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RISK ASSESSMENT FOR INSTALLATIONS WHERE LIQUEFIED PETROLEUM GAS (LPG) IS STORED IN BULK VESSELS ABOVE GROUND

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SUMMARY

This paper describes the current state of development of Quantified Risk Assessment (QRA) methods which will be used by the Health and Safety Executive (HSE) for the risk assessment of installations where LPG is stored in bulk vessels above ground. It describes the models used to calculate the consequences of potential accidents involving fireballs, flash fires, vapour cloud explosions and jet flames. Levels of thermal radiation, blast overpressure and individual risk are calculated and displayed as contours around the installation. If the population distribution around the installation is included, levels of societal risk can also be calculated. The methods used are implemented on interconnecting micro and mainframe computers.

INTRODUCTION

A number of accidents such as those at Flixborough in 1974 and Seveso in 1976, has led to Governments in the European Community being concerned about the potential for certain industrial activities to give rise to serious injury or damage beyond the immediate vicinity of the work place. These activities have commonly come to be known as 'major hazards'.

It is the duty of the Health and Safety Executive (HSE) in the UK to give advice to local planning authorities on safety aspects associated with new developments in the vicinity of existing major hazards and also proposals for the siting of new major hazards. For such installations e.g. where more than 25 tonnes of liquefied petroleum gas (LPG) such as propane or butane is stored, a consultation distance is assigned by HSE. This distance, for bulk storage installations, is currently based on the inventory and the size of the largest vessel. Advice on particular developments within the consultation distance is dependent primarily on the type of development and its distance from the hazardous installation. Over the past few years this advice has been based on a quantitative assessment of consequences e.g. fireballs and explosions and a qualitative appreciation of the likelihood of these consequences.

The approach described above was endorsed by the Advisory Committee on Major Hazards (Ref 1). However, HSE has considered that it would be desirable to improve the technical basis, and hence the quality of advice, by adopting a fully quantified risk assessment technique for predicting the risks, both to individuals and to society, which an installation imposes on people in its vicinity. Although several risk models have been developed by various organisations over the last few years, it was considered appropriate for HSE to develop its own model so that HSE could maintain and enhance its expertise in this important area and also for reasons of impartiality and consistency with HSE's toxic risk assessment procedure (Ref 2).

It is not the purpose of this paper to describe the nature of the advice given to planning authorities, or the criteria which are used to judge acceptability. Rather the paper outlines the present state of HSE's risk assessment method for LPG which is still at an early stage of development. Initially the method is being developed for installations with a vessel capacity of up to 200 tonnes. The paper describes the methodology and models used, plus an indication of some of the outputs which will be obtained. Subsequent work will look, in detail, at sensitivity testing of individual models. The general approach has been to adopt a best estimate approach wherever there is sufficient data; in areas where data is lacking a conservative approach has been used.

AN OVERVIEW

An overview of the complete flammable risk assessment program is shown in Fig 1. The main inputs to the whole vessel failure calculation are the vessel size and fuel type. In addition, the environment within which the installation is located, in terms of distribution of population and potential ignition sources, is specified on a cartesian grid. Pipework sizes and process conditions are also required as inputs for the part of the assessment which deals with events other than whole vessel failure.

The program calculates the probabilities that certain levels of thermal radiation dose and blast overpressure will be experienced at the centre of each grid point for a hypothetical individual indoors and out of doors. These data are used to calculate radiation and overpressure contours. Each contour gives the distance from the source at which a specified level of radiation or over-pressure will be exceeded at a particular probability level e.g. 10^{-5}, 10^{-6} etc yr^{-1}.

Alternatively the probabilities of calculated levels of radiation and overpressure can be used with appropriate relationships linking dose with injury (probit equations) to derive individual risk levels and contours. If the population distribution is included in the calculation the results can be expressed as a societal risk which describes the frequency with which events of specified severity will occur.

