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HSE CONTRACT RESEARCH REPORT No. 94/1996

REVIEW OF FLASH FIRE MODELLING

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The release and dispersion of a cloud of flammable gas could result in various effects, ranging from non-ignition and safe dispersion through to vapour cloud explosion, with damaging overpressures. An intermediate outcome, which has received less attention than the explosion possibility, is that of a 'flash fire', in which the flame propagates back towards the release point at a rate which does not give damaging overpressures. The current modelling of this type of scenario is undertaken purely by taking the extent of the dispersion 'footprint' (to LFL or ½LFL), and assuming 100% fatality within this area. The study presented here has reviewed in detail the current methodologies. It has also broken the problem down into its main component parts - gas dispersion and flame propagation, and has assessed the current status in each area. Particular emphasis has also been placed on the interaction between dispersion and flame propagation, with the aim of identifying conditions under which the propagation is retarded, or even halted. A review has also been undertaken of the way in which flash fires are treated in complete risk assessments. This has included not only the immediate effects, but also the probability of escalation to potentially more damaging scenarios such as BLEVEs. Examples of typical risk calculations have been given, and a sensitivity study undertaken to demonstrate the likely effects of improving the accuracy of flash fire calculations. The report concludes by summarising the current status and indicating possible routes for the developing of an improved flash fire model.

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1.0 INTRODUCTION

1.1 Background

There are many industrial sites within the UK which handle or store hazardous materials in sufficient quantities that they may be considered to pose a risk to off-site personnel. Land use planning legislation requires that HSE is consulted concerning potential developments near such sites, and their advice would generally be supported by some form of quantification. The resulting requirement for some form of safety report for these sites will mean that not only should hazardous scenarios be identified, but that consequences should also be assessed. This will typically include source term calculations, gas dispersion modelling and an assessment of toxic or flammable effects.

When a dispersing cloud of flammable vapour is ignited, it can burn in a number of different ways. A flash fire or cloud fire occurs if ignition takes place within the flammable region of a gas cloud, generally at a point remote from the source. In circumstances where a cloud extends back to its original point of release, burn-back to the release source may occur, normally resulting in a jet or pool fire depending upon the scenario; the effects of such escalation may be more severe than the flash fire itself, e.g. a BLEVE may result. In the presence of sufficient obstructions, the flame may accelerate such that significant overpressures are produced, giving an unconfined vapour cloud explosion.

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.[(1982)], Clay et al[(1988)]). The boundary of the fire is defined by the gas cloud's downwind and crosswind dimensions. It is generally assumed that personnel caught within the fire boundary are fatalities and that those outside are not seriously injured. This approach predicts the extent of potential flash fires and provides generally conservative estimates of fatalities. More detailed modelling has been undertaken (e.g. Raj & Emmons[(1975)], Rodean et al[(1984)]), incorporating a flame propagation rate and using standard view factor techniques to calculate thermal radiation external to the fire. Unfortunately, this requires knowledge of the physical and chemical processes that take place during wind/flame interaction, which are currently not well understood.

The wind/flame interaction could cause the flame propagation process to speed up, slow down or cease, dependent on the wind conditions, dispersed cloud characteristics, ignition location, surrounding topography, etc. The relationships between different wind regimes and flame propagation rates may be obtained from experimental data, theoretical studies or both. The flame propagation is dependent on the thermophysical and chemical-kinetic properties of the gas cloud, turbulence and buoyancy of the gases, and is mainly controlled by the turbulent mixing in the field. Significant advances in the understanding and modelling of these processes have recently been gained.

This report discusses the present understanding and modelling of flash fires and presents a proposed framework for the modelling of flame propagation within flash fires. The purpose of this framework is to allow improved prediction of the effects of flash fires, both in terms of their direct effect on personnel and their contribution to escalation that may lead to more severe events.

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1.2 Objectives and Scope of Work

Objectives

The objective for the overall research programme is to develop a simple flash fire model to calculate the effects on people for risk assessment purposes. The two intermediate objectives relevant to the Phase I study reported here are:

- To identify relevant information on flame propagation characteristics.
- To clarify the effects of different wind environments, and topographic features, on the behaviour of flash fires.

Scope of Work

It was agreed that the scope of work should be sufficiently broad that it covered all aspects of the particular problem of flash fire modelling. One of the key features which had been identified was the determination of whether a flame front would propagate back towards the source in the case of a remotely ignited cloud. It was therefore necessary to ensure that the scope was able to cover all the physical features and parameters which would affect such propagation. It was therefore agreed that the study should include the following stages:

- Model review

  Current methodologies for the estimation of the consequences of flash fires will be critically reviewed.

- Parameter identification

  A literature review relating to flame propagation will be undertaken, which will provide appropriate information relating to the parameters which affect flame propagation. Those which are particularly relevant to the flash fire problem can then be identified.

- Laboratory data review

  This will enable small-scale data relating to flame propagation, ignitability, extinction etc to be identified.

- Field data review

  In view of the scale effects on flame propagation, it is particularly important to make use of full scale field data where available. This would include both dispersion of large releases, and the shapes of the resulting clouds, and such data as exists on ignited gas clouds, such as is available from the Maplin Sands experiments.

- Model specification

  The review indicated above should then provide sufficient information that the

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outline requirements for a model can be drawn up as a basis for further development in subsequent phases of the study.

- Reporting

  The final Phase I report will include details of all the reviews undertaken with a full discussion of the findings. Recommendations for further work in subsequent phases of the project will also be given.

1.3 Report Outline

Although the review, and hence this report, could have been structured around the scope of work as presented in Section 1.2, it was considered that a much more detailed structure was appropriate which reflected the many different aspects included in the review. Whilst the report is therefore structured so as to ensure that full details of the review are presented clearly, it is also written with a view to the practical application of any resulting methodology within a risk assessment.

Section 2 describes in greater detail the particular phenomenon which is under review, setting each aspect of the problem in the appropriate context. Section 3 then considers the risks from flash fire incidents and reviews the way in which they are currently modelled and assessed. In order to earth the report in practical application, this section also gives examples of the modelling of a typical case study using currently accepted methodologies, including a discussion of the sensitivity of the results to assumptions made regarding various of the key parameters.

As discussed in Section 2 (Phenomenology), the relevant effects were broadly divided into those relating to flame propagation and those related to dispersion. Section 4 presents the main review of flame propagation modelling, including effects such as ignitability, turbulence and equivalence ratio (concentration). Section 5 then reviews some of the most relevant aspects of dispersion, with particular emphasis on source conditions, cloud shape and the modelling of concentration fluctuations. All the data, both full scale and small scale, relevant to the flash fire problem is then drawn together and discussed in Section 6.

Section 7 discusses the application of the flame propagation and dispersion aspects, discussed in the previous two sections, to the modelling of flash fires. A framework for a simple flash fire model is proposed. The report concludes, in Section 8, with a summary of the main findings of the review.

2. PHENOMENOLOGY

2.1 Flash Fire Description

When a dispersing cloud of flammable vapour is ignited, it can burn in a number of different ways. If the vapour cloud has an aspect ratio close to unity, and is ignited while a substantial proportion of the cloud is still above the upper flammable limit, then a **fireball** will result, in which the initial flame rapidly propagates around the periphery of the cloud before burning the remaining fuel-rich cloud with a diffusion flame. The characteristics of this type of fire are its intense radiative heat flux, lift off from the ground, and relatively short duration. If the vapour cloud is well mixed at a concentration near stoichiometric, and there are obstacles or other confinements or obstructions which promote turbulence within the propagating flame, then an unconfined vapour cloud explosion, **UVCE**, may result. As its name suggests, the main effects from such an occurrence are overpressure damage rather than that due to thermal radiation. An unconfined vapour cloud explosion requires high turbulence levels (produced, for example, by the presence of obstructions in the flame path) to cause significant overpressures.

A **flash fire** or **cloud fire** occurs if ignition takes place within the flammable region of a gas cloud, generally at a point remote from the source. The concentration within the cloud will vary, with some regions at the edge below the flammable limit, while some close to the centre may be above the upper flammable limit. A band of flame spreads through the air at a relatively low speed, since either the mixture is weak (relative to stoichiometric), or because burning takes place in a narrow region where air can diffuse into the cloud and reduce the concentration below the upper flammable limit (UFL). The hazard range from the hot but low energy radiating flames is generally considered to be confined to the dimensions of the cloud and to engulfment.

In circumstances where a cloud extends back to its original point of release, flashback may occur shortly after ignition. This would normally result in a **jet** or **pool fire** depending upon the scenario; the effects of such escalation are described in Section 2.4(c).

The dynamics of a flash fire will depend upon a number of factors relating to both dispersion and flame propagation. These are discussed in the following sections.

2.2 Relevant Features of Cloud Dispersion

a) Release conditions

A jet release will cause significant turbulence near the source. If this turbulence extends far enough downwind, it could increase the probability of the flame propagating back to the source. A jet impinging on a surface could induce further turbulence.

The duration of release will also affect the shape and size of the cloud. The extremes which are usually taken in risk studies are for instantaneous or continuous releases, which would give respectively a spreading transient puff or a long, relatively narrow, steady state plume.

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b) Substrate conditions

For releases of refrigerated materials such as LNG, heat drawn from the ground will increase the buoyancy of the cloud and therefore enhance its tendency to lift-off. Ground roughness, will also modify both the velocity profile of the ambient wind and its turbulence properties.

c) Density of dispersing gas

A gas which is denser than air will disperse as a flat, relatively wide, cloud, compared with a neutrally buoyant plume. A material such as LNG will start to disperse as a dense cloud due to its low temperature. As it absorbs heat from the atmosphere and substrate, so it will become positively buoyant and lift off. The lift off will affect the probability of the cloud encountering an ignition source, while the flat shape of dense cloud will affect the way in which the flame would propagate.

d) Cloud homogeneity

A cloud which is mixed uniformly to a flammable concentration would support a flame which, after accelerating to a steady state, could travel at a fixed speed throughout, assuming that there are no other features to modify its behaviour. In practice, a dispersing cloud, particularly from a continuous source, will show a decrease of concentration with distance from source, and across the width of the plume, such that some regions are outside the flammability limits, whilst the remainder varies continuously between LFL (lower flammable limit) and UFL. Further inhomogeneties will also be introduced by the atmospheric turbulence, such that, especially at the edges of the cloud, the following features are relevant:

- **intermittency**. At a given position, a plot of concentration against time will not in general be constant (continuous release) or smoothly monotonically decreasing, after the initial rise (instantaneous release), which is what would be predicted by time- or ensemble- averaged dispersion models. It is more likely to be 'spiky', such that, for a position with a mean concentration (C) equal to LFL, there may be substantial periods when the instantaneous concentration C(t) is below LFL, and, conversely, where $C < LFL$, there may be some occasion when $C(t) > LFL$.

- **connectivity**. At a given time, the cloud will be characterised by a spatial variation in concentration. Dispersion models will predict a smooth variation between $C = 0$ at the edge, through $C = LFL$ at some bounding hazard range contour to $C > LFL$ in the centre or upwind part of the cloud. In practice, the cloud is likely to appear 'patchy', due to turbulence etc, so that there may be some regions where $C > LFL$ which are surrounded, and cut off from the bulk of the cloud, by regions where $C < LFL$. Clearly flame propagation through such regions in less likely than if $C > LFL$ throughout a large connected region.

e) Turbulence

Atmospheric turbulence is the main agent in dispersing a flammable gas cloud. That turbulence is affected by general atmospheric conditions (see (f)) and can be modified

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by obstructions (see (g)). However, in the case of a dense gas, the interaction between the cloud and the atmosphere may result in suppression of turbulence, and the degree of suppression may well depend upon local gas concentrations in the cloud. The residual turbulence within the cloud will determine the level of concentration fluctuations, and hence the intermittency and connectivity. In addition, the length and time scales of the turbulence, and their relationship to the relevant flame propagation scales, will also be important.

f) Other atmospheric conditions

Although turbulence is very significant in the dispersion process, the mean windspeed will also play an important part. For higher mean windspeeds, continuous plumes will be shorter, while instantaneous puffs may travel further. The shape and extent of the flammable region will therefore be affected by windspeed, as will the probability of finding an ignition source. Atmospheric humidity may also have an effect on the dispersion characteristics of certain flammable gases, such as LNG.

g) Obstructions and topography

The cloud dispersion will be modified by the presence of obstacles, and larger scale topographical features. Enhanced mixing in building wakes will reduce concentration and increase turbulence, whilst channelling may increase flow speeds, and possibly increase concentrations. Slopes, escarpments etc could accelerate or decelerate the flow, and both obstructions and topography could result in modifications to the shape of the cloud.

2.3 Relevant Flame Propagation Effects

a) Fuel type

It is well known that different fuels burn at different speeds, with for example, propane burning faster than methane. It therefore follows that faster-burning fuels are likely to burn more rapidly, to be less affected by atmospheric conditions and to be more likely to burn back to source.

b) Atmospheric conditions

The windspeed is found to affect the flame burning velocity, and could either enhance or suppress flame propagation. The effects of turbulence in dispersion are described in 2.2(e), but it will also affect the burning velocity (see 2.3(e)). Atmospheric humidity may also affect the flame propagation.

c) Concentration effects

It is well known that flame speed varies with gas concentration, and that the maximum flame speed occurs when the mixture is close to stoichiometry. At the flammable limits, particularly LFL, the flame speed is significantly below its maximum, and this would affect the potential for flame propagation within the cloud. In addition, the ignition energy required will increase as the LFL is approached, and it may be possible for ignition to occur in regions of low mean concentration due to the fluctuations noted in Section 2.2(d).

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d) Burning regime

In the optimum case of a stoichiometric mixture, the gas will be pre-mixed, and the flow properties are well known. For higher concentrations, there is an excess of fuel, such that air has to be entrained before complete combustion can occur. In the extreme of a fuel-rich mixture (C > UFL), this will result in a diffusion flame, with very different burning characteristics. For a cloud with a spatial variation of concentration, the flame which is initiated in a fuel-lean region will propagate initially as a pre-mixed turbulent flame, but may at some point in the cloud undergo a transition to a more intense diffusion flame.

e) Combustion effects

The rate of burning may be modified by feedback from the flame itself, or from the additional convective flows set up. The following features may therefore be relevant:

- back radiation, pre-heating areas of the cloud
- expansion at flame front, possibly propelling the flame across regions where C < LFL, thus by-passing any lack of connectivity.
- air entrainment into flame, modifying the concentration within adjacent areas of the cloud.
- flame geometry, including flame wrinkling (due to internally or externally produced turbulence), which contributes, via increased flame area, to flame acceleration.

