions about tolerably safe locations for temporary buildings. Also shown are the frequency contours for overpressure exceeding 100 mbar (Figure 7) as an example of the type of output available from Shepherd, and which would cause moderate damage to non-blast resilient buildings.

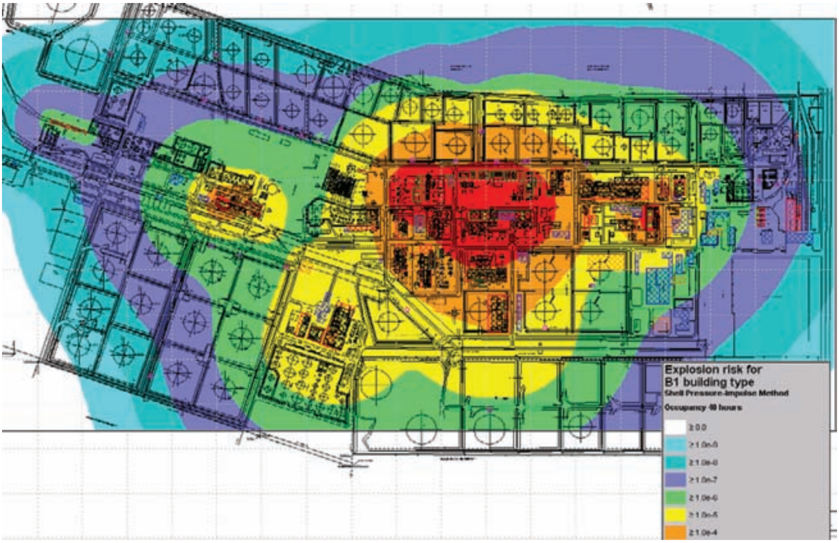

Figure 6. Base case – Individual risks for trailer type temporary with occupancy level of 40 hr/week

A contour plot of the frequency of occurrence of flammable vapour is also shown in Figure 8. This is the basis for the explosion risk, and indicates areas where vapour cloud releases are more likely.

Before any conclusions are drawn, it is prudent to verify all assumptions made in the calculations with other experts, e.g. on leak sizes, leak frequencies, building type and building occupancy, and then to do a number of sensitivity runs to analyse the impact of these assumptions on the calculated risk contours.

In the example below, there are several buildings which could be considered not to meet the acceptability criteria for the maximum individual risk (MIR). From a closer inspection of the results it was evident that the process areas of a compressor house, cat cracker unit and Topping unit were major contributors to the MIR in buildings in their vicinity. These areas are enclosed by light-weight panels which do not permit natural ventilation to disperse flammable leaks.

An obvious way to reduce the risks from these enclosures would be to study the effect of converting the enclosures into shelters by removing at least one wall. This would allow flammable leaks to disperse safely to the outside but, on the other hand, could not prevent them from entering neighbouring congested areas. It would also allow potential leaks from neighbouring process areas to create explosions within the shelter. We found, however, an overall reduction in the explosion risks by typically one