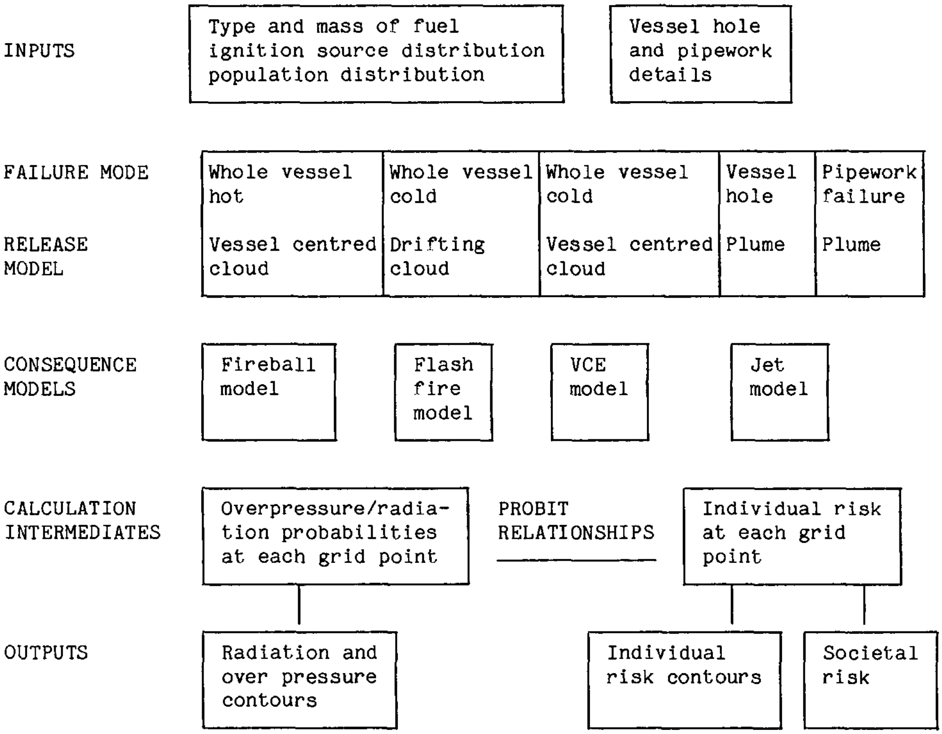

Fig 1. Overview of flammable risk assessment program

INPUTS

A particular feature of the risk assessment methodology described in this paper is the use of a grid to define the population distribution and potential ignition sources around the LPG installation. The starting point for this specification is a large-scale map of the area which is overlaid with a cartesian grid. The dimensions of the grid can be chosen, as an input to the program, so as to provide an adequate resolution of the ignition sources and population distribution. Thus for an LPG installation involving, say, a 25 tonne storage vessel an ignition and population grid of 25 m x 25 m might be used. A larger grid size may well be used to define an area around a vessel of larger size (eg 200 tonne). Using the map of the area, each grid square is designated as either industrial, urban, rural or special. This designation is then used to define the probability of ignition of a drifting cloud by considering the number and type of ignition points encompassed by the cloud. Ignition probabilities are considered to be highest over industrial areas. It is assumed that a 200 tonne release of LPG which drifts over industrial land has a probability of ignition very close to unity. An arbitrary choice of probability of ignition of 0.999999 has been used. By a consideration of the number of grid centres which the cloud covers whilst drifting and dispersing to below the lower flammable limit, the probability of ignition at each grid centre traversed by the dispersing cloud can be determined. Ignition probabilities for urban and rural grids have been set at 0.8 and 0.04 respectively of the probability of ignition of an industrial grid. Areas of the environment which are not adequately described by industrial, urban or rural designations can be assigned a special probability; this would usually be either zero or unity. The sensitivity of the results to these ignition probabilities will be examined.

The grid designation also provides the program with default values for the population distribution, although the facility exists to specify any population density in each grid position if this is needed.

FAILURE MODES AND RELEASE MODELS

Modelling of whole Vessel failures

Risk assessment is carried out using a suite of computer programs implemented on interconnecting micro and mainframe computers. This combines a fast response with ease of use and graphics output capabilities. The risk assessment programs are based around three event trees, which describe the various possible outcomes of hypothetical releases of LPG. Probabilities are assigned to a set of potential releases of LPG and to each branch of the tree to provide a set of probabilities for each of the potentially hazardous events. The first tree, Fig 2, describes events attributable to whole vessel failures, both hot and cold.

The main features of this event tree are:

- Hot vessel failure, (BLEVE) giving a fireball
- Cold vessel failure leading to
    - a vessel centred cloud which is released mainly in an upward direction and then either

  - ignites immediately giving a fireball or
  - ignites later giving a flash fire or vapour cloud explosion or
  - does not ignite

- a cloud which is released in a downward direction and then either

  - ignites immediately giving a fireball or
  - drifts away from the release point and is then ignited as a flash fire or vapour cloud explosion or
  - does not ignite

The possible consequences of a whole vessel failure which are considered are therefore

- Fireball
- Flash fire
- Vapour cloud explosion
- Dispersed unignited cloud

The consequence models for these events give predictions of radiation effects only from the fireball and flash fire but both radiation effects and overpressure effects from the vapour cloud explosion.

Hot vessel failures

This is a BLEVE caused by flame impingement on the vessel. It is assumed that on failure all of the LPG in the vessel is released and burns as a fireball.