2.4 Resultant Hazards

a) Within cloud

It has generally been assumed that any personnel within the confines of a flash fire, usually defined as the cloud envelope to LFL or ½LFL mean concentration, would become fatalities. The only exception to this is where sheltering effects due to being inside buildings are included. Given that the flame may not propagate completely throughout the cloud, and that, if it does so, it may take a finite time to do so, it may be possible to make some allowances for escape from a cloud to mitigate the overall effect.

b) Outside cloud

The burning of the cloud will release thermal radiation, which may affect personnel outside the cloud. Since the fire is of a transient nature, it is frequently assumed that effects outside the cloud are not significant. However, if the flame does not propagate back to the source, but is also not extinguished, there may be a small area of the cloud which effectively burns in a steady state manner for some time. Normal thermal dose relationships, giving radiation against exposure duration for 1% fatality, would then be used to assess the hazard. In this case, it would be necessary to incorporate the effects of flame size, shape, duration and surface emissive power as well as the transmissivity effects of the atmosphere.

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c) Escalation

Whilst the flash fire in itself is generally considered to have rather limited effects, it is recognised that such an event may escalate, especially if the flame burns back to a continuous source. The primary ways in which escalation may occur are:

- **explosion.** If there are significant obstructions which cause flame acceleration, an 'Unconfined Vapour Cloud Explosion' (UVCE) will result. The hazards from this scenario are those of overpressure.

- **fireball.** For a cloud with an aspect ratio close to 1, and a fuel-rich centre, flame propagation into this centre may result in a fireball, in which the burning is very intense and the flame will tend to lift off from the ground. The hazard from this event is increased radiation to the surrounding area.

- **jet fire.** Where the flame burns right back to a pressurised release, it is likely to form a stable jet fire which may give high radiation for an extended duration. This is most likely to occur for vapour releases, but could also occur for 2 phase or liquid releases where vaporisation is rapid. The main hazard will again be thermal radiation, but jet fire impingement onto other plant and equipment could result in further escalation (eg. **BLEVE**).

- **pool fire.** Where the flame burns right back to a vaporising liquid pool release, a pool fire will result, with thermal radiation effects, again for an extended duration. If the pool engulfs other equipment or tanks, then there may be further escalation, as for the jet fire.

It should be noted that the first two of these require particular geometries of the cloud or its surroundings to be present, but do not require complete burn-back to the source. The latter two require burn-back, but are otherwise independent of many of the features mentioned in Sections 2.2 and 2.3, except insofar as they allow the flame to propagate sufficiently through the cloud.

Clearly, further escalation may be possible if equipment is located within the affected area, and further inventory could become involved. Combustible materials, such as wooden structures etc, could also become involved in the subsequent fire, but are unlikely to contribute greatly to the overall effects. As with any fire event, however, property losses could become significant.

3. RISKS FROM FLASH FIRES

3.1 Incidents

In order to make progress with the understanding of flash fire phenomena, it is useful to review data relating to incidents in which flash fires have occurred. However, it appears that generally the damage caused by flash fires is less widespread or spectacular than that caused by 'Vapour Cloud Explosions' (VCEs), and in many cases it is not clear whether a flash fire developed into a VCE or not. A number of reviews of such incidents have been undertaken with a variety of objectives. Insurers are clearly concerned about the property losses, and therefore tend to focus on the more damaging incidents (especially VCEs). Other reviews aim to improve the understanding of the physics, and have therefore included more information on flash fires, although such information is frequently very limited in extent. In addition to reviews of this nature, some papers have also been identified which discuss specific incidents in some detail.

Davenport[(1983)] provides a list of incidents in which there were significant insurance losses due to 'vapour cloud incidents'. Out of 152 incidents, it was clear that most involved explosive effects at some stage of their development, but about 25 recorded either significant cloud drift (50-500m) or significant delay (3-30mins) before ignition. In some of these cases, the flash fires which may have resulted appeared also to have caused overpressure effects. In none of the cases was an indication given of the time taken to burn back to source. This study was updated in Lenoir & Davenport[(1993)], in which it appeared that 5 of the additional 50 incidents could have been flash fires, and the information provided was consistent with the features already noted above. Further detail on many of the incidents was presented in Gugan[(1978)] from which two in particular appeared to have 'flash fire' characteristics. Thus, in the Gulf Refinery, Pa (1966) and Barcelona (1974), incidents, cloud dispersion had taken place before ignition, but it appeared that the mixture would have been burning near the rich limit, giving characteristic diffusion flame effects.

A more detailed technical review is given by Lewis[(1982)], which focuses upon transport-related incidents, including those from pipelines. Of the 40 incidents selected as covering a wide range of materials, release conditions, fire effects etc, around 30% were found to have involved significant vapour cloud spread prior to ignition.

A slightly different type of review was undertaken by Wiekema[(1984)], with the objective of further developing VCE models. 165 incidents were identified and analysed in various ways and the resulting statistics provide an insight into both flash fires and VCEs. An analysis was then undertaken of the other features of the incidents, comparing 53 known flash fire events with 62 known explosions. The highest mass category ($> 10^5$kg) included a greater proportion of flash fires than of VCEs. All explosions were semi-confined, but so also were 65% of flash fires. No explosions occurred with an ignition delay in excess of 30 minutes although this accounted for 24% of flash fires. The 'damage' effects of flash fires in all cases were less severe than those of explosions.

Several papers deal with individual incidents. For example, the recent review presented in van Wingerden[(1994)] cites two specific examples of flash fires from propane releases in the US during the 1970s. In the first (Lynchburg, 1972), 8.8t was

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discharged from a ruptured overturned tanker. The cloud extended at least 60m before igniting and formed a 'ball of fire' at least 120m in diameter. One fatality was recorded at 80m from the tanker. In the second incident (Donnellson,1978), a pipeline at 1200psig was ruptured, resulting in a hole of size 0.84m and a propane cloud covering 30 hectares. 2 fatalities were recorded inside a building and 3 who fled the cloud sustained 90% burns, with one dying subsequently from the wounds.

There are further incidents categorised as pool fire, jet fire and BLEVE events which were initiated by flash fires. Van Wingerden[1994] describes the Feyzin (1966) incident. A BLEVE killed or injured 100 people in its vicinity. However, the event was initiated by ignition of a propane spill by a car on a nearby motorway causing a flash fire which burnt back to the propane storage area. Similarly, at Mexico City (1984) a flash fire initiated a train of escalation resulting in approximately 500 fatalities, mainly due to BLEVEs. Lees[1980] discusses the Flixborough incident (1974) and states that there is evidence that there may have been a flash fire as well as a VCE.

It would appear that flash fires are generally not well defined within the incident reviews which have been undertaken, with the distinction between flash fires and VCEs being blurred. In many cases, detailed characteristics of flash fire events have not been recorded because of their less damaging effects. In addition, the transient nature of the burn-back makes it extremely difficult to obtain characteristics of the flash fire event such as estimates of flame propagation speeds. However, the review of incidents illustrates both the direct effect of flash fires in terms of fatalities and their importance in the escalation to other categories of process plant fires, resulting in a more significant threat to personnel and tending to produce severe effects in terms of material damage to the plant.

3.2 QRA Methodologies

3.2.1 Background

The last 15 years has seen a rapid increase in the use of quantified risk assessment, particularly in relation to 'Major Hazard' industries. The typical hazards from such industries include toxicity, fire and explosion, and much effort has been expended in developing methodologies for assessing both the consequences and the risk associated with the handling and storage of flammable materials. Much of the work in this area has been focused upon the consequences of igniting LNG or LPG clouds, and, within this field, most attention has been paid to the effects of explosions, primarily because of the perception that the immediate damage and escalation potential is greater when there is a significant overpressure as well as the thermal effects of a fire.

This review has focused upon methodologies proposed for determining risks for all large scale fire events, which in some cases means that little information is given specifically on flash fires. All stages of risk assessment have been considered, including event trees, fire radiation modelling, and determination of ignition probabilities.

3.2.2 Overall risk modelling

A wide-ranging review of the literature has revealed many papers on the subject, some of which set out proposed or recommended methodologies. Others, whilst not

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specifically setting out flash fire models, provide useful background information. Hardee et al(1978), for example, relates specifically to LNG hazards; it does give models for fireballs, distinguishing between diffusion and pre-mixed burning, but assumes that in all cases there is flame lift-off. Some references, such as Crawley(1982) and Crocker & Napier(1988) are almost purely descriptive, although both provide useful discussion and background material. Bagster & Pitblado(1989) give considerable detail on pool and jet fires and BLEVEs, but do not mention flash fires. Guidance produced by the Major Hazards Assessment Panel of IChemE (MHAP(1988)) discusses all types of fire, but does not give a model for flash fires. Eisenberg et al(1975) consider all possible effects of marine spillages, including flash fires, and includes estimates of potential losses.

Some general papers were also identified which discussed hazards without specifically outlining methodologies. Roberts(1981/82), for example, gives details of cloud formation in the context of LPG hazards, but then discusses fireball effects rather than those of flash fires. More recently, attention has been focused on offshore fire hazards, as a result of which Cowley & Johnson(1991) discussed both 'cloud fires' and fireballs. It does not set out or recommend specific models but does provide a useful review of related work.

The modelling of flash fire consequences is only one element of any QRA and is discussed further in Section 3.2.3. However, in most cases, initiating release scenarios would be tracked through an event tree to determine potential outcomes and, after the inclusion of suitable failure and reliability data, the frequencies of those outcomes. Barry(1992), Clay et al(1988) and Harris et al(1990) all include typical event trees with flash fire outcomes. Barry(1992) and Purdy et al(1988) also consider escalation, such as 'flash fire and jet fire', the jet fire occurring when the fire has burnt back to source. Purdy et al(1988) specifically identifies that such escalation would only occur in the case of a continuous release source. Figure 3.1 shows an event tree for a continuous release of flammable vapour.

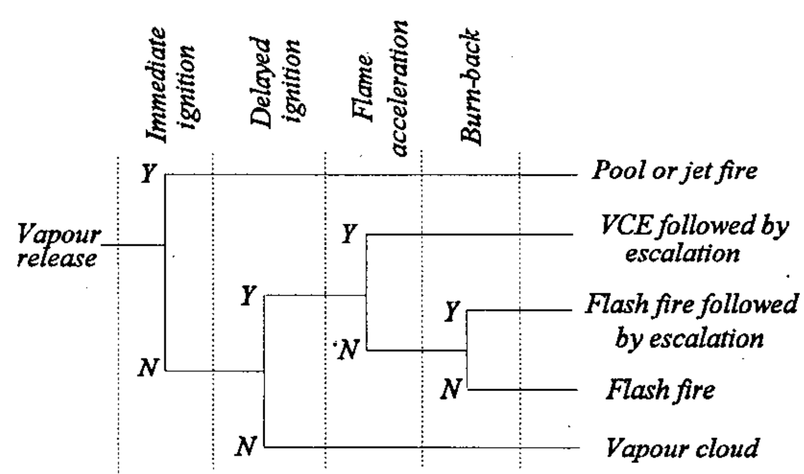

Figure 3.1 Event tree for release of flammable vapour

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3.2.3 Fire modelling

In many cases where a flash fire model is given, the model is very simplistic in assuming that the fire covers the dispersion footprint, and that its effects are felt either not at all or only to a limited extent beyond this area. Considine & Grint(1984), Carter(1991) and Barry(1992) all fall into this category, but do not indicate whether the footprint should extend to LFL or ½LFL. Hertzberg & Lamnevik(1983) specifically suggests that LFL defines this envelope, and that the heat emitted should be taken as 50% of that available within the flammable cloud. Purdy et al(1988) also suggests the use of LFL, and proposes that personnel remaining indoors survive, while Sellers & Keer(1992) recommends the use of ½LFL. Kinsman(1991) suggests the use of LFL to define the area for flashback, but the use of ½LFL to determine hazard range for burn injury. Clay et al(1988) is a slightly more sophisticated variant, suggesting different levels of harm at r, 1.1r, 1.2r etc where r is a typical cloud radius, and allowing for different indoor or outdoor exposure.

A number of papers include more detailed modelling of the fire, and of the flame propagation. Raj & Emmons(1975) treats the flame front as a wall of fire of specified thickness and height travelling back through the cloud as a diffusion flame. Viewfactor techniques can be used to calculate the external incident thermal radiation from the flame front. It is only strictly valid for equivalence ratio (ϕ) greater than 1, but has been validated against some field data. Based on experimental observations, the model assumes that the burning speed is proportional to wind speed. Van Wingerden(1994) discusses the Raj & Emmons(1975) model giving recommendations for its uses and example calculations. Lees(1980) describes the model of Eisenberg et al(1975), which is similar to a fireball model, giving effective thermal radiation and half-life of the cloud fire as outputs. Eisenberg et al(1975) consider all possible effects of marine spillages, including flash fires, and include estimates of potential losses. Considine et al(1982) recommends use of a model which is similar to that of Raj & Emmons(1975), but using flame dimensions based on trials reported by Raj et al(1979), giving sufficient detail that thermal radiation effects outside the cloud can be calculated. Considine & Grint(1984) gives a slight variant on this type of model, assuming that the flame travels radially from the ignition point, and concludes that the envelope of the burning cloud defines the hazard range for continuous release. For instantaneous releases, graphical results are presented which depend upon whether any of the cloud has concentrations above UFL or not.

