THE SENSITIVITY OF RISK ASSESSMENT OF FLASH FIRE EVENTS TO MODELLING ASSUMPTIONS

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Based on reviews of modelling techniques and data from flash fire field trials, models for the prediction of the burn area of a flammable cloud (in terms of fraction of mean LFL of the cloud), flame speed through the cloud and heat transfer from the flash fire have been produced. The validity of the typical assumptions used in the modelling of flash fires has been tested through comparison against these models and a set of revised assumptions is provided relating to the likelihood of fatality of people caught within a flash fire and the mitigating effects of shelter and escape from the cloud. A sensitivity analysis is performed in order to identify which assumptions or aspects of flash fire modelling are the most critical in terms of off-site risk. The analysis suggests that risk assessments are most sensitive to the definition of burn area of the cloud, and therefore also to dispersion modelling, and to the proportion of people within shelter who are fatalities as a result of secondary fires.

Keywords: Flash fires, flammable gas clouds, quantified risk assessment

INTRODUCTION

Flash fire models used for the purpose of risk assessment are usually based on gas dispersion modelling combined with the probability of ignition (e.g. Considine et al (1) and Clay et al (2)), where the boundary of the fire is defined by the downwind and crosswind dimensions of the gas cloud. On behalf of the Health & Safety Executive, a detailed review was conducted (3), which considered incident and experimental data and risk assessment techniques related to flash fire modelling. This review allowed a framework for an improved flash fire model to be produced, which was developed further in a subsequent study (4). Models for the prediction of the burn area of a flammable cloud (in terms of fraction of mean LFL of the cloud), flame speed through the cloud and heat transfer from a flash fire were produced. The study also assessed the validity of typical assumptions used in the modelling of flash fires and a set of revised assumptions was provided relating to the likelihood of fatality of people caught within a flash fire and the effect of shelter and escape from the cloud in reducing fatality levels.

This paper outlines working models for determining the effects of flash fires, which were then used in testing which aspects of flash fire modelling are most critical in calculating off-site risk.

KEY MODELLING ISSUES

When a dispersing cloud of flammable vapour is ignited, its mode of burning will depend on its shape, levels of turbulence present at ignition (or generated during the fire event by the presence of obstacles) and the fuel concentration. Generally, a flash fire is considered to occur when a dispersed gas cloud is ignited within its flammable region, causing a wall of flame to spread throughout the flammable region and back to the release point. In this paper, and as given by CCPS

(5), a flash fire is defined as 'the combustion of a flammable gas or vapour and air mixture in which the flame propagates through that mixture in a manner such that negligible or no damaging overpressure is generated'.

The current approach to flash fire modelling is simplistic in assuming that the burn area covers the dispersion footprint, and that its effects are felt either not at all, or only to a limited extent beyond this area. Current risk assessments for flammable materials which use this simple approach tend to be dominated in the far-field by flash fires and there are a number of possible areas in which the modelling of these events may be over-conservative:

1. *Uncertainties in dispersion analysis of flammable gas clouds.* As suggested by Cracknell & Carsley (6), uncertainties in predicting distance to LFL (or fraction of LFL) may mask other uncertainties in the determination of burn area. Uncertainties may relate to the use of models for complex topographies or the need for simplifying assumptions in defining source properties for events. Even where the scenario fits the type of release for which the dispersion code is designed, uncertainties may still result in large discrepancies between models.
2. *Effect of assumptions regarding burn area.* The fraction of mean LFL taken as the burn area is strongly dependent on the level of mixing (concentration connectivity) within the cloud.
3. *Effects of ignition location and timing on burn area.* Ignition is likely to occur before a cloud disperses to its maximum size. The cloud area at ignition, and thus the risk, is sensitive to ignition modelling. Also, fireball effects may occur if ignition occurs early in the dispersion of the flammable cloud.
4. *Likelihood of fatality for fire engulfment.* At present it is conservatively assumed that 100% of unsheltered people caught within the burn area of a flash fire event are fatalities.
5. *Effect of shelter on likelihood of fatality.* It is generally assumed that buildings provide some form of shelter from a flash fire. The probability of fatality will depend on the integrity of the building within a flash fire, whether gas has entered the building resulting in explosion effects and whether escape is possible from any secondary fires produced.
6. *Possibility of escape from cloud.* Escape from the cloud area may be possible both before and after ignition. Escape will depend on the effectiveness of on- and off-site warning systems and emergency planning and, for large releases, the proximity of shelter.

OUTLINE OF WORKING MODEL

The working model consists of three parts; prediction of burn area (fraction of LFL for which combustion occurs), prediction of flame speed and prediction of fatality due to radiation effects. The development of each of these is described below. Full equations are provided by Rew et al (4).