Cold vessel releases

The catastrophic (i.e. whole vessel) failure of a pressurised LPG storage vessel will cause flash evaporation of some fraction of the vessel contents and turbulent air entrainment into the vapour-droplet cloud. It is possible to envisage a situation in which the bulk of momentum of the release is lost due to impact on the ground and surrounding structures resulting in a cloud which reaches equilibrium with its surroundings and drifts on the prevailing wind. Alternatively if the momentum is not lost, the release will be momentum driven and is likely to entrain sufficient air to dilute the cloud below the LFL before any significant drifting from the vessel occurs, i.e. the cloud remains vessel centred.

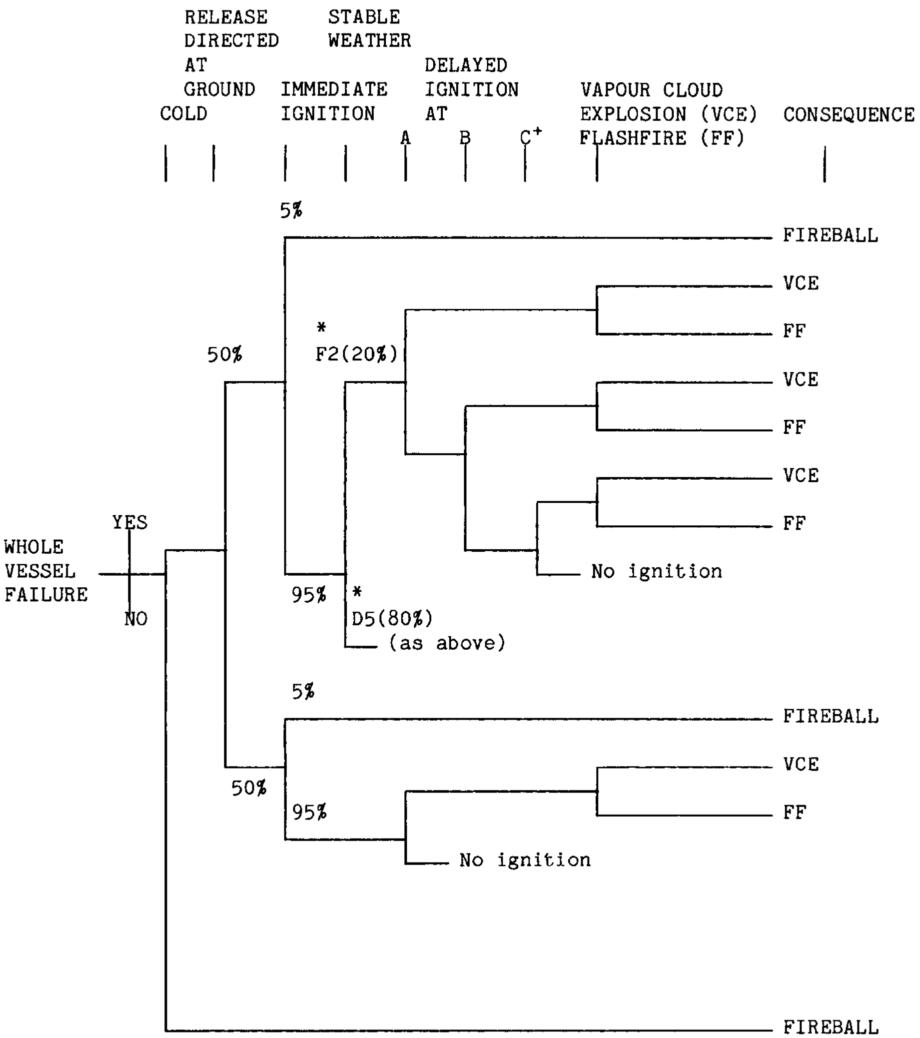

Fig 2. Event tree showing potential consequences of hot and cold whole vessel failures.

$^{+}$ Several delayed ignition sources are possible

* F2 = Pasquill Category F weather with 2 ms^{-1} wind speed
D5 = Pasquill Category D weather with 5 ms^{-1} wind speed.

As there is no evidence to suggest any form of weighting for these two extreme possiblities we have chosen to model cold, whole vessel, failures as equally divided between upward and downward releases. For the vessel centred cloud the effect of wind is neglected and the distance to LFL is calculated as the radius of a hemispherical cloud. The method is based on the work of Maurer and others (Ref 3) and described in the 'TNO Yellow Book' (Ref 4).