Mudan & Croce(1988) review hydrocarbon fire modelling and discuss the models of Fay & Lewis(1976) and Raj & Emmons(1975). The former assumes that, based on small scale experiments, unsteady turbulent diffusion flames burn in a similar manner to fireballs. This is not confirmed by the field trials discussed in Section 4, although it is possible that very rich sections of the vapour cloud may burn in this way. Van Aerde et al(1988), dealing with LPG transportation incidents, distinguishes between pre-mixed and diffusion flash fires and recommends the use of the Considine et al(1982) method in the latter case. Holden(1989), whilst being mainly descriptive, also recommends the use of Considine et al(1982), and makes the observation that 'the chance of serious injury outside the burning cloud is slight'.

Rodean et al(1984) present a simple model for the dynamics of a flash fire, based upon observations of the Coyote trials (1980), which is applicable to central ignition of premixed clouds. The diffusive burning stage is assumed to follow the premixed stage

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and the model produces estimates of flame size. However, it does not specifically address the calculation of burning velocity within the flash fire and this parameter is required as an input to the model.

In all cases, current modelling is directed at determining fatalities within or outside of the cloud and assumes complete combustion of the vapour cloud back to the source. No models have been identified which consider burn-back to the release source or that are capable of modelling flame propagation other than in an empirical manner.

3.2.4 Ignition sources and probabilities

It is possible for a flammable vapour cloud to disperse without igniting, as recorded in Lewis[(1982)] and noted in Section 3.1. It is necessary therefore to ascertain likely ignition sources within a cloud and to assign ignition probabilities to them. This aspect of a QRA is not well covered in the literature, it being assumed that engineering judgement will be applied in individual cases.

Atallah & Schneider[(1983)] describe typical ignition sources, and give qualitative results of tests using 7% methane in air. It was concluded that neither vehicle electrical systems in their normal state, nor smouldering cigarettes would cause ignition, whereas traffic lights, particularly flashing ones, would. Barry[(1992)] makes the observation that 'flammable LPG vapours may be ignited fairly easily' and gives ignition probabilities for various sources. Considine et al[(1982)] relates ignition probability only to size of release and wind direction, but does distinguish between immediate and delayed ignition. Neither Barry[(1992)] nor Considine et al[(1982)] assume any dependence of ignition probability on concentration, apart from the requirements that the (mean) concentration is between LFL and UFL at the point of the ignition source.

The nature and location of the ignition source are important when determining the overpressure effects of VCEs. For example, Catlin[(1985)] distinguishes between the high overpressure caused by ignition near the centre of a hemispherical cloud and the low overpressures resulting from edge ignition. Mercx et al[(1993)], which is related primarily to offshore applications, observe that a high energy ignition source leads to higher overpressures; in the flash fire case, a high energy source may promote faster flame propagation and possibly increased turbulence. Jeffreys et al[(1982)] attempt to develop a database for ignition sources of LNG vapour clouds in urban areas, and also discuss the potential for ignition due to the vapour source itself.

3.3 Mitigation of Flash Fire Effects

The reduction of hazards resulting from handling of large quantities of flammables - particularly LNG and LPG - has been the subject of a number of studies. The scope of these studies has ranged from hazard control at source, by reducing flammable hazard ranges and fire sizes and intensities, through to the effects on humans of sheltering and the ability to escape from the hazard.

Atallah & Schneider[(1983)] provides a good overview, specific to the US LNG industry, of research in the early 80's relating to accident prevention and hazard control. Although none of the measures relates specifically to flash fires, two of them, spray curtains and insulated bunding materials, would reduce dispersion distances. Prugh & Johnson[(1988)] also provides comprehensive guidelines for vapour release mitigation,

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including design, engineering and management, detection and warning as well as spray curtains etc as discussed below.

Reduction of flammable hazard ranges, and hence of the extent of any potential flash fires, was also the subject of a number of more specific detailed studies. McQuaid & Moodie[(1983)] discusses the scope for hazard reduction using water spray barriers. Alpert[(1982)] presents both CFD and experimental results on the effectiveness of such barriers.

Rather less emphasis has been placed upon the specific reduction of fire effects. However, Harris et al[(1990)] describes work on the effects of obstacles on flame propagation, with implications for design, specifically of offshore facilities, to minimise the probability of a flash fire escalating to give damaging overpressures. As part of its wide-ranging discussion, Prugh & Johnson[(1988)] includes comments on the possibility of ignition source control. West et al[(1975)] describes tests on LNG clouds and fires in which the following mitigation measures were assessed:

a) High expansion foam. This could be used either to reduce the vapour concentration, or to control the fire.
b) Dry chemical agents for extinguishing LNG fires.

Mitigating the direct effects on humans has been discussed in a number of papers, mainly in the context of ensuring that risk assessment results are realistic. Crawley[(1982)], for example, cites a flash fire in which more than 90% of the occupants of buses which were caught in the fire survived. To allow for such effects, Clay et al[1988)] quotes lower radiation doses (beyond the cloud boundary) for those sheltering indoors. Escape and evacuation are also discussed in Prugh & Johnson[(1988)] and Prugh[(1984)], although the latter primarily relates to escape from toxic releases.

It therefore appears that the greatest scope for risk reduction in relation to flash fires lies in two areas: minimisation or removal of ignition sources, and provision of refuges in which shelter can be obtained. A further factor which should also be taken into account is the potential for escalation, for which the primary condition is the presence of obstacles which confine the propagating flame and result either in damaging overpressures or in more rapid burn-back.

3.4 Examples of Risk Calculations

3.4.1 Definition of Case Study

The requirement for flash fire modelling occurs most frequently in the performing of risk assessments for LPG installations. The consequences of LNG releases will also involve the calculation of flash fire effects, but, at least in the UK, LNG studies are less common than those for LPG. In order to focus the findings of this review it was decided to identify typical flash fire scenarios, to extract detailed information on such scenarios from the literature, and to compare the modelling of such scenarios to determine the sensitivity of the results to the range of current methodologies.

A number of LPG risk assessment studies have been presented in the literature, some relating to fixed installations, and others relating to LPG transportation. Since, in the latter case, there is the possibility of a greater number of people being affected by a

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flash fire, the assessment of transportation risks presented in Purdy et al(1988) has been used as a case study. In that study, LPG release rates of 2kg/s and 36kg/s were used with the smaller rate giving a very small contribution to risk.

For comparison, Barry(1992) gives a more recent assessment of the risks from a typical LPG bulk storage facility in the US. For that assessment, a range of typical release rates was given, including 30kg/s resultant upon the rupture of a flexible hose. Such release rates would also be typical for LNG releases, although a large pipeline at a refinery may result in releases of order 100kg/s.

The remainder of Section 3 will therefore focus upon LPG vapour releases of around 30-36kg/s. However, comments are included, where relevant, on the differences which would apply to LNG due to different properties (density etc) and storage conditions (refrigerated rather than pressurised).

3.4.2 Dispersion Modelling

Several of the papers reviewed include calculations of the dispersion of LPG for use in flash fire consequence analysis. Barry(1992), Considine et al(1982) and Considine & Grint(1984) give results for 30kg/s pressurised releases. These are generally provided for 5D and 2F wind conditions, although Barry(1992) only gives results for 2C conditions. Purdy et al(1988) quotes areas covered by 36kg/s releases for both 5D and 2F conditions, while Considine & Grint(1984) gives empirically derived equations from which results for cloud length, width, height and area can be calculated for any release rate. Considine et al(1982) also gives hazard ranges for either pressurised or refrigerated releases.

The results from these studies are summarised in Table 3.1, in which comparisons are also given with results from the WS Atkins dense gas dispersion program SLUMP.

Reference	Release rate (kg/s)	Conc. criterion	Wind	L (m)	W (m)	h (m)	A (m^2)
Purdy et al(1988)	36	LFL	5D 2F				7300 185000
Considine & Grint(1984)	36	LFL	5D 2F				8000 185000
Considine & Grint(1984)	30	LFL	5D 2F	86 308	125 821	1.6 1.0	6440 151700
SLUMP	30	LFL	5D 2F	125 260	65 320	3.4 1.3	5700 52000
Considine et al(1982)	30	LFL	5D 2F	151 239			
Considine et al(1982)	30 (refrigerated)	LFL	5D 2F	117 185			
Barry(1992)	30	½LFL	2C	203	244		

Table 3.1 Comparison of LPG dispersion results

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L = downwind distance to criterion concentration
W = typical maximum cloud width
h = typical cloud height
A = area covered by criterion concentration contour.

It is evident that, although Purdy et al[1988] and Considine & Grint[1984] appear to be in good agreement, significant differences still remain between the results of models which are commonly in use. In many cases, the cloud height is not given and, while this parameter is not used in most flash fire models, it does have an effect on the area covered, and hence the risk posed by a flash fire.

3.4.3 Radiation effects on personnel

In most cases, it is assumed that either 100% or 99% of people within the flammable cloud are fatalities. This makes no allowance for any mitigation due to protection in buildings, attempts to escape etc. Some studies, however, have assumed that the fatality rate for those within buildings is reduced, to either 50% or 0%.

Some authors, have also allowed for thermal radiation effects beyond the cloud. Considine & Grint[1984] gives results showing the range *from the edge of the cloud* to 50% and 1% fatalities, as a function of cloud radius and cloud height. The method suggested in Clay et al[1988] is more detailed and gives similar ranges as a function only of cloud radius, but also includes effects for indoor personnel. A comparison between these methods and the 'simple' method which assumes no effects are felt beyond the cloud edge has been undertaken for the results presented in the 6th line of Table 3.1, ie. 30kg/s, 2F wind and an effective cloud radius of: $\sqrt{151700/\pi}$ - $220m$

Distance (m)	Simple		C12		C13	
	Fatality (%)	Contrib. to risk (1000m²)	Fatality (%)	Contrib. to risk (1000m²)	Fatality (%)	Contrib. to risk (1000m²)
220	100	152	100	152		
222	0	0	50	0.4		
223			1	<0.1		
242			0		100	184
264					50	17.5
286					1	0.4
Total risk		152		153		202

Table 3.2 Risk contribution to flash fires, outdoor exposure

Distance (m)	P7		Simple		C13	
	Fatality (%)	Contrib. to risk (1000m²)	Fatality (%)	Contrib. to risk (1000m²)	Fatality (%)	Contrib. to risk (1000m²)
220	0	0	100	152		
242			0	0	50	92
Total risk		0		152		92

Table 3.3 Risk contribution to flash fires, indoor exposure

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The results of this comparison have been presented in Tables 3.2 and 3.3. The 'contribution to risk' is quoted as the effective area covered, which, for example, for the outer ring of the Clay et al[1988] model, is 1% of the annular area bounded by circles of radii 264m and 286m. The resulting numbers can then be multiplied by the population density in order to estimate the number of fatalities. For normal areas and activities, it is assumed that population is indoors for 90% of the time, and outdoors for only 10% of the time, although this depends on the time of day, time of year, type of area etc.

It can therefore be seen that the differences between Considine & Grint[1984] and the simple model are negligible for outdoor risk, while Clay et al[1988] would suggest a greater than 30% increase in the potential fatalities. For indoor effects, the differences are more marked, and these may have the biggest impact on risk results.

A fixed cloud radius of 220m was deliberately used in these comparisons in order to remove any effects of differences due to dispersion modelling. However, if such differences are included, a cloud radius of 130m could have been used from the SLUMP results. The contribution to risk using this radius in the simple radiation effects model would be 53 compared with 152 in Table 3.2, thus demonstrating the greater uncertainties due to dispersion modelling.

Where the flame front is travelling relatively slowly, it is possible to calculate the heat flux incident upon individuals at specific locations by a time-step integration. It appears that this is not generally done, since, for example, Considine & Grint[1984] has found (as confirmed by Table 3.2) that there is very little effect outside the cloud. However, if a more detailed model were to be developed in which flame speeds varied through the cloud such that the flash fire duration was longer, such heat flux integration may be useful in determining the potential for escape.

One example in which radiation effects beyond the cloud have been calculated has been presented in Van Aerde et al[1988], based on the model of Raj and Emmons[1975]. This sets out a method in which the flame speed is calculated as a function of time, and then the flame position, shape and height are calculated. When these are combined with view factors, it is then possible to calculate the variation of incident heat flux with time, and hence the overall thermal dose. The example given is for a 1m deep 100m diameter propane cloud, instantaneously released and uniformly diluted in a 2m/s wind to 10% concentration, its UFL. The results shown are for an observer 100m from the cloud centre, and at the opposite side to the edge ignition. This shows an almost linear increase in heat flux to a maximum of just over 40 kW/m^2 after 18 seconds before decreasing to zero at 22 seconds.

The model presented assumes that the flame speed is directly proportional to (in this case, 2.3 times) the mean windspeed. Clearly this may be affected by the cloud concentration and its variation (conveniently assumed uniform in the example), and, in a very shallow cloud, by the boundary layer windspeed profile. Although no allowance for escape was included, the method could clearly be adapted in this way.

3.5 Sensitivity Study

3.5.1 Risk sensitivity

The results presented in Tables 3.2 and 3.3 can be combined with population densities in order to determine the total number of people who are likely to become fatalities. Examples are presented below in Table 3.4 for typical suburban and rural population densities, as quoted in Purdy et al(1988).

Area	Pop. density ($/km^2$)	Model	
		'Simple'	C13
Suburban	1310	199	265
Rural	210	32	42

Table 3.4 Number of fatalities for flash fire incident

The difference in modelling of the flash fire effects would therefore give changes to the total number of fatalities in an incident, thus modifying societal risk results. Individual risk results, which depend upon hazard range rather than hazard area, will be less affected by this modelling.

As indicated in Section 3.4.3, most current modelling does not consider the flame movement effects. As an example of the inclusion of such effects, consider the case where the flame propagates back from the edge of the cloud to the source at a speed of 2.5m/s, perhaps for a 2F wind condition, and people within the cloud attempt to escape from the cloud by travelling at 2.5m/s. For a circular cloud, this would suggest that all those caught in the cloud will be able to escape if they move in the direction of travel of the flame front, and sufficiently ahead of it. If escape is attempted in the transverse direction, only those in an area which approximates to the 90° sector surrounding the ignition point at the edge of the cloud would be unable to escape. For a uniform population density, the potential for escape would therefore reduce the expected number of fatalities, by a factor of at least 4. In practice, this factor would be modified both by possible non-uniformities in population density, and by potential for escape from the cloud *before* ignition takes place.