Definition of burn area

If ignition occurs within the flammable region of a release then it can be argued that the flame will propagate to one of the following three extents;

a. *Localised burning.* Combustion occurs in a small region around the ignition point but fails to spread to the rest of the cloud.
b. *Downwind propagation.* The conditions within the cloud are sufficient to sustain propagation of the flame downwind of the ignition point.
c. *Burn-back.* The conditions within the cloud are sufficient to sustain flame propagation upwind, back to the source of the release, i.e. the mean flame speed is greater than the wind speed.

Burn-back (case c) will result in escalation of the scenario to a pool or jet fire. The extent of both the burn-back and downwind flame propagation (case b) of the flame from the ignition point will determine the 'burn area'. In the Maplin Sands trials (7) and other studies conducted by Shell (8,9), it was found that flames burnt downwind to beyond the mean lower flammable limit (LFL) but not as far as the distance to ½ LFL. However, at present, no clear guidelines exist for defining the fraction of LFL to which flames will propagate. This is partly due to the highly non-homogeneous nature of a dense gas cloud, with the likelihood of flame propagation being dependent on the statistical probability of the flammable pockets within the cloud being connected to each other. Furthermore, the expansion of combustion products as the flame front progresses through the cloud is likely to affect the mixedness of the unburnt cloud ahead of it.

As a first approximation, it is assumed that a flame can travel from one point to another if there is a path between the two points where the fuel concentration is always between the flammability limits, and that the effect of expansion of combustion products is small in the lean region of the cloud. The existence of this path can be modelled using Percolation Theory, which is widely used in many engineering fields and describes how sites or nodes within a random field are connected to each other. Using a 'potential' model of continuum percolation, as described by Sahimi (10), a critical occupied volume (or area) fraction, ϕ_c, can be defined at which the system begins to percolate (i.e. at which a flame path exists). Assuming that the scale of concentration fluctuations of interest within a dense gas cloud are small compared to its width and length, but not its height, then the cloud can be represented as a two-dimensional lattice and ϕ_c can be taken to be equal to 0.44 (Scher & Zallen (11)). Suitable assumptions must then be made regarding the dispersion of the fuel. Using the empirical correlations for concentration fluctuations proposed by Wilson (12), the relationship between ϕ_c and the concentation properties of the cloud can be calculated and the results are illustrated in Figure 1 for $\phi_c = 0.44$. These results can be used to determine whether flame propagation will occur at a certain point within the dense gas cloud and thus to define the fraction of LFL at which combustion can occur.

Using this model, the burn area for a 5 kg/s release of propane from a pool source has been predicted to extend to 0.5 LFL close to the source and to 0.8 LFL on the downwind centreline of the cloud. This latter value compares to that of 0.9 LFL given by Evans & Puttock (8) for sustained burning of a flammable gas cloud at its downwind limit, based on medium-scale trials. However, it should be noted that this method is suitable only for continuous pool releases over flat terrain, as it uses the correlations for concentration fluctuations proposed by Wilson (12), and presently does not include modelling of concentration fluctuations for instantaneous and horizontal jet releases.

Prediction of flame speed

Observations of full-scale flash fire trials suggest that ignition is followed by a transient partially premixed flame passing through the flammable regions of the cloud, followed by a yellow diffusion flame burning through the rich section of the cloud. For the special case of centreline ignition at the downwind edge of the flammable region of the release, a likely flame path is illustrated in Figure 2. Flame speed varies with gas concentration, being at its maximum when the mixture is close to stoichiometry, and is increased by the presence of turbulence. Thus the flame will travel along the path of least resistance (i.e. greatest flame speed) towards the spill point and, initially, when the mean concentration is below stoichiometric, the path of least resistance will be at the maximum concentration, and hence along the plume centreline. The flame will then tend to spread along the stoichiometric contour, around the edge of the rich region of the cloud. This latter stage of the flame propagation matches observations of the Maplin Sands field trials, given by

Jenkins & Martin (7), where the flame front advances along the better-mixed edges of the cloud until a constant velocity, horseshoe shaped, diffusion flame is produced. As suggested by Raj (13), the speed of the diffusion flame front is dependent on the premixed flame speed through the stoichiometric regions of the cloud. The width of the diffusion flame will depend on the rate of air entrainment into this region.

In order to calculate flame speed at a certain position within a cloud, firstly the concentration closest to stoichiometry for which there may be a connected path through that part of the flame is calculated, based on Percolation Theory model discussed above. The laminar flame speed as a function of stoichiometry is approximated by a quadratic fit to experimental data and the turbulent flame speed is defined in terms of the laminar flame speed and the turbulence of the atmosphere using Gulder's (14) correlation. The flame speed with respect to the ground is evaluated in terms of the turbulent flame speed, the wind speed and the effects of gas expansion on a plane flame, noting that the latter may produce a factor of 2 to 3 increase in flame speed.