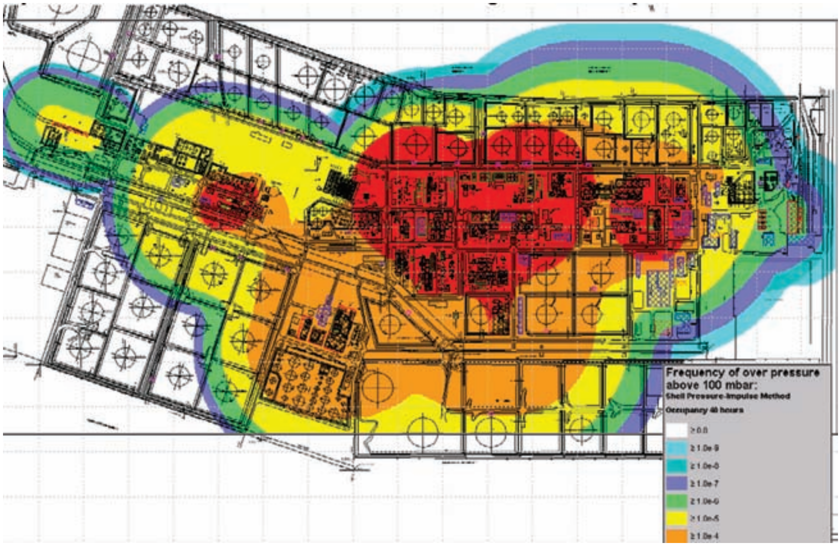

Figure 7. Base case – Frequency of overpressure above 100 mbar from site explosions

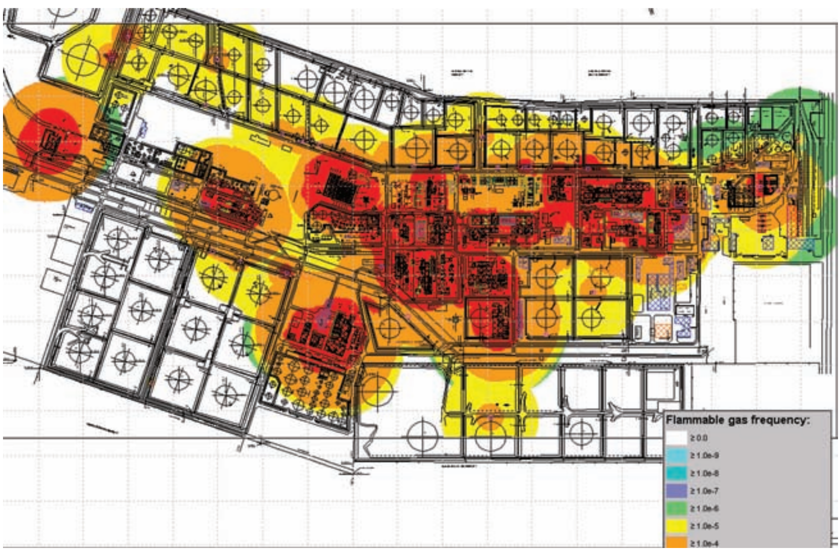

Figure 8. Base case – Frequency of flammable vapour clouds

order of magnitude to the occupied buildings with high risk in the vicinity. Safe dispersion of flammable clouds dominated over ignition and explosion. The risk for buildings with low risk, considered tolerable, was either unchanged or increased only slightly due to the small additional chance of explosion from external hits.

When the baseline results have been generated for a site then informed decisions can be made concerning options to reduce risks. Apart from the siting of temporary buildings and improving the layout and orientation of process units, several other options are possible. For new buildings the methodology allows the design overpressure and impulse to be calculated for a given level of risk at a particular location. For existing buildings the effects of upgrading the structure, re-siting or reducing manning levels can be quickly screened.

COMPARISON WITH API RP752 GENERIC FREQUENCIES OF MAJOR EXPLOSIONS

API RP752 Table C.1 gives a list of generic frequencies of major explosions for different refinery units derived from comprehensive historical databases, and is reproduced in Table 1. Overpressure and impulse exceedance curves for the API refinery units were calculated from a number of different refineries using the methodology described in this paper. If an overpressure of 350 mbar is assumed to be the threshold for major damage and escalation, a value often used by the insurance industry, the exceedance curves can be used to derive the frequency at which this overpressure is exceeded and then compared directly with the API generic values. The results of this analysis are shown in Table 1.