Sheltering effects could also be included in more detail if flame speed is considered. For example, knowledge of building locations would enable 'safe' regions around them to be identified, based upon people's response time, speed and distance from the ignition point.

A further factor which would affect the consequences of a flash fire is the location, and timing of the ignition. For clouds which cover the areas indicated in Table 3.1, it is quite likely that an ignition source will be encountered before the cloud has established its full extent. Identification of ignition sources is therefore important, as is the assessment of ignition probability. Some detail of typical ignition probabilities is given in Barry(1992); use of such information is likely to reduce calculated risks compared with the worst cases generally assumed.

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When a flame propagates back to the source of a continuous release, there will almost certainly be escalation to a further fire event which may have worse consequences. For example, Purdy et al[1988] shows that the greatest contribution to risk originates from the BLEVE following a flash fire, and gives the following hazard ranges:

Vessel Capacity (te)	Flash Fire		BLEVE	
	50%	1%	50%	1%
20	70	90	110	175
40	80	110	160	245

Table 3.5 Comparison of flash fire and BLEVE hazard ranges for instantaneous releases.

It can be seen that in this particular case, BLEVE hazard ranges are roughly twice those for flash fire only. Thus, if the development of a more accurate flash fire model could result in the identification of conditions under which escalation would not occur, then more realistic risk calculations can be undertaken.

3.5.2 Discussion

It has been shown that the results of flash fire consequence modelling are not very sensitive to the range of simple 'models' which are currently in use. The results are, however, sensitive to differences in dispersion modelling, and to the inclusion or otherwise of sheltering effects. It also appears that most flash fire analyses predict consequences which could be ultra-conservative in the following respects:

i) It is assumed that the flammable cloud has developed to its full steady state size before ignition occurs.

ii) It is assumed that the ignition occurs at the centre of the cloud, and that the whole cloud is rapidly engulfed before there is any potential for escape.

iii) It is also assumed that, for any continuous release, the flash fire will burn right back to source and escalate to a pool fire, jet fire or BLEVE.

In order to improve the risk analysis results which would be obtained for flash fire scenarios, the overall modelling would therefore need to consider the following areas:

a) Improved identification of ignition sources and their probabilities, such that the effects of non-worst-case flash fires can be assessed.

b) Use of realistic flame speed modelling in order to enable escape and mitigation probabilities to be determined.

c) Combination of gas dispersion modelling and flame speed modelling to determine conditions (if any) under which burn-back, and hence escalation, would <u>not</u> occur.

4. REVIEW OF FLAME PROPAGATION MODELLING

4.1 Ignitability of Flammable Vapour Clouds

The ignition of a flammable vapour cloud at its edge will not always result in propagation of a flame front through the cloud back to its release point. If the flame propagates back to the source then it is likely to occur in two stages; first a premixed clean-burning bluish flame in the lean mixture of the cloud and then a diffusive yellow flame in the rich mixture of the cloud. It should be noted that the transition between these two stages is not distinct and the flame is likely to exhibit both premixed and diffusive burning characteristics at some stages in its travel. The success of the propagation of the flame to its source (termed 'light-back' in a number of references) will depend on both the cloud dispersion features, discussed in Section 2.2, and the vapour cloud flame propagation effects, discussed in Section 2.3. This section of the report discusses ignition and light-back in relation to parameters such as fuel type, atmospheric conditions (windspeed and turbulence) and intermittency of gas concentration within the flammable vapour cloud.

4.1.1 Flammability limits

Ignition of a hydrocarbon gas requires the gas mixture with air to be within its flammable limits as well as the presence of an ignition source of sufficient energy or strength. However, the definition of flammability limits is vague, as discussed in the review of flammable limits given by Lovachev[(1979)]. The flammability limits for a homogenous mixture of fuel and oxidant can be defined as the limits of concentration (or pressure) at which a sufficiently powerful ignition source can initiate combustion and produce a flame front which is self-sustained and capable of propagating over the region of combustible gas mixture. Therefore, in theory, the flammability limits are independent of the ignition source type and strength and of the confinement of the gas cloud. In the review, Lovachev questions the applicability of laboratory determined flammability limits to large confined and unconfined gas clouds. This is a theme repeated by Andrews[(1991)] where it is stated that flammability limits are not satisfactorily explained and experimentally determined values tend to be dependent on the geometry of the apparatus, in many cases due to the effects of heat loss and extinction by convection. For example the lower flammability limit of methane/air mixtures may vary experimentally from 4.0 to 6.6% by volume of methane and the upper limit from 12.8 to 15.2% by volume.

Flammability limits, by definition, are related to the burning velocity of the fuel-air mixture as is illustrated by Figure 4.1, given in Nettleton[(1978)], where it can be seen that the limits occur where the burning velocity tends to zero. However, in practice, the limits may occur at a finite burning velocity due to heat losses and active-species losses, both by diffusion. In safety studies, the upper and lower flammability limits of methane are typically assumed to be 5 and 15% respectively. Nettleton[(1978)] suggests that, due to the uncertainty attached to the use of flammability limits in safety studies, limits should be expressed in terms of a probability band.

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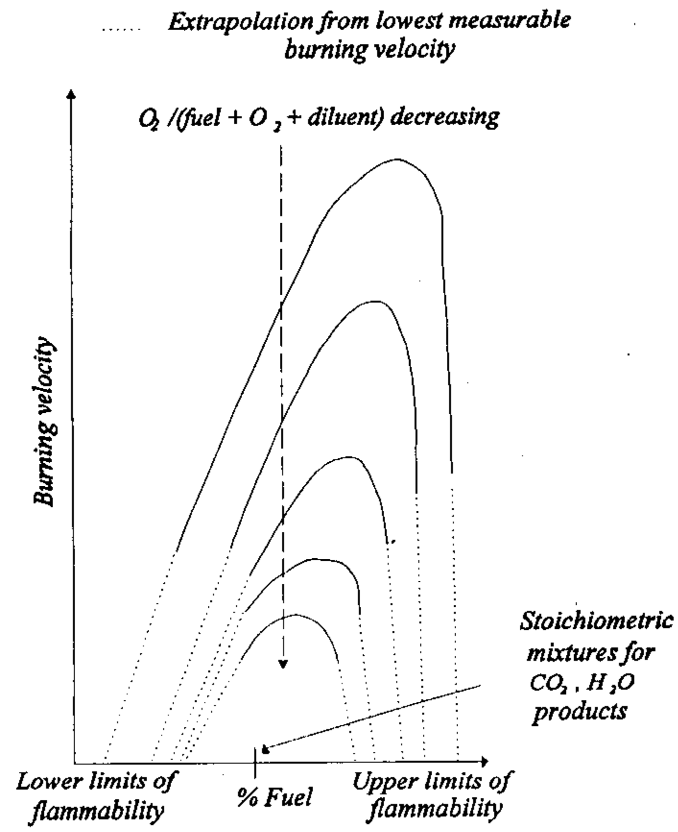

Figure 4.1 Relationship of gas mixture flammability limits to laminar flame speeds (Nettleton[1978])

Nettleton[1978] also discusses the importance of considering the effect of mixture temperature and pressure and initial turbulence on the width of the flammability limits. In the context of atmospheric dispersion of flammable gases, the effect of pressure is not relevant. Temperature may be relevant to the limits of vapour clouds resulting from spills of cryogenic liquids. Narrow limits are associated with lower temperatures as confirmed by Andrews[1991].

Nettleton[1978] suggests that the effect of turbulence is to widen the flammable limits of hydrocarbon gas-air mixtures. This is based on an approximate theoretical analysis of turbulent to laminar burning velocities. It is suggested that turbulence sufficient to produce burning velocities of 5 times the laminar burning velocity will result in a reduction of more than 30% for the lower flammability limit of methane-air. However, this theory appears to be contradicted by the experimental studies reported by Abdel-Gayed et al[1982]. Isotropic turbulence was generated in an explosion vessel using fans. It was found that the flammability limits of methane-air were narrowed as turbulence increased. Lovachev[1979] reviews experiments conducted on turbulent fuel-air mixtures and shows that, as the Reynolds number is increased, the flammability limits first seem to be widened until at high Reynolds number the limits start to narrow. However this may be a function of ignition strength used within the experiments. Abdel-Gayed et al[1982] found that increasing the spark ignition energy (from 5mJ to 1.5J) in their experiments widened the flammability limits. It was concluded by Lovachev[1979] that the apparent narrowing of limits at high turbulence was due to using weak ignition sources where the fact that turbulized mixtures required stronger ignition sources than quiescent gases was not taken into account. Andrews[1991]

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agrees with this conclusion and discusses recent experiments that indicate that fast turbulent flames can propagate in mixtures at or near the conventional flammability limits. This would suggest that turbulence effects cannot be neglected.

4.1.2 Effects of ignition type and strength

As noted by Gibbs[1991], there are many different ignition source types including flame, spark, arc, hot gas, hot surface, adiabatic compressions, shock wave, impact and thermal radiation. In general, ignition sources provide the necessary energy for initiating combustion although a flame ignition source also supplies free radicals for the combustion process. A distinction can be made between spark ignition sources and hot surface ignition sources. In spark ignition sources, the rate of energy deposition is high and this type of source is characterised by ignition energy. For example, a 1mJ spark can initiate combustion in a quiescent gas-air mixture. Hot surfaces have low energy fluxes and are characterised by ignition temperature.

A concept important to the discussion of ignition strength is the idea of a minimum volume of flammable gas required to sustain ignition. For a given flame volume, there is a balance between heat generated by the exothermic reaction and heat lost to the surroundings. The heat generated scales with the volume whereas the heat lost scales with the flame surface area. The minimum volume of gas required to sustain ignition is where the heat generated matches the heat lost. The minimum ignition energy is that required to bring the minimum volume to a temperature that will allow combustion.

This concept leads directly to the dependence of ignition on the gas temperature and fuel equivalence ratio within a dispersed vapour cloud. The lean or rich areas of the cloud produce less energy per unit volume than a stoichiometric mixture and require an ignition source with a higher temperature or greater ignition energy.

The concepts of minimum ignition energy and minimum ignition volume are also relevant to the effect of turbulence on ignition of flammable vapour clouds. As discussed above, experiments conducted by Abdel-Gayed et al[1982] showed that the width of the flammable limits were dependent on ignition strength. This can be attributed to increased dissipation of energy at high levels of turbulence. This effect is strongly related to the concept of quenching of flames at high turbulence intensities which is discussed further in Section 4.2. Observations of the experiments suggested that quenching occurred in highly turbulent flames when the diameter of the ignited kernel is less than four times the flame thickness rather than approximately equal to the flame thickness for non-turbulent mixtures. This suggests an increase in minimum ignition volume and thus minimum ignition energy. Abdel-Gayed et al[1982] also suggests that increased ignition energy is required due to the effect of small eddies being dissipated before reaction is completed. Tromans & Furzeland[1986] have undertaken a numerical study of the ignition of premixed gases which shows that the minimum energy for ignition increases with the Lewis number of the mixture and with stretch of the flame front, an important feature of flame quenching. It should be noted that many of the experiments and theories on the effects of turbulence on ignition and flammability limits relate to high turbulence intensities that are unlikely to be created by atmospheric conditions, although in some cases may be produced by the effects of release of a gas at high pressure. The effect of turbulence on ignition and flammability limits is likely to be significant only for the latter cases.

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4.1.3 Effect of non-homogeneity of gas cloud

So far, the discussion on flammability limits has been confined to homogeneous gas mixtures. However, as discussed in Section 2.2, the concentrations within a cloud formed by releases of hydrocarbon gas into the atmosphere do not vary smoothly across the cloud but exhibit intermittency and patchiness. Various experimental studies on the ignition of hydrocarbon gases have been undertaken to assess the effect of intermittency and the probability of light-back to the release source and these are discussed in Section 6.4.

These studies, by Smith et al[(1986)], Birch et al[(1989)] and Evans & Puttock[(1986)], introduced the idea of the existence of a path of sufficient concentration to allow flame propagation back to the source ie. 'light-back'. The probability of this path occurring depends on the intermittency of the concentration in the jet which can be modelled using probability density functions. The path must be able to sustain flame propagation of sufficient velocity to be capable of overcoming the downstream velocity of the gas cloud, produced by the release momentum of the cloud and the ambient wind velocity.

It was found that there was a variation in mean concentration at the light-back locations with respect to the mean lower flammability limit which suggested that the probability density function for concentration is dependent on both position within the cloud and the type of release. The turbulence in high momentum free jets will differ from that produced by ambient conditions (windspeed and stability) and ground roughness effects in the dispersion of dense gases.

4.2 Premixed Turbulent Flame Propagation

The premixed flame propagation stage is characterised by its bluish flame, suggesting that the chemical reaction is completed quickly without the production of significant quantities of soot. The flame propagation tends to be transient. Mean velocities over the ground of the order of 5-20 m/s are typical for LPG and LNG slumping gas clouds although peak velocities may reach 40m/s (see Section 6.2) and the actual speed is intermittent in nature. In a cloud formed by a high pressure jet release, increased turbulence within the cloud may produce propagation velocities of the order of 100-200m/s, as for the turbulent jet experiments of Smith et al[(1986)] and Birch et al[(1989)].

It should be noted that the distinction between the premixed and the diffusive burning stages of a flash fire is not clear. Between the stoichiometric concentration and the upper flammable limit, the change between the two regimes is gradual and is further complicated by the intermittency of concentration which may allow patches of premixed combustion to occur in areas of mean concentration above the upper flammable limit. Similarly, diffusive burning may occur in areas of mean concentration below the stoichiometric concentration. The relationship between the two modes of flame propagation also seems to vary in the experiments conducted for dense gas clouds. Cowley & Johnson[(1991)] notes that the wall of flame in the cloud propagates in an unsteady way due to the intermittent gas concentrations. In experiments, the bluish premixed flame may race over the top of the cloud leaving the yellow premixed fame behind. Raj[(1977)] suggests that in methane gas cloud experiments the flame burned back to the source as a mixed diffusion/premixed 'fire wall'. The experiments on propane gas clouds of Evans & Puttock[(1986)] suggested that the diffusive burning followed the premixed flame propagation.