The model has been shown to produce reasonable predictions of flame speeds observed in the Maplin Sands field trials. Use of the flame speed model for scenarios with turbulence levels typical of industrial plant, or of built-up areas, would suggest that the flame speed is likely to be far greater than those seen at Maplin Sands, where the ground roughness was low (mud flats). Thus for most practical release scenarios it is unlikely that the flame speed will be less than the ambient wind velocity (as was observed for some of the Maplin Sands trials) and burn-back to the source will almost always occur.

Simple modelling of external heat transfer from flash fires

As illustrated in Figure 3, and as originally suggested by Raj & Emmons (15), the external radiation from a flash fire can be calculated by modelling the fire as a wall of flame which moves through the cloud away from the ignition point. The majority of external radiation from the flash fire comes from the rich diffusive burning regions (mean concentration greater than stoichiometric), with a lower intensity of radiation emitted from the 'premixed' burning regions. Due to concentration non-homogeneities in the cloud, the 'premixed' burning region consists of patches of gas at low concentration, burning with a bluish flame and emitting negligible radiation, interspersed with patches of rich gas mixture, burning with a higher intensity yellow flame. It is assumed, for LPG and LNG releases, that the rich region of the cloud emits 30% of its heat of combustion as external radiation ($f_s = 0.3$) and that the lean region emits 10% ($f_s = 0.1$). These values are consistent with surface emissive powers observed in the Maplin Sands trials. The speed at which the wall of flame moves is taken from the model for flame speed within flash fires outlined above.

RISK ASSESSMENT METHOD

Fatality criteria for external radiation and fire engulfment

Two studies (16,17) have recently been completed which review methods for determining the likelihood of fatality for people exposed to thermal radiation from hydrocarbon fires. These studies recommend fatality criteria for an average population, based on a thermal dose, $I^{4/3}t$, where I is the heat flux at the location of the target group and t is the duration of exposure to the flux, as summarised in Table 1. However, these criteria are derived for radiation incident on a target population located outside the boundary of the fire event and require modification if used to predict fatalities due to engulfment within a fire. Based on medical data it was postulated that in order for high levels of fatality to occur, a significant proportion of skin area must receive full thickness burns (approximately 30% body surface area for 50% fatality) and that this severity of burn occurs at 1000 $(kW/m^2)^{4/3}s$. Typically, the unclothed area for an average population is also 30% and, therefore, all of the unclothed area must be exposed to the full thickness burn dose in order to produce 50% fatality. If the population is located outside the boundary of the fire, the thermal radiation can only be incident on half of the exposed skin area at a point in time and so it can be crudely assumed that the cumulative incident dose required to cause 50% fatality is double the dose for full thickness burns, i.e. 2000 $(kW/m^2)^{4/3}s$.

Fatality criteria	Percentage fatality for an average population	Thermal dose $(kW/m^2)^{4/3}s$
Dangerous Dose	1 to 5%	1000
SLOD (Significant Likelihood of Death)	50%	2000

Table 1 Fatality criteria for an average population

If the population is engulfed in the fire event, then all the unclothed skin area will be simultaneously exposed to the heat flux. Thus the cumulative dose for 50% fatality reduces to 1000 $(kW/m^2)^{4/3}s$. The threshold dose for ignition of certain types of clothing may be as low as 1800 $(kW/m^2)^{4/3}s$ and fatality is highly likely (50% or higher) if ignition occurs. For engulfment within a fire, this dose will already have caused severe full thickness burns over 30% of the body surface area and this proportion will increase if clothing is ignited. Thus it is assumed that, for fire engulfment, a dose of 1800 $(kW/m^2)^{4/3}s$ will result in 100% fatality for an average population.

Probability of fatality for engulfment within flash fires

Flash fire models used for the purpose of risk assessment usually assume that personnel caught within the gas cloud burn area are fatalities and that those outside are not seriously injured. When people are engulfed in a fire, they are subjected to both radiative and convective heat fluxes. For a flash fire event, the radiative flux will come from both adjacent flame areas and also from more distant, but more intense, areas of the fire. The convective flux will be dependent on the temperature and speed of flow of combustion products around the engulfed personnel.

The calculation of heat transfer within the lean regions of a flash fire (where the mean concentration is less than the stoichiometric concentration) requires determination of the temperature of combustion products around personnel caught in the fire, the speed of the combustion products and the duration for which personnel are exposed to the combustion products. These properties vary depending on the position within the flammable gas cloud, and Rew et al (4) use CFD analysis of Maplin Sands Trial 50 to provide such data. All positions within the burn region were found to produce thermal doses far in excess of the dose for 100% fatality, 1800 $(kW/m^2)^{4/3}s$. Close to the stoichiometric contour, the thermal dose is as high as 40,000 $(kW/m^2)^{4/3}s$. However, outside the burn region the thermal dose drops off rapidly. Thus the analysis suggests that the currently used assumption, that all those caught within the burn area of a flammable gas cloud are fatalities, is a reasonable one.