For drifting clouds the dispersion code 'DENZ' (Ref 5) has been used with a source term generated by considering the flash fraction of the LPG and subsequent air entrainment and equilibrium between the vapour pressure in the cloud and around the residual liquid. The HSE version of DENZ calculates the radius and height to LFL and the mass of vapour above the LFL of a drifting cloud from the mass vapourised in the release, as a function of downwind distance from the source of release. Two weather categories are used, although the facility exists to consider other weather/wind speed combinations. The two categories considered are Pasquill stability F with a wind speed of 2 ms^{-1}(F2) and Pasquill stability D with a wind speed of 5 ms^{-1}(D5).

The radiation and overpressure effects of a drifting cloud are calculated in the following manner. For each wind direction the leading edge of the cloud is allowed to move forward in incremental steps the size of the ignition grid. At each step the ignition probability is computed by considering the ignition sources encompassed. Radiation and blast effects are calculated at the centre of each population grid with an associated probability (derivable from Fig 2).

The cloud is then allowed to move on one step i.e. drift so that the cloud front contacts the centre of the next ignition grid and the calculation repeated. The number of directions is specified, with different probabilities if required, and in this way the cloud is made to drift in a representative number of equally spaced directions from the release point. The calculation is carried out for both F2 and D5 weather conditions.

Modelling of holes in vessels

The event tree shown in Fig 3 describes the various possible outcomes of a vessel hole below the liquid level. The main features of this event tree are:

- Vessel holes below the liquid level leading to
  - a drifting cloud which then either
    - ignites giving a vapour cloud explosion on flash fire or
    - does not ignite.

The cloud can disperse in either F2 or D5 weather. The dispersion is calculated using the computer code 'CRUNCH' (Ref 6). The possible consequences of a vessel hole are, as previously, a vapour cloud explosion or a flashfire.

Any consequences from vapour releases from a vessel hole or liquid releases which ignite immediately will be included in the overall risk assessment by influencing the event probability assigned to the hot, whole vessel failure. This probability is an important input to the assessment and is determined separately by considering factors such as plant lay-out. It is very unlikely however that releases from a vessel hole in the vapour space, or releases from the liquid space, which are ignited immediately will have any direct off-site consequences and these events have not been included explicitly in the vessel hole calculations.

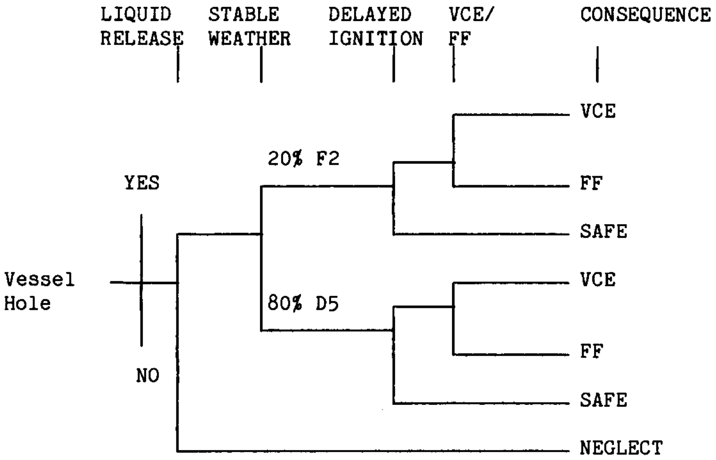

Fig 3. Event tree showing potential consequences of liquid emissions from vessel holes.

Modelling of pipe-work failures

The event tree shown in Fig 4 describes the various consequences of pipe-work failures. The main features of this event tree are:

- Liquid releases from pipework failure leading to
  - a jet flame when immediate ignition occurs or
  - a drifting cloud which then either
    - ignites giving a vapour cloud explosion or flash fire or
    - does not ignite

The cloud is dispersed in both F2 and D5 weather. The possible consequences of a pipework failure are therefore a vapour cloud explosion, flashfire or jet flame.