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4.2.1 Relationship between premixed flame speeds and burning velocities

Premixed flames are not limited by requiring entrainment of air (or oxygen) and therefore are able to propagate through a turbulent flammable gas mixture with a characteristic turbulent burning velocity, U_t. The turbulent burning velocity can be defined (Harris[1983]) as the speed at which the flame front or reaction zone moves relative to the unburnt gas-air mixture ahead of it. It should be noted that U_t is not necessarily the speed at which the flame front moves through the mixture as the flame front may be pushed forward by expansion of burnt gases trapped behind it. Therefore, the maximum possible flame speed U_f (assuming all burnt gases are trapped behind a planar flame front) is related to the turbulent burning velocity by the expansion ratio E:

$$U_f = EU_t$$

$$E = \frac{T_f}{T_i}\frac{N_b}{N_u}$$

T_f = flame temperature to which burnt products are raised (K)
T_i = initial temperature of fuel-air mixture (K)
N_b/N_u = molar ratio of combustion products to reactants.

In addition, wind velocity, U_w, must be considered. The flame speed with respect to the ground, U, will be related to the flame speed, U_f, as follows, (assuming that the flame is propagating in the opposite direction to the wind):

$$U = U_f - U_w$$

The above velocities are dependent on the type and direction of release and on properties of the gas cloud such as turbulent levels and aspect ratio. A further velocity can be defined which can be considered to be a fundamental property of the gas mixture and is called the laminar burning velocity, U_L. It is the speed at which a laminar flame front moves relative to the unburnt mixture ahead of it.

In the past 20 years a large amount of work, both theoretical and experimental, has been undertaken with the aim of relating the turbulent burning velocity to the laminar burning velocity. This work has utilised a wide range of theories (eg. flamelet concepts) and mathematical techniques (eg fractal geometry) to produce both analytical and numerical solutions for the turbulent burning velocity. The rest of this section reviews a selection of this work and discusses how turbulence produces both an increase in burning velocity and, under certain conditions, quenching of the flame and possible extinction.

4.2.2 Regimes of turbulent pre-mixed flame propagation

Turbulent pre-mixed flame propagation can be divided, at least for the purposes of prediction, into 3 zones. These zones are illustrated in the phase diagrams of Figure 4.2, as given by Peters[1986]. The three turbulent flame propagation zones, ignoring the

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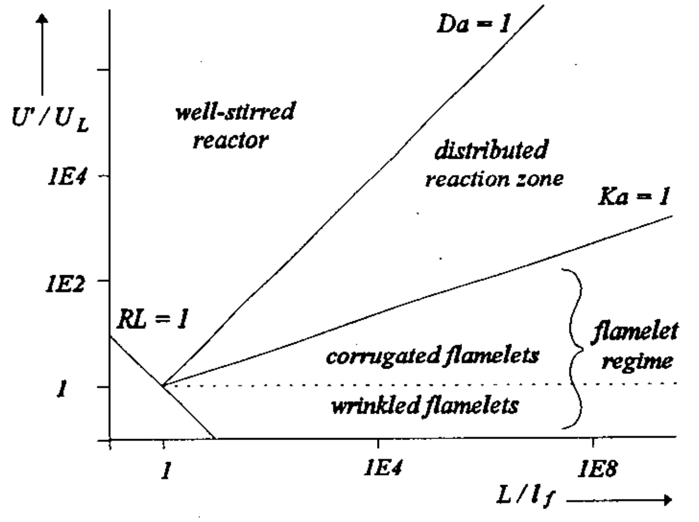

Figure 4.2 Turbulent pre-mixed flame propagation regimes (Peters[1986])

well-stirred reactor, are the wrinkled flamelet, corrugated flamelet and the distributed reaction regimes. Below a turbulent Reynolds number, Re_t, of 1, the flame propagation is laminar. The boundaries between the regimes are defined by the turbulent Damkohler number, D_a, and the turbulent Karlovitz number, K_a. For a Damkohler number of greater than 1, the chemistry of the flame can be considered to be fast compared to the fluid transport processes which is the assumption for all three zones. The Karlovitz number is a measure of the importance of flame stretch; for a Karlovitz number of greater than 1, flame stretch starts to become important, as in the distributed regime.

A Karlovitz number of less than 1 defines the flamelet regions of turbulent flame propagation. It is assumed that within the flamelet region the effect of turbulence is to increase the laminar flame area without changing the structure of the flame itself. A Karlovitz number of 1 is equivalent to the flame thickness being equal to the Kolmogorov scale of turbulence within the flow. Thus at a Karlovitz number of greater than one, the flame thickness is greater than the Kolmogorov scale and the smallest eddies in the flow field can enter into the flame structure. The flamelet zone is divided into the wrinkled and the corrugated flamelet regimes, the transition between them occurring when the turbulence intensity of the flow, U', is equal to the turbulent burning velocity. The properties of the corrugated flamelet regime are not fully understood but it is postulated by Peters[1986] that, if the 'turbulence intensity' (ie turbulence velocity) is greater than the burning velocity, then these eddies can convolute the flame front sufficiently to form multiply connected reaction sheets. The wrinkled flamelet regime can be considered to be a single flame sheet (Williams[1985]).

In the distributed reaction regime, the turbulent mixing by eddies within the flame sheet causes increased burning rates and a thicker reaction zone. However, increased turbulence intensity causes flame stretch (local fractional increase of flame surface). Due to differential diffusion of heat and reactants this may lead to a reduction in the effect of turbulence in increasing the turbulent burning velocity and eventually to extinction of the flame (depending on the equivalence ratio of the gas mixture).

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4.2.3 Models for the wrinkled flamelet regime

There has a been a large amount of work devoted to this regime as discussed in reviews by Bradley(1992), Gulder(1990), Peters(1986) and Williams(1985). Typically, the increase in burning rate is considered to be related to the increase in flame area, as originally proposed by Damkohler(1940):

$$\frac{U_t}{U_L} = \frac{A_t}{A_L}$$

A_t = time averaged surface area of turbulent flame front (m^2)
A_L = projected area of flame front in plane perpendicular to the direction of flame propagation (m^2)

Fractal geometry can be used to calculate the increase in flame surface area. This method is used by Gouldin(1987) to give the following relationship for the turbulent burning velocity:

$$\frac{U_t}{U_L} = \left(\frac{L}{\eta}\right)^{D-2} = Re_L^{\,0.25}$$

$$Re_L = \frac{u^1 L}{\nu}$$

L = integral length scale of turbulence
η = Kolmogorov length scale
D = fractal dimension, assumed to range between 2.3 and 2.4
ν = laminar viscosity of unburnt mixture

Fractal analysis requires the definition of outer and inner cut-off length scales. The analysis by Gouldin(1987) assumes that the outer cut-off is equal to L and that the inner cut-off is equal to η. However, this assumes that the flame wrinkling is due to transport processes only and that those processes are not coupled with the reaction process. Bradley(1992) suggests the use of the Gibson scale, L_G, as the inner cut-off. The Gibson scale is larger than the Kolmogorov scale and is the smallest size of eddy that can contribute to flame wrinkling. For smaller eddies, the eddy lifetime is less than the chemical lifetime of the laminar reaction. The use of the Gibson scale gives the following correlation:

$$\frac{U_t}{U_L} = 1.5\,\frac{U'}{U_L}$$

Note that U_L cancels, showing that the relationship is based purely on turbulence and not on chemical kinetics.

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Another approach that can be used for the modelling of the wrinkled regime is that of 'flamelets'. The principle behind flamelets is that, if the chemical timescale is small compared to convection and diffusion within a flame, then reaction can be assumed to take place in an asymptotically thin layer. As discussed by Peters(1986), flamelets have a defined inner structure which has been developed for both premixed and diffusive conditions. The most prominent implementation of flamelet theory to turbulent combustion is the Bray-Moss-Libby (B-M-L) model as discussed by Libby et al(1979) and Bradley(1992). The B-M-L model uses a presumed pdf for a reaction progress variable (either normalised product mass fraction or normalised temperature). This model has been used within various numerical codes used for the modelling of explosions, for example the TNO REAGAS and CMR FLACS-89 (Van den Berg et al(1991) and Van den Berg et al(1987)), in combination with k-ϵ models for turbulence. However, Bradley(1992) states that its shortcoming is its inability to predict directly the turbulent flame speed.

Further examples of the use of flamelets for predicting turbulent burning velocities are correlations produced by Pope and Anand(1984) and Anand and Pope(1986). They used Monte-Carlo simulations of pdf equations giving correlations of the following form:

$$\frac{U_t}{U_L} = C \frac{U'}{U_L}$$

The constant C is equal to 2.1 for constant density ratios and 1.5 for large density ratios.

Gulder(1990) lists various other correlations and outlines the production of a correlation based on a turbulence model developed by Tennekes(1968) which proposes that dissipative eddies within the flow can be modelled as vortex tubes. The resulting correlation is shown to match closely 200 data points collected by the author for this regime:

$$\frac{U_t}{U_L} = 1 + 0.6 \left(\frac{U'}{U_L}\right)^{1/2} Re_L^{1/4}$$

As noted by Bradley(1992) there are several non-self-contained correlations that have also been developed for this regime (and may extend into the other regimes) based on experimental values of turbulent flame speed. An example is that of Abdel-Gayed & Bradley(1981), which is further discussed in Section 4.2.5.

4.2.4 Corrugated flamelet regime

In addition to the non-self-contained correlations of the wrinkled flamelet regime that extend into the corrugated flame regime, Gulder(1990) has produced the following correlation:

$$\frac{U_t}{U_L} = Re_L^{1/4} \exp\left(a \left(\frac{U'}{U_L}\right)^{1/2}\right)$$

This correlation is based on the assumption that the flame sheet is no longer wrinkled but is thicker and contains pockets of burnt gases in an unburnt environment and vice-versa. It appears to match experimental data for this regime and at low U'/U_L reduces to the Gulder(1990) wrinkled flamelet equation, as described in Section 4.2.5.

4.2.5 Distributed reaction regime and flame quenching effects

As discussed in Section 4.2.2, the distributed reaction regime flame sheet is characterised by increased thickness and by the presence of eddies within the sheet increasing the mixing rate, leading to higher turbulent burning velocities. However, the effect of flame quenching, due to these internal eddies, may result in a reduction in turbulent burning velocity and extinction.

Bradley(1992) has produced correlations for U_t/U_L from about 1650 measurements of U_t covering all three regimes of turbulent combustion and based on the data of Abdel-Gayed et al(1987) and Bradley et al(1992). The correlations are based on the wrinkling factor U'_k/U_L (U'/U_L for fully developed r.m.s. turbulent velocity) and the product of the Karlovitz stretch factor and the Lewis number, KLe. It was found that higher values of KLe produced lower turbulent burning velocities for constant U'_k/U_L. At sufficiently high stretch rates the flame is quenched. Using this concept of limiting stretch rate, Bradley(1992) has calculated the ratio of U_t/U_L with stretch to U_t/U_L without stretch using numerical techniques based on a probability density function of stretch rates for the flame. It should be noted that the equivalence ratio of the gas mixture is not only used in determining the laminar burning velocity but also affects the value of KLe and thus the ratio of burning velocity with stretch to that without stretch. Quenching is not limited to cases of high turbulence intensity but may occur in the flamelet regimes for gas mixture equivalence ratios near the rich or lean limits.

Bray(1990) used the experimental data of Abdel-Gayed et al(1987) to produce the following correlation for turbulent burning velocities:

$$\frac{U_t}{U'} = 0.875\,K^{-0.392}$$

For isotropic turbulence, K, the Karlovitz stretch factor, can be calculated as follows:

$$K = 0.157\left(\frac{U'}{U_L}\right)^2 R_L^{-0.5}$$

This model has been incorporated into the latest version of the CMR FLACS code (van Wingerden et al,(1994)) for modelling enclosed hydrocarbon explosions where effects of flame stretch and extinction are important due to the high intensities of turbulence induced in the explosion. Similarly the British Gas explosion model, CLICHE (Catlin(1990)), uses a correlation for turbulent burning velocity based on an analysis by Bray(1986) and calibrated against the Abdel-Gayed et al(1987) data.

It should be noted that the analysis by Bradley(1992), Bray(1990) and Bray(1986) are based on highly stretched laminar flamelet modelling of turbulent combustion. Bradley(1992)

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gives reasons for this type of flamelet modelling being applicable beyond the wrinkled and corrugated flamelet regimes (ie. at a Karlovitz number greater than 1).

Another approach has been developed by Gulder[1990] based on correlation of experimental data with the Damkohler and Reynolds numbers of the reaction sheet. It was proposed that turbulent burning velocity scaled as follows;

$$\frac{U_t}{U'} \quad \alpha \quad Da_L^{3/8} Re_L^{-3/8} \quad \alpha \quad \left(\frac{U_L}{U'}\right)^{3/4}$$

The choice of the non-dimensional groups (Da_L and Re_L) was made based on their use in correlations produced by Pope & Anand[1984] and the work of Libby, Bray and Moss[1979]. Pope & Anand[1984] produced the following correlation based on Monte-Carlo solutions of a joint probability density function for velocity and a reaction progress variable

$$\frac{U_t}{U'} = 0.25 + \log_{10} Da_L$$

Adbel-Gayed & Bradley[1981] have also produced a correlation, based on experimental data, that spans the three regimes. At high turbulence intensities it reduces to the following correlation, as discussed by Wheatley & Martin[1990]:

$$\frac{U_t}{U_L} = \left(\frac{U'}{U_L}\right)^{0.5} (1.34 Re_L^{0.47} + 10.9 Re_L^{0.22})^{0.5}$$

4.2.6 Choice of premixed turbulent flame propagation model

The above discussion touched on the issues of importance when considering the use of a turbulent flame propagation correlation. The choice will depend on the regime, whether flamelet or distributed, which will depend on the turbulence intensity of the gas cloud. The correlations presented are representative of a wide range that have been produced in the last two decades and, as noted by Peters[1986], this may reflect the large scatter in experimental data that exists.