Effect of shelter on probability of fatality

It is generally assumed that buildings provide some form of shelter from a flash fire. The probability of fatality will depend on the integrity of the building within a flash fire, on whether gas has entered the building resulting in explosion effects and on whether escape is possible from any secondary fires produced. Where gas ingress to buildings results in internal flammable concentrations, it would be conservative to assume that the probability of fatality is 100%, due to both burn and explosion effects.

If the flammable concentration within a building does not reach the lower flammable limit, then the probability of fatality of the occupants will depend on whether the building ignites and on the probability of evacuation from the building. Various criteria exist for ignition of wood due to radiated heat, e.g. Lawson & Simms (18). However, there is uncertainty in the application of the above criteria to ignition of buildings caught within a flash fire. This is due to heat transfer occurring by convection as well as by radiation, and also the wide range of materials used in building construction. In order to determine reliably whether ignition of the building occurs, more extensive data is required on ignition of building materials by the thermal dose transferred during a flash fire event. In the sensitivity analysis described in this paper it is assumed that ignition does occur and that a secondary fire is initiated.

Once it has been determined whether a building will ignite during a flash fire event, the likelihood of fatality for building occupants must be estimated. Data taken from the 1993 Home Office Fire Statistics (19) give some indication of fatalities in fires which are similar (in some respects) to a flash fire engulfing a building. For example, malicious fires in dwellings may produce a rapidly growing fire with no warning. However, the percentage of fires where fatalities occur is of the order of 0.5 % for this type of fire. Similarly, for fires caused by bombs, petrol bombs or other incendiary devices, approximately 1% resulted in fatalities. Fires caused by fuel supplies or other fuel-based appliances may also produce fires with little prior warning. Although it is likely that most of these fires originated indoors, the fatality rate is again very low (less than 2%). However, the following should be noted when applying the Home Office data to the determination of the probability of fatality (or percentage being unable to escape) for occupants of a building ignited by a flash fire event:

- people are likely to evacuate a building if they perceive a fire inside it to be serious. However, it is not clear how people would react if the exterior faces of the building were engulfed by fire and, if people attempt to evacuate, whether fatalities may result;
- the initial rate of fire development is likely to be significantly greater for ignition by a flash fire than for the majority of fire events comprising the data given above;
- fire brigade action will have had some impact on the statistics above, but will not be as effective for aiding escape from the large number of dwellings that are likely to be alight after a flash fire;
- flash fire events may produce localised blast effects, and external flames and missiles (glass fragments etc.) may penetrate buildings, increasing fatality levels.

It is evident that there are large uncertainties in estimating the effect of secondary fires on fatality levels. However, as an initial estimate, use of the Home Office Fire Statistics suggests that the proportion of occupants who become fatalities is likely to be small (of the order of 5% say). This assumes that flammable concentrations of gas do not build-up within the building and that external blast effects and flames are unable to penetrate the building boundaries.

Likelihood of escape from flash fires

Escape from the effects of flash fires can be considered to occur either:

a) before the arrival of the flammable cloud, i.e. evacuation as part of an emergency plan;
b) during or after the arrival of the flammable cloud, but before ignition occurs; or
c) after ignition of the flammable cloud, before the arrival of the flame front.

Detailed consideration of evacuation **(a)** has been considered by Purdy & Davies (20), mainly in connection with toxic releases. When a release of gas occurs, the cloud may travel quickly, not allowing sufficient warning for effective evacuation to be implemented. Therefore, as noted by Lees (21), shelter is generally preferred to evacuation, the exception being where escalation of an on-site event threatens loss of containment from a tank or vessel, and where there is sufficient warning of the likely outcome. The likelihood of escape of personnel during or after the arrival of the flammable cloud **(b)** will depend on whether the release is on-site or has travelled off-site. For many on-site cases, it could be expected that personnel will have already vacated the area of the release before ignition occurs, especially where the flammable region is visible (for releases of liquefied gases in humid conditions). For off-site dispersion of flammable gas, the likelihood of escape is lower; the population may be ignorant of the potential hazard or may be trapped within an external area e.g. playground.

Even after ignition occurs **(c)**, it could be argued there is some scope for escape of personnel away from the flame front. However, people are unlikely to choose the optimum direction for escape and it could be argued that they would not start to escape until the flame front was within reasonable proximity (of the order of 50-100m say). Even when escape is seen to be necessary there may be a delay before escape commences; a delay of 5 seconds is assumed by Nussey (22) for jet fire events. Therefore, it is assumed that escape from a flash fire once ignition has occurred is unlikely in most situations.