Table 1. Comparison of API RP752 generic frequencies of major explosions with the results using the present methodology

Process unit	API RP752 frequency of major explosion/yr.	Average Shepherd result. Frequency of overpressure greater than 350 mbar.	Number of refineries in sample	Average pulse duration, ms
Alkylation	5.1×10^{-4}	4.5×10^{-4}	4	60
Cat cracking	6.5×10^{-4}	5.7×10^{-4}	3	73
Cat reforming	2.6×10^{-4}	8.1×10^{-4}	4	55
Crude	4.9×10^{-4}	5.3×10^{-4}	4	69
Hydrotreating	2.0×10^{-4}	7.0×10^{-4}	3	45
Hydrocracking	5.6×10^{-4}	11.0×10^{-4}	2	59
Average of above units	4.5×10^{-4}	6.9×10^{-4}		60

The predicted overall average frequency is about 1.5 times higher with individual comparisons being mostly less than a factor of two. Note that the predicted average pulse durations all fall within the range 45-73 ms, overall average 60 ms.

The accuracy of this result is remarkable given the uncertainties in the database, the assumption about "major explosion" overpressures, and in the methodology itself. Although this comparison only tests the explosion source prediction, the result is encouraging and is well within the uncertainty bounds normally associated with risk analysis.

REFERENCES

API, 1995, API Recommended Practice 752, "Management of Hazards Associated with Locations of Process Plant Buildings", May 1995.

Baker, W.E., Cox, P.A., Westine, P.S., Kulesz, J.J. and Strehlow, R.A., 1983, "Explosion Hazards and Evaluation", Elsevier.

Barker, D.D., Lowak, M.J., Oswald, C.J., Peterson, J.P., Stahl, M.W. and Waclawczyk, J.H., 1996, "Final Report: Conventional Building Blast Performance Capabilities", 1995 Technology Cooperative, Wilfred Baker Engineering Inc. (Confidential).

Chamberlain, G.A., 2004, "A methodology for managing explosion risks in refineries and petrochemical plants", AIChE 38th Loss Prevention Symposium, Session T7004 Advances in Consequence Modelling, New Orleans, 26–30 April.

CCPS, 1996, "Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires". Center for Chemical Process Safety of the American Institute of Chemical Engineers.

Chynoweth, S., 2001, "Dispersion in Congested Environments". Major Hazards Offshore 27-28 Nov, The Paragon Hotel, London.

Cox, A.W., Lees, F.P., and Ang, M.L., 1990, "Classification of hazardous locations". I.Chem.E.

EP Forum, 1992, Hydrocarbon Leak and Ignition Database, EP Forum Report No. 11.4/180, E&P Forum, London.

Jeffries, R.M., Gould, L., Anastasiou, D. and Pottrill, R., 1990, "Derivation of fatality probability functions for occupants of buildings subject to blast loads", Phase 4. WS Atkins Science and Technology Contract Research Report 147/1997.

Lees, F.P., 1996, "Loss Prevention in the Process Industries", Reed Educational and Professional Publishing, Chapter 17.

Oswald, C.J. and Baker, Q.A., 2000, "Vulnerability Model for Occupants of Blast Damaged Buildings", 34th Annual Loss Prevention Symposium, March 6–8.

Puttock, J.S., 1995, "Fuel gas explosion guidelines – The Congestion Assessment Method", 2nd European Conf. on Major Hazards Onshore and Offshore, I.Chem.E., Manchester.

Puttock, J.S., 1999, "Improvements in guidelines for prediction of vapour cloud explosions", Intl. Conference and Workshop on Modelling and Consequences of Accidental Releases of Hazardous Materials". San Francisco, Sep–Oct.

Puttock, J.S., 2000, "The use of a combination of explosion models in explicit overpressure exceedance calculations for an offshore platform". Proc. Int. Conf. "Major Hazards Offshore – practical implications", London, November.

Puttock, J.S., 2001, "Developments in the congestion assessment method for prediction of vapour cloud explosions", 10th International Symposium, Loss Prevention and Safety Promotion in the Process Industries, Stockholm, 19–21 June, p 1107–1133.

Shield, S.R., 1993, "A model to predict the radiant heat transfer and blast hazards from LPG BLEVEs". AIChE Symp. Series, Vol. 89.