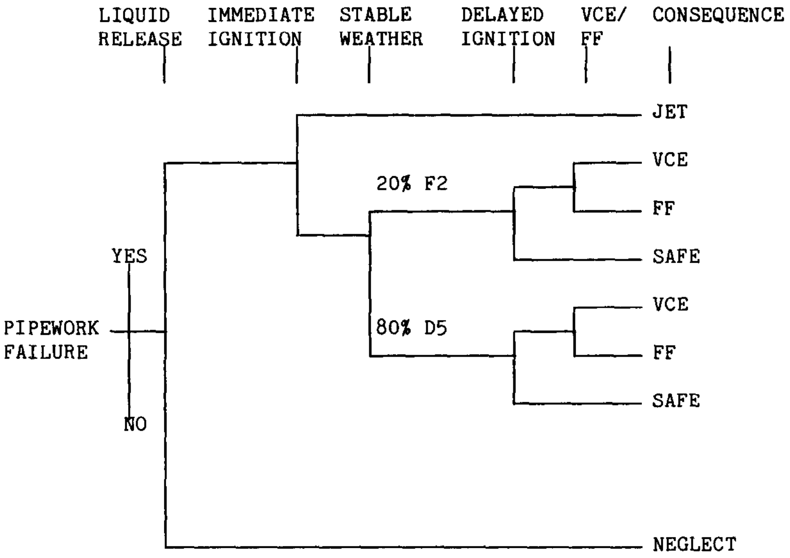

Fig 4. Event tree showing potential consequences of liquid emission from pipe-work failures

Any consequences from vapour releases from a pipe work failure are included in the overall assessment by influencing the event probability assigned to hot, whole vessel failure (as above).

CONSEQUENCE MODELS

Fireball Model

A fireball is assumed to be spherical and resting on the ground. The radius, R, metres is given by;

$R = 29\ m^{1/3}$ m = mass of LPG in the fireball (tonne)

Duration of the fireball, t (secs), is given by the equation

$t = 4.5\ m^{1/3}$ for $m < 37$ tonne

or $t = 8.2\ m^{1/6}$ for $m > 37$ tonne

The fireball model is based on the work of Roberts (Ref 7) and Fay and Lewis (Ref 8). Calculations may be performed for any value of m. Values representative of the normal high and low storage levels will be used and generally these will be assumed to be between 80% and 40% of the maximum vessel capacity respectively.

Thermal radiation received at a distance x, q is given by

$q = q\ (\text{fireball}).F.\tau$

where q(fireball) = The emissive power of the fireball kWm^{-2}
$= 235\ P^{0.39}$
where P = Pressure in the vessel at time of burst, normally taken as relief valve setting and assumed to be 1.45 MPa for propane or 0.52 MPa for butane

This gives the emissive power of the fireball as 270 kWm^{-2} for propane and 180 kWm^{-2} for butane

$$F = \frac{R^2 x}{(R^2 + x^2)^{3/2}} \quad \text{(the configuration factor)}$$

$$\tau = 1 - 0.0565 \ln x \quad \text{(atmospheric transmissivity)}$$

Radiation is determined in terms of a radiation dose, V, which is $q^{4/3}t$ $(kWm^{-2})^{4/3}$ s. This is calculated for the centre of each grid point and is considered to be the radiation received by people out of doors. For people indoors the building is likely to afford some protection and initially it has been assumed that the dose within the radius, R, of the fireball is 3000 $(kWm^{-2})^{4/3}$ s falling as $1/R^2$ to 200 units at 3R from the fireball centre.

Flash Fire Model

(i) People out of doors

Thermal radiation dose, V, is fixed at 3000 units ($(kWm^{-2})^{4/3}s$) within 1.1 R where R is the radius (m) of the flash fire. After that the following relationship between radius and dose units has been adopted:

Radius	Dose units, V
1.1	3000
1.2	2300
1.3	1000
1.4	200

(ii) People Indoors

Radius	Dose units .V.
up to 1.1	2300
over 1.1	zero

Vapour cloud explosion model

(i) Overpressure from VCE

To calculate blast effects from VCE, the 'ACMH' model (Ref 1) is used. The model requires the mass of vapour in the cloud as an input. This mass can be taken as the total mass for a cloud in the initial momentum driven phase, but for a drifting cloud the mass above the LFL is used as derived from DENZ. It is assumed that the cloud explodes with a TNT efficiency of 0.3. Overpressure is related to scaled distance by using the 'Kingery and Pannill' equation (Ref 9).

(ii) Radiation Effects from VCE

People outdoors and within the ignited cloud are considered to be exposed to 3000 $(kWm^{-2})^{4/3}$ s of radiation. It is assumed that people outside the ignited cloud boundary are not exposed to injurious levels of radiation from a VCE, nor are people inside buildings.

Jet Flames

For jet flames, a flame length is calculated using the following equation which is derived from the American Petroleum Institute publication APIRP521 (Ref 10).

$$F = \frac{(H_c m)^{0.444}}{161.66}$$

where F = Flame length (metres)
H_c = Heat of combustion $(J\ kg^{-1})$
m = Mass flow rate $(kg\ s^{-1})$

The flame is assumed to be conical and is modelled by a single point source located at 4/5 of the flame length from the origin.