SENSITIVITY ANALYSIS

By using the above assumptions in combination with models for ignition probability, gas dispersion and ingress into buildings and data on population characteristics, the number of fatalities caused by a flash fire event, given that a release of flammable material has occurred, can be calculated. The event tree in Figure 4 illustrates the logic behind such a calculation noting that P_o is the probability that people will not be sheltered (taken to be 0.1 for D weather conditions and 0.01 for F weather conditions (23)). P(A) is the probability that a cloud of area, A, has ignited, noting that it may ignite before it reaches its maximum burn area, and is calculated using the method currently implemented in Flammables RISKAT (2). Ignition is assumed to occur at the edge of the cloud and results from strong, continuous sources, with source density, μ (sources/m^2):

$$P(A) = 1 - e^{-\mu A}$$

Typical values for the conditional probabilities used in the event tree are given in Table 2, which also lists credible variations on these values based on the discussion above. Table 3 gives ignition source data and population characteristics for urban and rural land use areas. The sensitivity of risk is examined for two release scenarios, as defined in Table 4, and for both 2F and 5D conditions. It can be seen from this table that the maximum burn area of the continuous release (for either LFL or ½ LFL) is sensitive to the windspeed used in the gas dispersion modelling. This contrasts with instantaneous releases for which, as shown in Figures 5 and 6, the maximum burn area at mean LFL is not significantly affected by either weather conditions or ground surface roughness (although it should be noted that the effect of initial cloud aspect ratio has not been investigated in this study).

Parameter	Description	Base Case	Variation
A_{max}	Maximum burn area	LFL	½ LFL
P_{fi}	Unsheltered probability fatality	1.0	0.5
P_{fo}	Sheltered probability fatality	0.5	0.05
P_e	Probability escape	0.0	Escape model (4)
P_o	Probability outside	0.01F, 0.1D	0.0
z_0	Ground surface roughness	0.1m	0.2m

Table 2 Variation of parameters considered within sensitivity analysis

Property		Urban	Rural
Population density, ρ_P (people/m^2)		2.5E-3	5.6E-5
Ignition source density, μ	Day, 5D	2.5E-5	1.2E-6
(sources/m^2)	Night, 2F	3.8E-6	1.9E-7

Table 3 Data for Urban and Rural land-use types

Property		Instantaneous	Continuous
Material		Liquefied Propane	
Quantity/rate		200 tonne	50 kg/s
Initial concentration		13.4 % (V/V)	100 %
Initial aspect ratio		1.2	-
Pool size		-	2m by 2m
Area at mean LFL	2F, z_o = 0.1m	48 hectares	15 hectares
	5D, z_o = 0.1m	48 hectares	1.2 hectare
	2F, z_o = 0.2m	44 hectares	12 hectares
	5D, z_o = 0.2m	44 hectares	0.9 hectares
Area at ½ mean LFL	2F, z_o = 0.1m	94 hectares	26 hectares
	5D, z_o = 0.1m	79 hectares	2 hectares

Table 4 Release scenario properties

The results of the sensitivity analysis are illustrated in Figures 5, 6 and 7, which show a large variation in fatalities per event between the base case releases. The difference between the instantaneous release over urban land (Figure 5) and the continuous release over urban land (Figure 7) can be attributed to the difference in flammable cloud area. The difference between the instantaneous release over urban land (Figure 5) and rural land (Figure 6) is due to the difference in population densities between these land-use types.

The figures show that, in general, changing assumptions regarding the burn area of the release has a large effect on fatalities per event, noting that burn area is affected by dispersion modelling as well as whether LFL or ½ LFL is used for the flammable region. In general, increasing the burn area increases the number of fatalities, the exception being for an instantaneous release in 5D conditions over urban land, where changing the burn area has no effect on number of fatalities. This results from the modelling of ignition probability and Figure 8, based on analysis conducted by Spencer & Rew (24), illustrates the effect of ignition source density on flash fire risk for an instantaneous release, assuming all other parameters remain constant. It can be seen that the risk peaks at a critical ignition source density, μ_c sources/m^2. This peak occurs where the density is such that there is a high probability that the cloud ignites close to its maximum size. For densities higher than this critical value, the cloud will almost certainly have ignited before it can reach its maximum size. For densities lower than this critical value, the cumulative probability that the cloud will ignite is reduced, even when the cloud reaches its maximum size. Thus, for the 5D instantaneous release over urban land, the source density is greater than the critical value, the cloud ignites before it can reach its maximum burn area, and increasing the maximum burn area to ½ LFL has no effect on fatalities. For all other release conditions studied, the source density is well below the critical value and any increase in the maximum burn area, whether due to changes in the dispersion modelling or use of ½ LFL rather than LFL, will increase the number of fatalities. Thus Figure 8 illustrates the high sensitivity of flash fire risk to ignition probability modelling, and illustrates the uncertainty that can be introduced when two areas of modelling (i.e. of ignition probability with flash fire effects) are combined. It should also be noted that Figure 8 considers risk from flash fire effects only and, due to event escalation and other types of event, the total risk is unlikely to be reduced by increased ignition source density around a site.