It is clear that, for high turbulence intensities, such as for releases of high pressure jets, and for gas mixtures near the flammable limits, quenching of the turbulent burning velocity will be important. In the flamelet regimes the turbulent burning velocity is dependent on both the inner and outer length scales. The outer length scale (integral length scale) will be larger in atmospheric releases than for the length scales studied in laboratory experiments and thus validation of a turbulent burning velocity model may be difficult.

The review of models suggests that those based on stretched flamelet analyses (Bradley[1992], Bray[1990] and Bray[1986]) allow prediction of the effects of both flame wrinkling and flame stretch. They provide good prediction of data presented by Abdel-Gayed et al[1987] and Bradley et al[1992]. Further data collated by Gulder[1990] would need

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to be utilised to assess their applicability to each of the three combustion regimes. These models are used in current confined explosion codes (Considine et al[1982], Van Wingerden et al[1994]).

4.3 Non-Premixed Turbulent Flame Propagation

The non-premixed, or diffusive, burning stage of a flash fire is characterised by its relatively high levels of radiation due to incandescent soot particles within the flame. The propagation of the flame tends to be steady and, as discussed in Section 4.2, propagates after or with the premixed flame back to the release point. Non-premixed combustion differs from premixed combustion in that the diffusion of reactant and oxidant to the flame reaction zone is the rate-limiting step. Thus the speed at which the flame propagates is dependent on the rate of air entrainment to the flash fire and therefore the concept of burning velocity cannot be applied to the modelling of the flame propagation rate.

The methods of modelling the diffusive flame propagation for a hydrocarbon release ranges from empirical models, through flamelet analyses to numerical modelling.

4.3.1 Empirical models

Raj & Emmons[1975] have produced a model for the calculation of external radiation produced from a flash fire resulting from a spill of LNG or LPG. It requires the input of a flame speed for the region of the cloud where the mean concentration is above stoichiometric, ie. for the diffusive burning stage of the flash fire. As further discussed in Section 6.3, it was proposed that the flame speed should scale linearly with the ambient windspeed. However, the empiricism of this correlation restricts its use to ground-lying gas clouds of a similar size and over similar terrain.

4.3.2 Flamelet analysis

Another concept in the modelling of diffusive burning is the use of flamelets. As discussed in Section 4.2.3, the principle behind flamelets is that the chemical time-scale is small compared to diffusion and convection within the flame and the reaction can be assumed to occur in an asymptotically thin layer. Therefore, in diffusion flames, equilibrium chemistry rather than chemical kinetics can be assumed. As discussed by Peters[1986], the use of flamelets is made practicable through a flame-attached co-ordinate system based on mixture fractions within the flame. A two-variable statistical representation of the combustion process can be used, the variables being the mixture fraction, Z, and the instantaneous scalar dissipation rate at stoichiometry, X_{st}. X_{st} represents the heat conduction out of the reaction zone compared to the heat generation within it and is therefore a measure of diffusion flame stretch. Although stretch leads to quenching in both diffusion and premixed flames, the mechanism is different and diffusion flamelets quench at lower levels of stretch than for premixed combustion.

Liew et al[1984] have used the flamelet concept to model turbulent jet diffusion flames with a library of stretched diffusion flamelets using elementary kinetics combined with a numerical code that provided the turbulence properties of the jet.

Cook[1990] has applied flamelet modelling to an integral model of non-premixed jet flames predicting flame trajectory and lengths and mean temperatures of the flame.

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The intermittency of concentration in the jet was modelled using an assumed probability density function.

The modelling of jet stability and lift-off also has relevance to the modelling of flame propagation in jets. Peters[1986] describes the application of flamelet theory to intermittent turbulent jets. In jets, the mean scalar dissipation rate decreases with distance from the nozzle and therefore, for a flame burning at large distances downstream of the release point, the probability of quenching increases with decreasing distance from the nozzle. However, increasing distance from the nozzle will also increase the probability that there are patches that are not connected to an ignition source and therefore stay unignited. Peters[1986] suggests the use of percolation theory to model this lack of connectivity, and illustrates the use of this theory in the calculation of lift-off heights for turbulent jet flames. Near the nozzle there is a distance where the probability of an ignited portion of the flame travelling upstream reduces to zero due to local quenching of the diffusion flamelets. Note how this compares with methods for calculating the lift-off heights based on premixed turbulent combustion, for example Kalghatgi[1981]. In this method it is assumed that the lift-off height is at the point where the local average flow velocity in the jet equals the premixed turbulent flame speed in the opposite direction. Williams[1985] questions the validity of the assumption of thorough molecular-scale mixing in the jet, which is used by Kalghatgi[1981].

It would seem that diffusion flamelet theory may be useful in describing the flame propagation velocity of the non-premixed sections of the vapour cloud. However this would require modelling of the air entrainment to the fire and turbulence properties within the cloud. The use of percolation theory in combination with flamelet theory has been shown to model the lift-off of turbulent jet flames, which has some similarity to the burn-back of the non-premixed regions in the jet or cloud.

Furthermore, the use of mathematical techniques such as percolation theory may be applicable to modelling connectivity in the premixed regions of the dispersed clouds.

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5. REVIEW OF RELEVANT DISPERSION EFFECTS

5.1 Source Conditions

In the event of an incident involving the release of a flammable substance, many of the factors which affect the potential for a flash fire, or other major accident event, are related to the source conditions. The source conditions cover a wide range of factors including the chemical and physical properties of the substance, the initial temperature and pressure, the release duration (instantaneous or continuous) and release location (high or ground level). The source conditions are responsible for determining:

- i) the release rate
- ii) the total released quantity
- iii) the release characteristics (momentum, buoyancy)
- iv) turbulence generated by the release

All these parameters, together with the ambient conditions, determine the flammable characteristics of the release, for example the extent of the flammable region, the flammable cloud shape and proximity to ignition sources and the fluctuations of concentration within the cloud.

Prugh & Johnson[1988] provides a general review of the types of release which could lead to the formation of a hazardous gas cloud, based on the physical properties of the material and the storage conditions:

- Non-condensing vapour - Vapour releases with boiling point well below ambient temperature.
- Condensing vapour - Vapour releases with boiling point above ambient temperature. Some of vapour will condense to form aerosol.
- Two-phase flow - Flashing liquid releases. Cloud will contain aerosol as well as vapour.
- Non-flashing liquid - Liquid released at a temperature below its boiling point. Vapour released from subsequent pool. There may be some aerosol release, particularly if the release is pressurised.

Prugh & Johnson[1988] also notes that many of the most severe incidents following hazardous releases involve flashing liquid releases, as very large vapour clouds can be formed when the loss of containment occurs with substances above their normal boiling point.

Marshall[1980] provides a series of simple relationships for predicting the size of flammable vapour clouds arising from continuous releases into the atmosphere. These relationships are particularly useful in identifying the effect of source conditions on dispersion in that they relate to the following three cases, with different dispersion mechanisms:

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i) Atmospheric dispersion of an emission assumed to have no initial momentum or buoyancy.
ii) Jet dispersion in still air of an emission with initial momentum but no buoyancy.
iii) Plume dispersion in still air of an emission with initial upward buoyancy but no momentum.

Marshall(1980) also notes that, whilst the above may be considered a restricted set of dispersion conditions, the largest clouds will be formed when the fewest dispersion mechanisms are effective.

Morrow et al(1983) describes the development of a pipeline break model to assess the flammability hazards associated with an LPG pipeline rupture. The model estimates the time dependent flow rate of LPG and the subsequent dispersion including the effects of gravity spreading. The various source conditions which may affect the release rate and dispersion are identified, although there is no specific consideration of flash fires.

Lantzy(1992) provides a summary of the issues involved in source term determination and identifies a number of areas where additional research is required. The overall conclusion reached was that existing source term models, for phenomena such as two-phase flow, aerosol formation and dynamics, pool spreading and evaporation and multi-component release models, can be used to simulate some aspects of the physics and chemistry of releases. However, there remains disagreement among experts as to which model is most applicable in any given situation.

5.2 Cloud Shape and Lift-Off Potential

The shape of a flammable vapour cloud will affect the probability of ignition and the subsequent rate of flame propagation back to the release source. Both the shape and the potential for lift-off of the cloud will determine whether the flammable region will encounter ignition sources which, in most process plant areas, are located close to ground level. The shape of the cloud will determine whether the burnt gases in the flash fire can be vented or are trapped behind the flame front. As discussed in Section 4.4.3, for flat or elongated clouds, ignited at their edge, the burnt gases are free to vent laterally to the flame propagation direction and do not accelerate the flame front. For hemispherical clouds, ignited at their centre, the burnt gases are trapped behind the flame front and as they expand the flame front is pushed forward.

5.2.1 Cloud shape

The shape of a vapour cloud will depend on three main factors, whose effects are discussed below:

i) the source conditions
ii) the local terrain
iii) the meteorological conditions

The shape of a vapour cloud may be very dependent on the source conditions. Clancey(1977) describes a few of the simplest situations. In the event of the sudden

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break-up of a container, the vapour expands rapidly until it is virtually at rest. If the release is at a height then a spherical cloud is formed, and if the release is at ground level then a hemispherical cloud is formed. However, if the release of vapour takes a significant time then the cloud becomes elongated to form an expanding plume. Hertzberg & Lamnvik[1983] describes a similar approach in which instantaneous propane releases in neutral atmospheric conditions are modelled as a circular cloud.

Cox[1980] emphasises the point that the estimation of levels of damage following loss of containment requires the prediction of the likely cloud shape prior to ignition. It reviews the various types of release that are possible and summarises the principle dispersion modelling approaches. The basic models considered are:

- buoyant and dense releases from stacks, using integral plume models.
- instantaneous and continuous Gaussian dispersion models.
- Dense gas box models.

For a dense gas release, spreading by gravity is initially the dominant dispersion mechanism and so the vapour cloud is circular in shape. The action of the wind begins to direct the cloud in the downwind direction, and obstacles such as buildings, dikes, slopes and vegetation may begin to influence the cloud shape.

Colenbrander & Puttock[1983] describes some of the 1980 Maplin Sands field trials and compares the results of continuous and instantaneous releases of LNG and refrigerated propane with predictions made by HEGADAS. Two of the instantaneous LNG spills produced very elongated clouds in the wind direction, largely due to the finite pool evaporation time. Conversely, two instantaneous propane spills in low winds showed nearly circular shapes for the clouds, demonstrating the strong influence of gravity spreading.

Chan[1992] describes the use of numerical simulations using the FEM3A model to simulate the dispersion of vapour in barrier field experiments and a comparison with the field data. The field trials involved releases of LNG with and without vapour barriers and demonstrated the influence of such obstacles in modifying the cloud shape and in reducing the distance to the LFL.

The problems associated with the evolution of a cloud of low temperature light gas in the atmosphere have been considered in Kestenboim et al[1991], which describes the development of a mathematical model to assess the effect of various factors (initial shape and temperature, condensation of atmospheric moisture) on the dynamics of the cloud and its dangerous properties. The model can be used to assess spills of liquid hydrogen, which would evaporate forming a turbulent low temperature cloud of light gas. As it is heated by mixing with the air and as a result of the condensation of atmospheric moisture, the cloud rises and is dissipated. The cloud shape is thus modelled as a buoyant rising thermal.

Chirivella & Witcofski[1986], Witcofski & Chirivella[1984] and Witcofski[1981] report the findings of hydrogen vapour cloud dispersion experiments conducted by NASA at White Sands. The experiments consisted of ground spills of up to 5.7 m^3 of liquid hydrogen, with spill durations of approximately 35 seconds. The results indicated that, for rapid spills, thermal and momentum induced turbulence causes the cloud to disperse to safe concentrations and become positively buoyant long before mixing due to normal

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atmospheric turbulence becomes a major factor. The ground level cloud travel for such releases was found to extend approximately 50 to 100 m, followed by a 0.5 to 1.0 m/s cloud rise rate. Conversely, prolonged gentle spills, such as might occur due to the rupture of a hydrogen pipeline, are characterised by prolonged ground level cloud travel. This is caused by reduced spill-induced or momentum-induced cloud turbulence, and is thought to be aggravated by long term cooling of the ground.

5.2.2 Lift-off potential

Meroney[1979] describes a wind tunnel study of the behaviour of buoyant plumes released at ground level in a turbulent shear layer. When wind velocities are significant near the ground, buoyant gases do not necessarily rise upwards immediately, but may drift along the ground for some distance. Briggs characterised the criterion for plume lift-off by a parameter L_P defined as:

$$L_P = \frac{g \; H \; \Delta\rho/\rho_a}{u_*^2}$$

where u_* is the friction velocity, H is the gas layer depth, and $\Delta\rho/\rho_a$ is the relative density of the gas compared with atmospheric density. Briggs originally suggested that lift-off would occur for $L_P > 2$ but admitted that the uncertainty may be a factor of ± 4. The study described by Marshall[1987] suggested alternative criteria, and indicated that L_P values associated with line sources ranged from 4.5 to 1600, demonstrating the uncertainty in lift-off predictions. The downwind distance to lift-off for line, area or point source releases correlates as $x/l_b > 0.24\ Fr^{1.5}$, and hence increased wind speed delays plume lift-off, whereas increased buoyancy hastens its onset.

5.3 Cloud Turbulence

As further discussed in Section 7.4, the predominant mechanism for increasing the flame speed in a flash fire is the turbulence already present in the vapour cloud. The degree of turbulence will be affected by the release conditions, ground roughness and gas density.

5.3.1 Roughness Effects on Dispersion and Turbulence

It is well established that the roughness of the underlying terrain has two principal effects when considering dispersion in the atmosphere. Firstly, the roughness of the ground plays a major role in determining the vertical profile of the mean wind speed, which affects the speed with which hazardous releases are adverted downwind. Secondly, flow of wind over rough ground generates turbulence in the boundary layer, which is one of the main factors which contributes to the dispersion of a release.

Britter and McQuaid[1988] reviewed the influence of surface roughness on the dispersion of dense gases. The conclusion reached was that the effect of surface roughness on dispersion was less for dense gas releases than for comparable passive releases, at least for surface roughnesses up to that corresponding to rough grass. However, it is noted that for dense gas flows through industrial sites the hazard ranges are reduced by a factor of around a half, compared with those for unobstructed terrain, together with a slight increase in the lateral plume spread.