The thermal radiation from this point source is calculated at a distance, x, from the point source as

$$q = \frac{f H_c m \tau}{4 \pi x^2 . 1000} \quad kWm^{-2}$$

where q = thermal radiation received (at distance x (metres)).
f = fraction of energy radiated
$\tau = 1 - 0.0565 \ln(x)$, atmospheric transmissivity

The radiation dose, $V = q^{4/3}$ s, experienced is calculated by assuming that a person remains stationary for 5 seconds and then escapes from the source at the rate of 2.5 ms^{-1} accumulating dose in 1 m steps.

BLAST/RADIATION PROBABILITIES AT EACH POINT

The program calculates at each grid point the dose of radiation or overpressure that results from each event shown in Fig 2, 3 and 4 and the associated probabilities. Thus at each grid point there is a series of doses V_1, V_2 ... V_n which have associated probabilities P_1, P_2 ... P_n.

If a specific dose is chosen, V_{int}, then if $V_{int} < V_2$, V_3 ... but $V_{int} > V_1$, then $P(V_{int}) = P_2 + P_3$ ... is the probability that the dose V_{int} will be exceeded at that point.

CALCULATION OF RADIATION OR OVERPRESSURE DOSE CONTOURS

Radiation or overpressure contours, which give specific probabilities of exceeding specific doses V_1, V_2, etc. are calculated by linear interpolation between grid points. Fig 5 shows a (now unused) 200 Tonne propane vessel situated in an industrial area. Other areas around the LPG vessel are designated as rural or urban. Because the vessel is near to the sea coast the special designation is also used for the sea. This area is assigned a zero ignition probability. Radiation contours show the probability per year of an individual out of doors being exposed to $(kWm^{-2})^{4/3}$ s as a function of distance from the 200 tonne vessel.

Fig 6 is similar to Fig 5 but shows the probability per year of an individual being exposed to an overpressure of 2 psi as a function of distance from the vessel.

THE USE OF PROBIT RELATIONSHIPS TO CALCULATE INDIVIDUAL RISK LEVELS FROM RADIATION DOSE AND BLAST PROBABILITIES

Where data exists which define the harmful effects on animals or people of exposure to over-pressure, thermal radiation or toxic gas) it is often useful to express these effects in mathematical terms. The analysis which is increasingly used in quantified risk assessment is probit analysis.

The probit function, Y, is calculated from a simple linear equation in terms of a suitable measure of 'dose'. The value obtained for Y is then converted into a percentage fatality from a 'look-up' table which links the value of Y with percentage chance of a fatal outcome. The percentage fatality obtained from the probit function is defined as 'the individual risk of death given dose'.

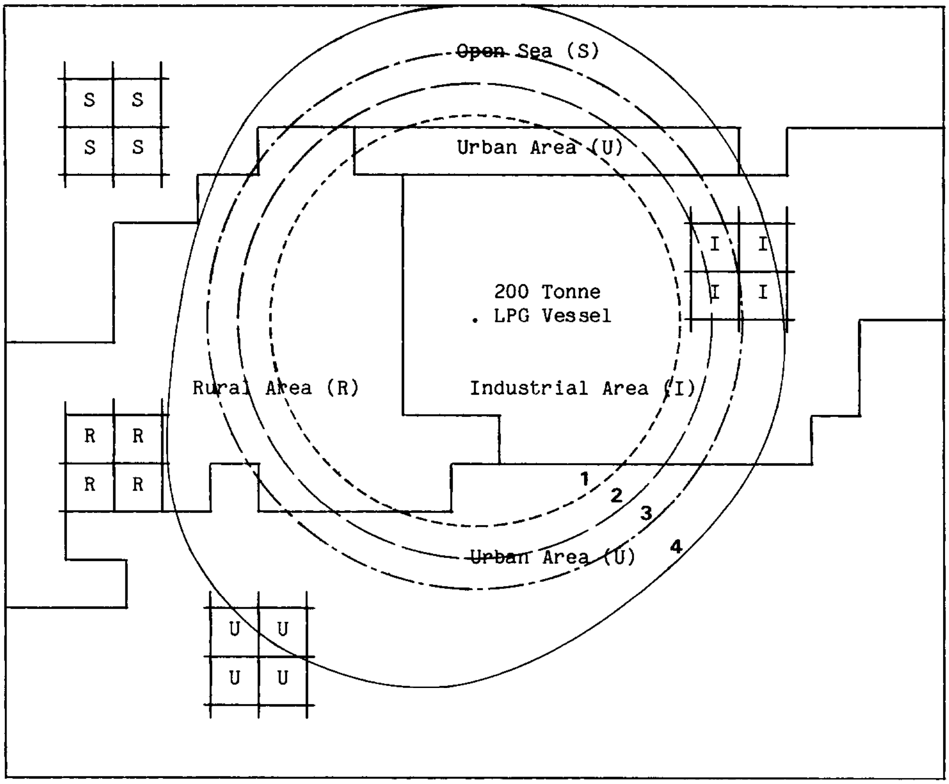

Fig 5. Use of a cartesian grid to describe the area around a (now unused) 200 Tonne propane vessel as Industrial, Rural, Urban or Special. Radiation contours for 800 $(kWm^{-2})^{4/3}$ s for whole vessel events only are also shown. There is some asymmetry evident for the 10^{-8} contour because of the asymmetric ignition grid.