For all the releases considered, decreasing the probability of fatality for those indoors, P_{fi}, by a factor of ten, from 0.5 to 0.05, produces a large reduction in the number of fatalities. This is due to the small proportion of people assumed to be outside and not sheltered from the fire. For 2F releases, where only 1% of people are assumed to be unsheltered, the number of fatalities is decreased by a factor of close to 10 from the base case. For the opposite reason, the probability of fatality for those caught outside, P_{fo}, and the probability of escape, P_e, have only a small effect on the number of fatalities per release. Reducing P_0 to zero, while keeping P_{fi} equal to 0.05, has a significant additional effect on the number of fatalities (a reduction by a factor of 3) for the 5D cases where P_0 was originally 0.1. However, assumptions regarding evacuation or escape have no effect for the 2F cases where only 0.01 of people are assumed to be outside in the first place.

One component of the modelling of flash fires which has not been investigated in the above sensitivity analysis is the effect of thermal radiation external to the burn area. CFD modelling (4) of Maplin Sands Trial 50, confirmed that the probability of fatality dropped rapidly from 100% within the burn region to very low levels just outside the burn region, suggesting risk calculations are insensitive to modelling of external radiation.

SUMMARY AND CONCLUSIONS

The analysis described above suggests that the modelling of flash fire risk is most sensitive to:

- the burn area of the cloud and thus to dispersion modelling assumptions (and, by implication, choice of dispersion model) and the fraction of mean LFL at which combustion is sustained;
- the modelling of ignition probability and, in particular, the assumed ignition source density;
- the likelihood of fatality for those indoors;

It should be noted that the sensitivity studies discussed above consider single flash fire scenarios in isolation and do not consider the importance of flash fire effects in relation to other process fire events, such as fireballs, BLEVEs and VCEs, or in relation to escalation of an incident. Particular risk studies will be sensitive to the relative frequency of these different fire events, as well as the relative frequency of different release modes and sizes. However, the analyses do illustrate the possible large effect on risk calculations of changing modelling assumptions. This has implications not only when comparing risk values, but also when considering which risk reduction measures should be implemented across a site. Based on the work described above, use of the following list of assumptions for flash fire modelling can be suggested:

1. Use of the model for burn area, based on Percolation Theory, suggests that for continuous releases, the mean concentration for burn area is closer to LFL than to ½ LFL, although it should be noted that experimental work and further analysis is currently being conducted to verify this conclusion. Different types of release and variations in topography are also being considered.
2. Those caught within the burn region who are unsheltered will be fatalities. Outside the burn region, the thermal dose drops sharply and it can be assumed for risk assessment purposes that there are negligible fatalities.
3. Approximately 5% of those caught within the burn region who are sheltered will be fatalities. This is based on the analyses presented above and assumes that flammable concentrations of gas do not build up within the shelter and that external blast effects and flames are unable to penetrate the building boundaries. It should be noted that there are significant uncertainties in the estimate of 5% fatalities and that, in light of the sensitivity of risk calculations to this value, further investigation of flash fire effects on buildings is currently being undertaken.
4. People are unlikely to be able to escape from the effects of the flash fire after the cloud has been ignited, i.e. the probability of escape from an ignited cloud is small. For special cases, where the flash fire flame speed is likely to be low, there may be value in considering the effect of escape within a risk assessment. However, as noted above, for most releases into industrial plant or built-up areas the flame speed is likely to be too high for escape to be practical and, in any case, the risk of a flash fire is relatively insensitive to the modelling of escape.
5. Evacuation or escape to shelter of off-site personnel before ignition occurs is considered to be improbable. However, the risk from a flash fire is sensitive to the number of people who are assumed to be indoors and this may warrant further investigation.