Petersen[(1990)] notes that many of the dispersion models used for estimating the concentration of heavier than air gases have only been tested against field and wind tunnel data bases with small surface roughness, and that data bases with large surface roughness are not generally available. It therefore describes wind tunnel experiments in a boundary layer wind tunnel where the effect of various surface roughnesses, ranging from flat grass land to an urban area, on the dispersion of releases with various gas densities. Heterogeneous roughness, typical of a refinery tank farm and process unit, was also investigated. The results of the study showed that large roughness elements can significantly reduce the concentrations. This has clear implications for flash fires in terms of reducing the extent of flammable gas clouds. However, the significance of the enhanced levels of turbulence is not addressed. Petersen[(1990)] also concludes that for heterogeneous roughness configurations, the entrainment and dispersion rates appear to be site specific and are not well modelled using existing techniques.

Seeto & Bowen[(1983)] describes field and laboratory experiments which show that, for LPG releases, an increase in roughness length of the surrounding terrain reduces the velocity at the cloud height and consequently increases the extent of the cloud's lateral and downwind spreading.

5.3.2 Density Effects on Turbulence

It has long been recognised that density effects can have a significant effect on turbulence. There are several issues to consider:

i) The atmospheric stability, as this affects the ambient levels of turbulence. In stable conditions, the density stratification of the atmosphere results in significantly reduced levels of turbulence, particularly in the vertical direction, leading to reduced dispersion and increased hazard ranges.

ii) Dense gas releases tend to form a layer on the ground, and entrainment of ambient air at the interface tends to be reduced due to the suppressed levels of turbulence, again leading to reduced dispersion.

iii) Buoyant gas releases tend to rise and this movement causes increased levels of turbulence and hence enhanced dispersion due to the greater entrainment. This tends to reduce the hazard ranges associated with buoyant releases.

It is emphasised that the levels of turbulence not only influence the dispersion of a release but will also affect flame propagation through the gas.

5.4 Concentration Fluctuations

As further discussed in Sections 7.4 and 7.5, concentration fluctuations within a flammable gas cloud will play an important role in the consideration of ignitability of and flame propagation within flash fires. Concentration fluctuations within a gas cloud may be characterised by features such as intermittency, connectivity and peak-to-mean concentration ratios.

One of the simplest models for evaluating concentration fluctuations is that of Gifford, which is described by Pasquill and Smith[(1983)]. A model is provided for the ratio of the

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instantaneous to time mean concentration at positions (x, y, z) relative to a continuous point source. Pasquill and Smith[1983] provided both theoretical and experimental values for χ_i/χ_τ in a range of conditions.

Wilson et al[1985] defines the intermittency at a point in a plume as the fraction of the time during which non-zero concentrations occur at that point, and describes the development of a semi-empirical Gaussian plume model, similar to Gifford's model, which predicts the intermittency. The model also gives the mean and variance of the non-zero time varying concentration in the plume. It was found that this conditionally averaged concentration fluctuation variance was only weakly dependent on the source size, while the intermittency caused by plume meandering was strongly dependent on the source size.

Intermittency in a plume is caused by two principal mechanisms. Firstly, local regions of fresh air may persist in the plume causing periods of intermittency with a time scale of the order of σ/u, where σ is the plume width and u is the wind speed. However, close to the source a second mechanism dominates the production of intermittency. In this region the plume is smaller than the energetic atmospheric eddies, and these large eddies cause the plume to meander in the crosswind direction, and to a lesser extent in the vertical direction. This meandering of the plume causes periods of zero concentration that persist for periods of order Λ/u, where Λ is the average integral scale of turbulence.

Poreh & Cermak[1990] describe wind tunnel experiments to measure vertical line-integrated concentrations in a plume from ground level sources in a boundary. Poreh & Cermak[1990] also describe further similar experiments to determine the intermittency of horizontal line-integrated concentrations across an elevated carbon dioxide plume diffusing in grid generated turbulence. The line-integrated concentrations were evaluated by measuring the attenuation of an infra red beam crossing the plume. The laboratory study showed that the time variation of the integrated concentration was determined by meandering of the plume. At the edge of the plume, $y/\sigma > 2$, the intermittency is smaller than 0.5, although during that time significant concentrations are still observed. Surprisingly, it was found that the statistical properties of the integrated concentrations at different locations downwind of the source exhibited an approximate similarity, which suggests that meandering induced intermittency remains important at extended downwind distances and that in-plume fluctuations only dominate at large distances. Poreh & Cermak[1990] does note, however, that the contribution from the in-plume fluctuations is attenuated when integrated values are considered.

Ride[1983] describes a probability density function (pdf) approach for modelling the concentration fluctuations in gas clouds and notes how important these fluctuations may be in considerations of the explosive and flammable properties of such clouds. A model is derived using the following 3 parameters to describe the probability density function:

i) the mean concentration, c
ii) the peak to mean ratio of concentration, c_*/c
iii) the mean number of pulses of concentration experienced, m

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The model allows various identities to be simply determined, such as:

$$c_*/c = (1 - \gamma)^{-1}$$

$$(\sigma/c)^2 = (c_*/c) - 1$$

where γ is the intermittency and σ is the standard deviation of the instantaneous concentration field.

Ride[(1988)] also describes a pdf approach to predict the concentration fluctuations in a dispersing plume. This model is based on 2 parameters:

i) the ratio of the instantaneous plume width and limits of meander, r
ii) the intermittency within the plume, γ_P

Results are presented showing the variation in intermittency across the meandering plume, and these clearly indicate that the intermittency profile can take many forms, few of which may be represented by simple functions. It is worth noting that the intermittency of meander (γ_M) and the within plume intermittency (γ_P) are defined separately:

γ_M : The probability that a point lies outside the plume
γ_P : The probability that the concentration at a point in the plume is zero

An alternative approach is described by Sreenivasen & Meneveau[(1986)] which addresses the speculation that several facets of fully developed turbulent flows are fractals. Sreenivasen & Meneveau[(1986)] concludes that several aspects of turbulence can be roughly described by fractals and that their fractal dimensions can be measured. However, this approach remains somewhat speculative and much work remains to be done before fractals can be usefully applied to the assessment of dispersion of flammable gas clouds.

Britter and McQuaid[(1988)] also consider concentration fluctuations, and emphasises that much of the problem concerns the averaging time over which concentrations are averaged. It is suggested that, for ground level concentrations on the plume centreline, the ratio of the concentration fluctuation to the mean concentration is between 0.2 and 0.3 for dense plumes, whereas the comparable ratio for passive plumes is about 0.35. For elevated plumes in an atmospheric boundary layer, the ratio on the plume centreline increases to 1.5, demonstrating that there are significant variations in the statistical properties of plumes in different situations.

6. DATA RELEVANT TO FLASH FIRE MODELLING

6.1 Full Scale Flash Fire Data

Full scale data on flame propagation within flammable vapour clouds, and resulting radiation, is limited. This is primarily due to the significant expense and labour effort involved, as discussed by Van Wingerden(1994). Table 6.1 summarises the most significant flash fire experiments for which data are available and gives the primary objectives of each. All of the test programmes involved spillage of liquefied gases onto land or water, which produced dense low-lying vapour clouds.

Test Programme	Fuel	Release/Release Rate	No. of tests	Primary objectives of test
Maplin Sands, Shell, 1980	LNG	20-40kg/s (cont) 3500-5000kg (inst.)	3 2	Flame propagation, thermal radiation and overpressure
	Liquefied Propane	20-55kg/s (cont) 4500kg (inst)	3 1	
Coyote, China Lake, LLNL, 1980	LNG	100-120kg/s (up to a maximum of 12000kg)	4	Flame propagation and thermal radiation
	Liquefied Methane	100kg/s (up to a maximum of 11000kg)	1	
Musselbanks, Terneuzen, TNO, 1983	Liquefied Propane	1000-4000kg (dispersed cloud inventory)	7	Flame propagation and overpressures with and without obstacles
China Lake, NWC, 1978	LNG	25-35kg/s (up to a maximum of 2500kg)	6	Flame propagation and thermal radiation
China Lake, US DOE, 1977	LPG	30-40kg/s (up to a maximum of 2500kg)	3	Flame propagation and thermal radiation

Table 6.1 Full-Scale Flash Fire Experiments

Maplin Sands. Blackmore et al(1982) and Mizner & Eyre(1983) discuss a series of LNG and LPG pool and flash fire experiments conducted at Maplin Sands on water. It was found that fuel type and release mode (continuous or instantaneous) affected the combustion behaviour of the vapour clouds. LPG fires produced smoky flames whereas the LNG fires tended to burn cleanly. For the continuous spills, ignition resulted in premixed combustion with a bluish, weakly luminous flame. This was followed by a diffusive burning of the fuel rich region of the cloud with an initially low yellow flame increasing in height as it propagated back to the release point. In a number of the tests, the diffusive flame front appeared to be stationary and did not propagate back to the source. It was noted that the area covered by a flash fire is approximately the same as that contained within the flammable region of the cloud before ignition. This is thought to be because thermal expansion almost all occurs in a vertical direction. It was also observed that no substantial pockets of flammable gas extended beyond these contours and that much air entrainment occurs in the burning region.

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Coyote. Libby & Williams[1976], Rodean et al[1984], Goldwire et al[1983] and Hogan[1982] describe the results of flash fire experiments on water at China Lake. A similar distinction between the premixed and diffusive burning stages to that observed in the Maplin Sands experiments was noted, although the gas cloud was ignited within the flammable region rather than at its edge as for the Maplin Sands trials.

Musselbanks. Van Wingerden[1994] and Zeeuwen et al[1983] describe vapour cloud experiments, the purpose of which was to investigate the effect of obstructions within the cloud on resultant overpressures. A number of experiments were conducted without obstacles and flame paths were measured from video recordings. Flame speed was found to be constant over large distances except where the flame propagated into more reactive mixtures within the cloud, causing high transient flame speeds. Flame height was seen to be dependent on mixture composition; the leaner the mixture the lower the flame height.

China Lake (NWC). Raj et al[1979] present the results of LNG flash fire experiments at China Lake. The LNG was released onto water but the ignition and flame propagation occurred on land. The flame appeared to propagate in three stages. A transient turbulent flame front propagated to the water edge where it slowed down producing a steady turbulent orange diffusion flame. The third stage was a transient burnout where the flame moved towards the LNG spill on the pond eventually producing a pool fire. Raj et al[1979] give flame profiles within the burning clouds as a function of time. It did not appear that the flame extended further upwind than the spill point, except for one instance.

China Lake (US DOE). Similar tests to the above were conducted for LPG and are described by Mudan[1984]. The flame propagation followed the same three stages.

In addition to the above programmes, relevant data on flame propagation in low lying vapour clouds is given by Raj & Emmons[1975] based on analysis of video footage of tests conducted by TRW, Gaz de France and AGA.

The magnitude of the overpressure waves produced when flammable gas clouds are ignited also been an area of concern. Arnaud et al[1992] describe attempts to measure the strength of the pressure wave generated by the ignition of a jet of natural gas. It was found that, as the gas flow rate increased, the maximum overpressure effects increased and that pressure amplitude varied with the inverse of the distance from the source. The evidence seems to be that the maximum overpressures produced are in the range of a few millibars and consequently any ignition would develop in a deflagrative, not detonative, manner.

Harrison & Eyre[1986] describe an experimental programme with the purpose of assessing the effect of obstacles and jet ignition on the combustion of large premixed gas clouds. A rig representing a segment of the cloud with central ignition was used. A number of unobstructed tests were performed which were found not to produce significant overpressures. Flame speeds were approximately 10m/s for natural gas and 30-40m/s for propane.

The influence of the initial shape of the flammable volume on the pressure, the effect of the size of the flammable region and the effect of energy released by ignition on the explosion regime obtained and on flame speeds are discussed in a review of

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experiments carried out by Leyer et al[1993]. In addition to many of the test programmes listed in Table 4.1, it describes tests conducted on homogeneous hemispherical clouds with central and edge ignition. It concluded that peak overpressures generated by the deflagration of flat volumes are smaller than those generated by spherical ones, that velocities remain low, that buoyancy effects need to be considered and that strong ignition without turbulence results in detonation or fast deflagration.

Zabetakis & Burgess[1961] considered the properties and flammability of hydrogen-air mixtures, plotted the vertical concentration profiles of the flammable cloud versus time after release and detailed flame width, height and cross-section as a function of time. Radiation effects at a certain distance from different size spillages were also measured.

McGuirk & Papadimitriou[1988] described experiments set up to determine the change in combustion of turbulent jets associated with different release rates, orientations and pressures. It concluded that horizontal releases produced greater flammable distances than downward releases and that turbulence generated by high pressure releases did not lead to faster flame speeds.

Many of the above papers cover several aspects of flash fire behaviour from dispersion to flame speed and radiation phenomena. These will be discussed in Sections 6.2 and 6.3. In addition to the experiments discussed above, a number of studies have been conducted on the ignitability of hydrocarbon releases and the effect of concentration fluctuations on flame propagation. These are discussed in Section 6.4. Section 6.5 discusses small scale experiments which, although far cheaper than full-scale tests, have their own intrinsic problems.

6.2 Flame Speed Data

Section 4.1 has described the main stages of vapour fire development observed in flash fire experiments. In general, a transient premixed flame was followed by a yellow diffusion flame propagating through the rich section of the cloud.

During the transient flame growth, an average flame propagation velocity with respect to the ground can be determined by video records or by other means. The flame speed with respect to gases can be obtained by adding the flame speed with respect to ground to the wind speed. Pikaar[1983,85] has considered propane and LNG flame speeds for premixed combustion in low-lying gas cloud experiments and a summary of these is shown in Table 6.2.

Test Programme	Flame speeds (m/s over ground)			
	Propane		LNG	
	Average	Range	Average	Range
Maplin Sands (sea)	12	5-28	5	2-10
Coyote (land)			20	5-40
Musselbanks (land)	15	10-32		

Table 6.2 Premixed transient flame speeds

It can be seen from the above that the propane flame velocity is generally higher than the LNG flame velocity and that flames appear to travel faster over land than over sea. Note that the high flame speeds in the Coyote trials (of up to 40m/s) may be a consequence of the point of ignition being in the centre of the flammable region. This causes burnt gases to be trapped behind the flame front, accelerating the flame front as they expand.