1 -------- 1×10^{-5} yr^{-1}
2 — — — — 5×10^{-5} yr^{-1}
3 —·—·—·— 1×10^{-6} yr^{-1}
4 ———— 1×10^{-8} yr^{-1}

Radiation Dose and Fatalities

The only probit equation commonly used for radiation effects is due to Eisenburg (Ref 11). This can be written as:

$$Y = -14.9 + 2.56 \ln V$$

where Y = the probit function

V = radiation dose $(kwm^{-2})^{4/3}$ s

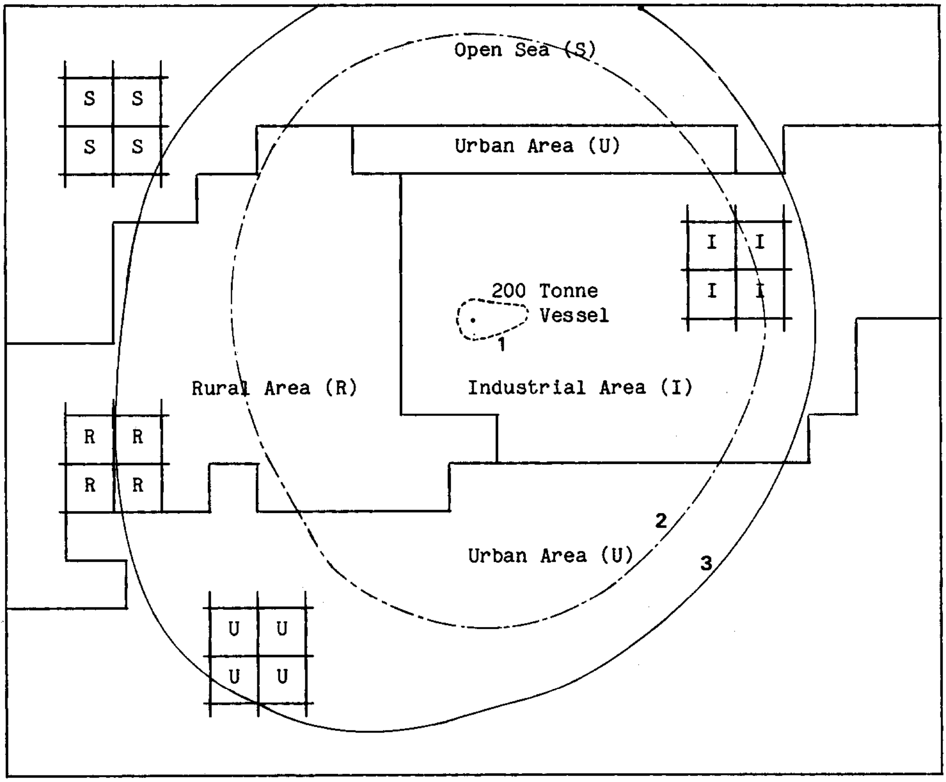

Fig 6. Use of a cartesian grid to describe the area around a (now unused) 200 Tonne propane vessel as Industrial, Rural, Urban or Special. 2 psi overpressure contours for whole vessel events only are also shown. The asymmetry of the contours is due to the asymmetrical ignition grid.

1 - - - - - - - - $1 \times 10^{-7}\ \text{yr}^{-1}$
2 —·—·—·— $1 \times 10^{-8}\ \text{yr}^{-1}$
3 ———— $1 \times 10^{-9}\ \text{yr}^{-1}$

This equation was derived from data relating to the atomic bombs dropped on Japan in the Second World War. This probit equation has been used to calculate fatalities from the radiation received from fireballs etc., except that a discontinuity has been introduced to take account of the ignition of clothing. The value of V for which this is likely to occur is dependent on the type of clothing (Ref 12) but for this analysis it has been assumed to be at 3000 $(\text{kWm}^{-2})^{4/3}$ s. Consequently at $V \geq 3000$ we have taken $Y = 8$ to give a 100% chance of death. It is also desirable to be able to estimate the fatalities that might occur should the population be 'sensitive', for example predominantly old people. For this purpose a sensitive probit, deduced from the Eisenburg probit, will be used.