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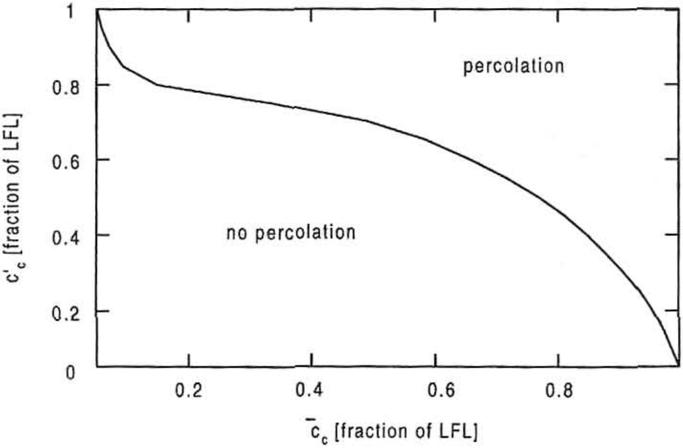

Figure 1 Mean and standard deviation of concentration giving critical occupied area fraction for an LPG release, $\phi_c = 0.44$

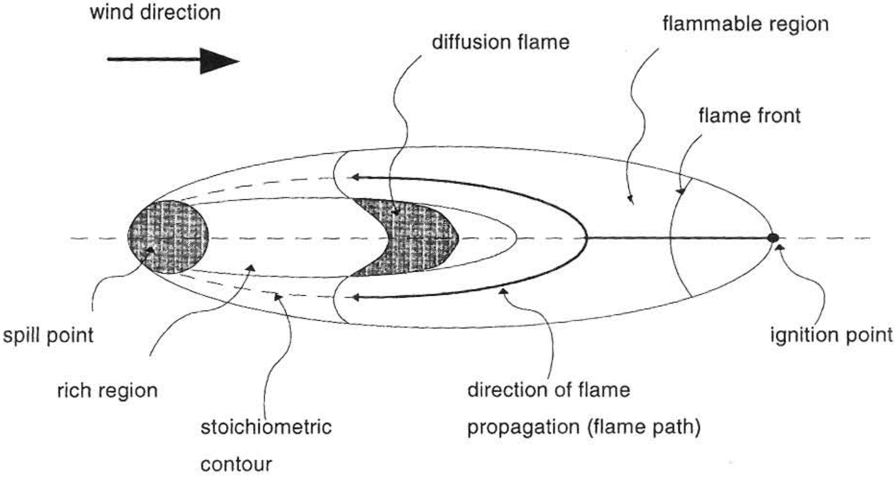

Figure 2 Flame path through a dense flammable gas cloud

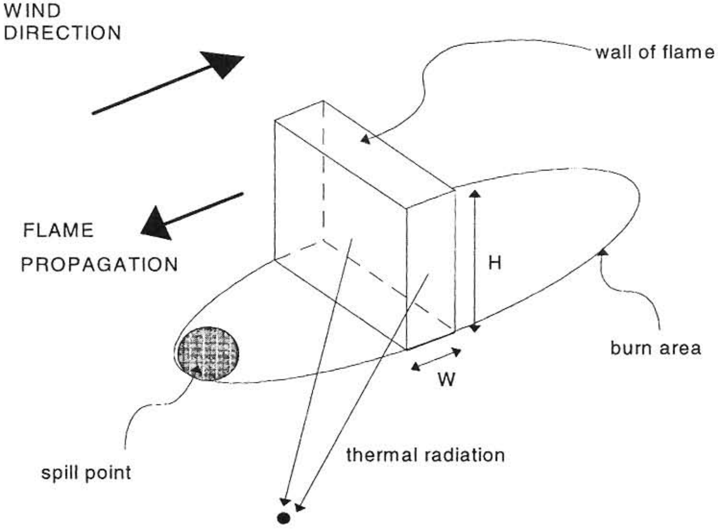

Figure 3 Thermal radiation effects model

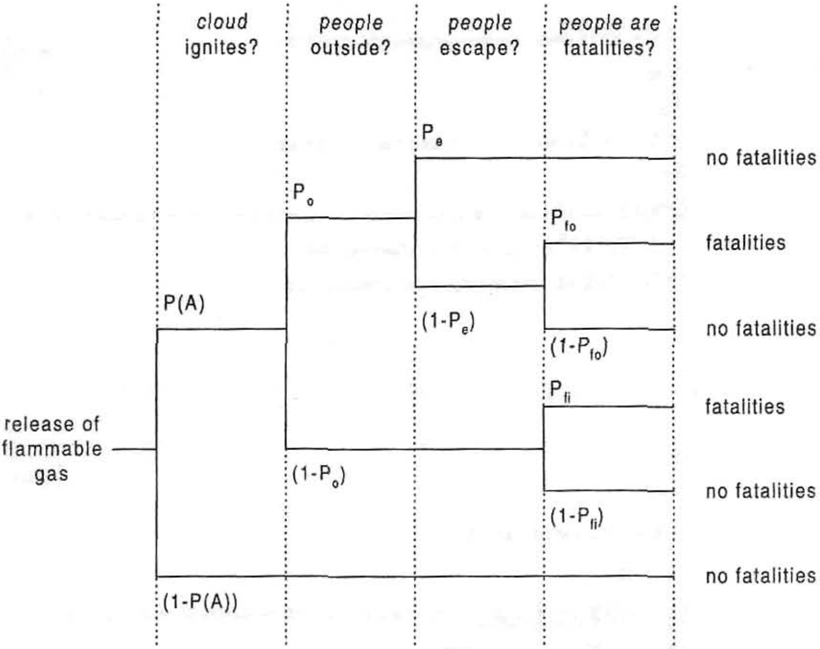

Figure 4 Flash fire event tree