Overpressure and Fatalities

A probit equation for the secondary effect (i.e. relating to collapsing structures and falls etc.) of overpressure on man from World War II flying bomb data has recently been derived (Ref 13), and is applied to the indoor population.

$$Y = 5.088 + 0.0236D^{2\ 30}$$

$$D = \text{scaled distance mkg}^{-1/3}$$

These functions are used to convert overpressure/radiation probabilities at each point to individual risk at that point (see Fig 1).

Calculation of Individual Risk

For either radiation or overpressure the relevant probit function is used to convert the corresponding indoor and outdoor doses into chance of fatal outcome. These chances of fatal outcome are 'individual risk of death given dose'.

Thus individual risk of death at a point, IR, can be written:

$$IR = \sum_{\substack{\text{all}\\ \text{doses}}} (\text{individual risk of death given dose})\ (\text{probability of dose})$$

Such an expression will apply separately to people indoors and out of doors.

The point values of individual risk (IR) are used to produce individual risk contours of 10^{-5}, 10^{-6}, 10^{-7}, etc. chances per year of a fatality by linear interpolation between grid points. This interpolation defines the position between the grid points at which the IR is exactly 10^{-5} year^{-1}, etc.

CALCULATION OF SOCIETAL RISK

The calculation of 'societal risk' from 'individual risk' is performed in the following way. The plant and its surroundings are partitioned into m sites by the grid, with N_i people at the i^{th}site ($i = 1, \ldots, m$), so that $N = m \sum_{i=1}^{m} N_i$ the total number of people who might be affected by an accident. We assume that an individual chosen at random from those at the i^{th} site will be killed (or otherwise injured) with a probability of P_i - the 'individual risk given dose' (see above). Letting X denote the number of people killed, the problem, then, is the derivation of a method for computing $F(n) = pr\ \{X \geq n\}$, the probability that at least n people will be killed (or otherwise injured) given the m pairs of parameters (N_i, P_i). The function F(n) is not a complete statement of societal risk because the probability P_i is the individual risk given dose, and in practice there will be a series of possible events, with different probabilities and different severities which can affect the population.

At each of the m, sites because any individual will be either killed or not killed it is reasonable to assume that the number of people killed follows a Binominal distribution. It follows, from this that for any one site the mean μ_i and variance σ_i^2 of X_i the number killed at the i^{th} site are given by

$$\mu_i = N_i\ P_i$$

$$\sigma_i^2 = N_i\ P_i\ q_i$$

Thus the mean, μ, and variance, σ^2, of X, the total number of people killed for all the m sites combined are given by

$$\mu = \sum_{i=1}^{m} \mu_i = \sum_{i=1}^{m} N_i P_i$$

$$\sigma^2 = \sum_{i=1}^{m} \sigma_i^2 = \sum_{i=1}^{m} N_i P_i q_i$$

Because the population can be affected by a series of events, E, of different probability and severity there is for each event a distribution of the number of people killed defined by μ_E and σ_E.

We have recently shown (Ref 14) that the distribution of X may be taken as Normal, with mean μ and variance σ^2 so that:

$F(n) = pr(X \geq n)$ by definition

$\therefore F(n) = 1 - pr(X \leq n)$

or : $F(n) = 1 - \Phi\left(\frac{n - \mu}{\sigma}\right)$

where $\Phi(\ )$ is the standard Normal cumulative distribution function. Thus for each event there is a normal distribution of the number of people killed defined by μ_E and σ_E.

In this way the societal risk is calculated from the pairs of parameters (number of people at each site, probability of death given dose at each site) which are used to calculate F(n) for each event and the probabilities of the various events such as fireballs, vapour cloud explosions and flash fires, which are derived from the event trees. Thus we can write societal risk as:

$$\text{Societal Risk} = \sum_{\substack{\text{all}\\\text{events}}} (F(n))(\text{probability of event occurring})$$

plotted against the number of people killed.

CONCLUSION

This paper has outlined the present state of HSE's risk assessment method for LPG which is still at an early stage of development. The methodology and models used have been described and examples of some of the outputs available have been given.

The purpose of developing a QRA method for LPG within HSE is to improve the technical basis and hence the quality of HSE's advice by a more precise consideration of the events which can occur and their likelihood thereby giving a refined impression of the risks.

In further developing this methodology it will be important to consider the sensitivity of the results obtained to the various assumptions made, and to the precise nature of the various sub-models included in the method. Future work (Ref 15) will examine this sensitivity and contrast the results obtained with both those from other fully quantified methods and with those from the 'consultation distance' approach, currently used by HSE.

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