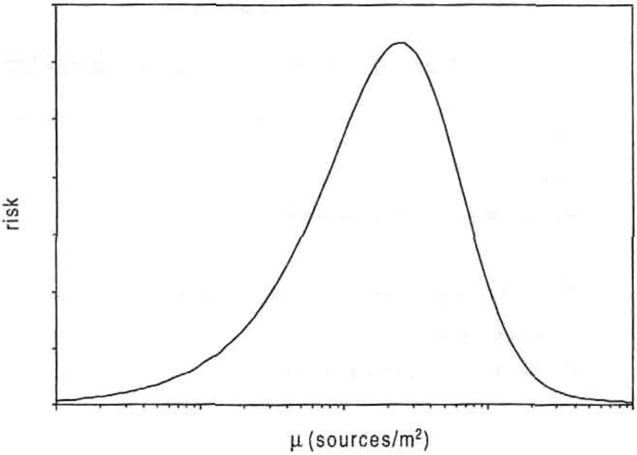

Figure 8 Variation of risk with ignition source density for a flash fire event

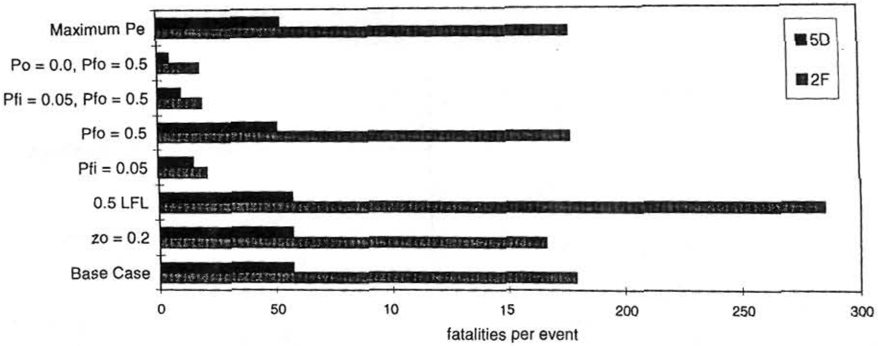

Figure 5 Sensitivity results for instantaneous release over urban land

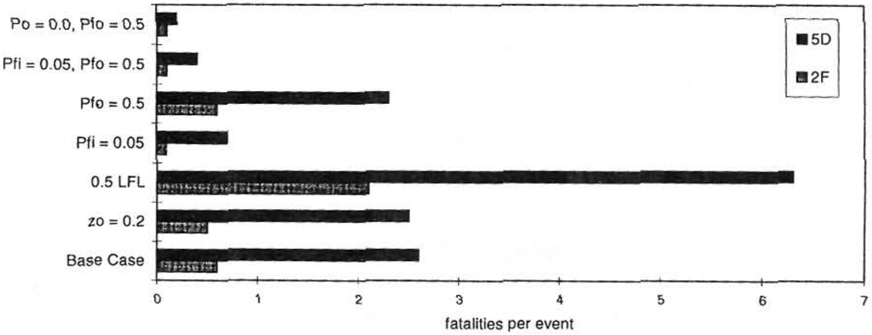

Figure 6 Sensitivity results for instantaneous release over rural land

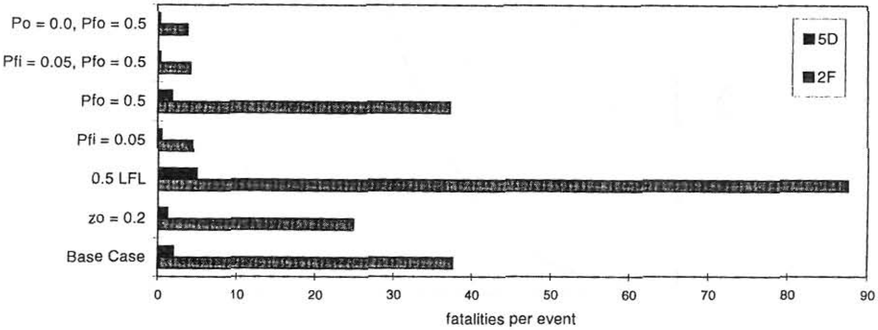

Figure 7 Sensitivity results for continuous release over urban land