Review of data from each of the experimental programmes described in Section 6.1 suggests that the transient flame speed also is dependent on location with respect to the ignition point within the cloud. For example, Raj & Emmons[1975] give flame propagation velocities for the China Lake, NWC LNG trials. Mean upwind premixed flame velocities varied from 8-17m/s whereas downwind flame velocities were less than 5m/s.

Zeeuwen et al[1983] and Zeeuwen & van Vingerden[1983] consider propane transient flame speeds into and away from the wind without and with obstacles and also consider lateral flame speeds. It was found that the flame speed was usually between 3 and 10m/s and was constant over distances greater than 10m from the source. However, in at least one case a flame speed of 32m/s was observed.

Tests with horizontal obstacles were carried out and, although only flame speeds perpendicular to the wind could be measured, flame acceleration occurred and flame speeds of up to 25-30m/s were observed across the obstacles. The flames decelerated after passing over the obstacles to speeds in the region of those shown in Table 6.2. However, flame acceleration was not observed when tests were carried out with vertical obstacles. This is thought to be due to vertical relief. The flammable mixture is low-lying, and so the flame front soon reaches the cloud boundary at the top. The upward expansion of combustion products is then unrestricted and this reduces the driving force behind the flame. When vertical confinement was introduced with vertical obstacles it was found that the flame speed increased continuously when travelling under the covered part, but decreased upon reaching the area with only vertical obstacles.

Although turbulent flame speeds are not sufficient to generate significant overpressures, the speeds are increased when clouds are dispersed over land, when wind speeds are increased and turbulence is increased and when channelling occurs or horizontal obstacles are in the path of the cloud.

The diffusive burning stage of a flash fire tends to be steadier than the premixed stage. Raj & Emmons[1975] have correlated the flame propagation velocities through the rich section of gas cloud on land and propose that the flame propagation velocity is proportional to the wind speed, as shown in Figure 6.1. Further data are available for the Maplin Sands experiments described by Hirst & Eyre[1983]. Propane diffusion flames, on water, propagated at approximately 11m/s at windspeeds of 6-7m/s. LNG diffusion flames propagated at approximately 5m/s for windspeeds of 4-6m/s. Thus, as for the premixed region, flame speeds in the rich region are dependent on fuel type (LPG flame speeds are higher than LNG flame speeds) and on substrate (flame speeds over land are higher than those over water).

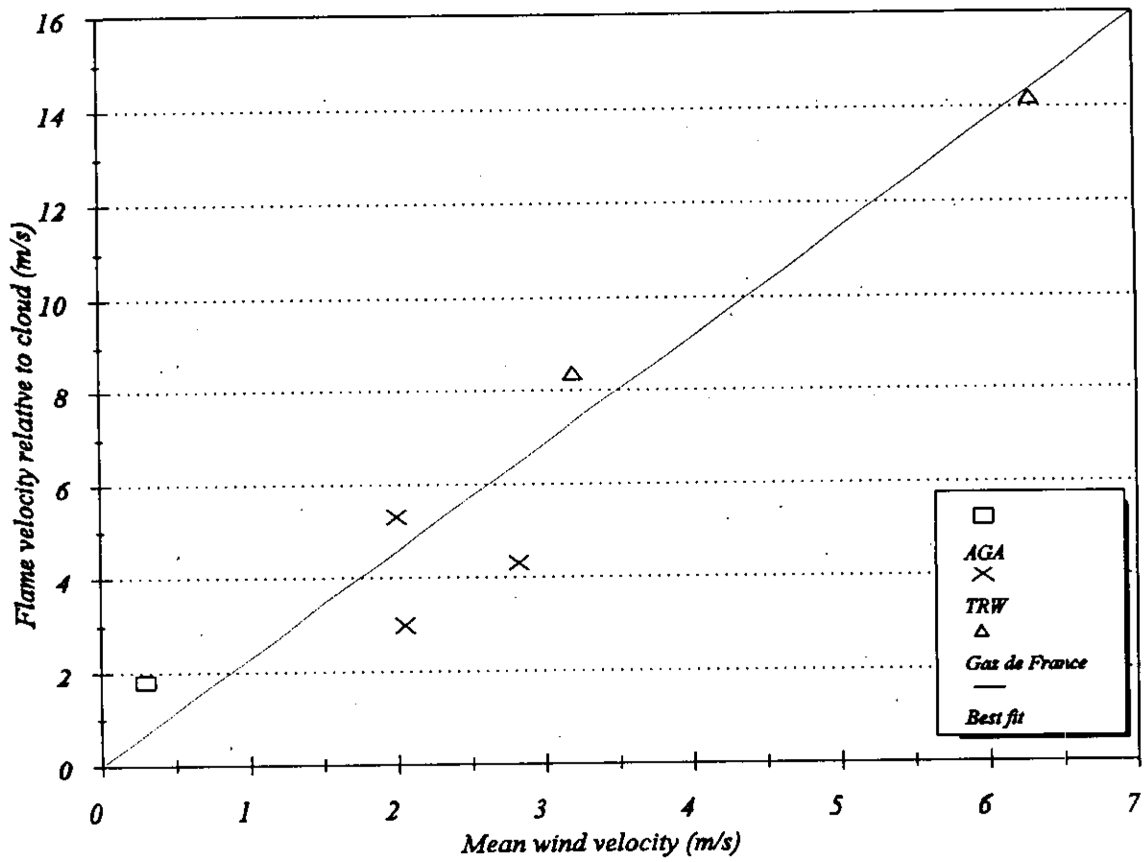

Figure 6.1 Flame velocities for LNG and LPG dense vapour clouds

Schneider[(1980)] mentions an interesting phenomenon in the China Lake, NWC, tests where dispersion had taken place over both land and water and subsequent ignition resulted in fast flame propagation over land but, once the flame reached the edge of the pond, the flame remained virtually stationary for about a minute before spreading through the cloud. A reason postulated for this is that condensed water droplets or ice particles in the fuel-air mixture over the pond inhibited combustion. Another cause may be the step change in ground roughness at the pond edge causing a step change in burning in burning rate. Diffusion flame propagation rates were asserted to be 4.5-6m/s for LNG and 11m/s for propane. Wind velocity tends to increase flame velocity, but also increases dispersion. Therefore, for a low concentration vapour cloud near LFL, a decrease in flame propagation speed may result.

The above discussion has been limited to flame speeds within heavy gas clouds where the dispersal of fuel is due to gravity (slumping) and wind effects. The resultant flame speeds tend to be of the order of 10m/s with transient peaks of up to 40m/s in premixed sections of the cloud. It should be noted that these velocities are small in comparison to flame speeds that occur in turbulent free jet releases where dispersion is dominated by the jet momentum.

As discussed by Smith et al[(1986)], flame propagation back to the release point within turbulent natural gas jets is possible at release velocities up to 190m/s. Therefore mean flame speeds of the order of 200m/s must be possible. In less turbulent vertical releases of natural gas, Arnaud et al[(1992)] observed mean flame speeds of 30-40m/s.

6.3 Flame Height and Radiation Data

The shape of the diffusive flame and its surface heat flux is required, in addition to flame propagation velocities, to calculate incident heat flux to personnel outside the flammable gas cloud. The flame height and flame width are defined as shown in Figure 6.2.

According to Mudan & Croce(1988), the flame width increases as a function of time, as the cloud propagates back to the spill point, until all the flammable gas is consumed. The rate of increase in flame width seems to be slightly less than the flame propagation velocity with respect to the ground. The ratio of diffusive flame height to flame width is relatively constant at about 1:2.5.

Flame plume lengths versus flame width are presented in Raj(1982) for various LNG vapour fire tests carried out at China Lake (Coyote, NWC, AGA, TRW) and Maplin Sands. The majority of the results indicate that the plume height is around 40-50% of the flame width. Smaller vapour fires indicated that a value of nearer 40% is obtained. Raj et al(1979) gave experimental values of flame length and width against time for LNG trials carried out at China Lake (NWC) which confirms the value of 50%. The only values which differ significantly from these are from an AGA test (Raj & Emmons(1975)). This test gave a height-to-width ratio of about 2, and this was used in the Raj and Emmons(1975) model.

Mudan(1984) discusses the results of the China Lake (US DOE) LPG tests. The width of the diffusive burning region was found to increase to approximately 30m before decreasing to a steady value of approximately 10m. Mizner & Eyre(1983) give flame height to width ratios for the Maplin Sands LPG tests as varying between 0.15 and 0.3.

The surface emissive power of a vapour fire can be difficult to determine since its duration is short. However, the thermal radiation is relatively constant over a short period and this can be used to determine average incident fluxes.

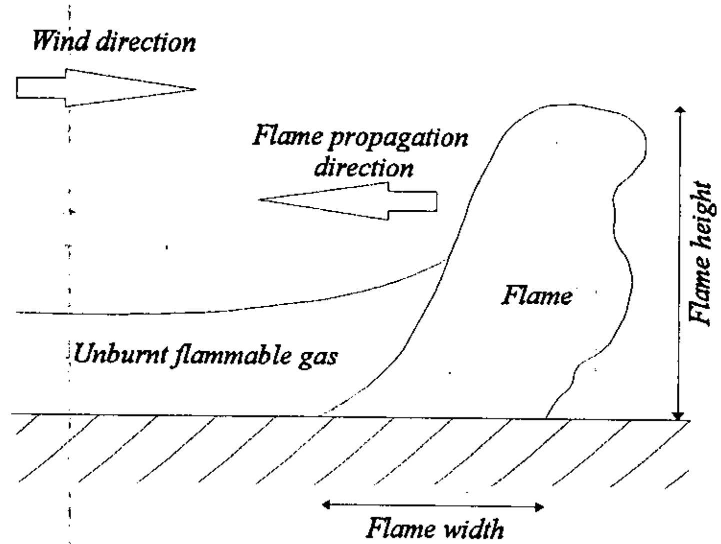

Figure 6.2 Cross-section through flame for a typical flash fire

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Raj[1982] states that large vapour fires had greater radiative emissive powers than pool fires due to better combustion as a result of good mixing and larger optical depths. The mean emissive power was found to be 210± 65 kW/m^2. Lind[1982] estimates the radiation from LNG flash fire tests at China Lake for various spill sizes. The radiation was found to be fairly constant at around 240-250 kW/m^2.

For the Maplin Sands trials, Mizner & Eyre[1983] found that the surface emissive power of the diffusive stage of LPG flash fires was found to be approximately 170 ±30kW/m^2. The flames tended to be clean burning until the fire burned back to the source whereupon the flames became smoky. The surface emissive power of the LPG flash fires in the China Lake (US DOE) tests were given by Mudan[1984] as approximately 220kW/m^2.

6.4 Ignitability of Vapour Clouds and Jets

A number of studies have been conducted to assess the effects of concentration fluctuations on the ignition and sustained flame propagation in both turbulent jet releases and dense gas dispersion of hydrocarbons. Although these studies do not explicitly give data relating to flame speeds or external heat radiation, they do provide insight into the effect of intermittency and connectivity of gas concentration on flame propagation. As discussed further in Section 7.4, an understanding of the effect of concentration fluctuations is key to the estimation of rates of flame propagation through a gas cloud. Table 6.1 lists a number of studies that have been undertaken to assess the effects of concentration fluctuations.

Study	Fuel and release mode	Objectives
Smith et al[1986]	Natural gas, propane and hydrogen jets	Ignition and light-back probabilities
Birch et al[1989]	Natural gas jets	Light-back region
Evans & Puttock[1986]	Liquified propane dense gas dispersion	Region of sustained burning.
Burgess et al[1974]	LNG	Ignition location
Hirst[1986]	Propane two-phase jets	Downwind travel of flame

Table 6.3 Tests on the ignitability of hydrocarbon releases

Smith et al[1986] describe ignition and flame propagation studies in turbulent jets of natural gas, propane and a gas with a high hydrogen content. The aim of the study was to derive probabilities of ignition and conditional light-back probabilities leading to the establishment of a stable flame at the release source. In the study, ignition along the gas jet axis was considered and it was found that at certain distances from the flame, although ignition occurred, the resulting flame kernel was convected downstream by the release momentum. The probability of localised ignition at a point on the jet axis was found to agree well with a calculated flammability factor, defined as the cumulative probability of a potentially flammable mixture occurring at a given point

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in a turbulent free jet. Previous measurements had shown that the probability function of concentration on the axis of a jet could be approximated by a Gaussian curve. The flammability factor is calculated as the area under the probability function between the upper and lower flammability limits of the gas. This study shows that, for releases of intermittent concentration, it is not correct to base the occurrence of ignition upon mean concentrations of the dispersion cloud but that a probability of ignition should be associated with each location along the jet axis. However, the probability of ignition decreased to zero at mean concentrations of ½ the lower flammable limit. Of particular relevance to escalation of incidents are the conditional probabilities of light-back given by Smith et al(1986). It was found that the transition zone between locations where ignited kernels always light-back or always blow-out is relatively narrow below release velocities of 170m/s and that the transition always occurred at distances from the source where the mean concentration was greater than the lower flammable limit. As the exit velocity increased, a velocity was reached where the probability of light-back reduced to zero and this velocity matched Kalghatgi's flame blowout criteria.

Birch et al(1989) conducted similar experiments to those of Smith et al(1986), examining the ignition characteristics of a turbulent natural gas jet in a cross-flow. The study was an extension of Smith et al(1986) and aimed to assess the effects of a cross-wind on the light-back transition zone. Light-back experiments were conducted at various locations around the dispersing jet producing a 'critical surface' within which ignition would always lead to flame propagation back to the source and outside which ignition leads only to isolated flame kernels being transported downwind. The location of this surface with respect to measured mean concentrations within the gas jet varied depending on the axial and radial position. Figure 6.3, from Birch et al(1989) shows light-back locations and mean concentration on the symmetry plane of the non-reacting jet.

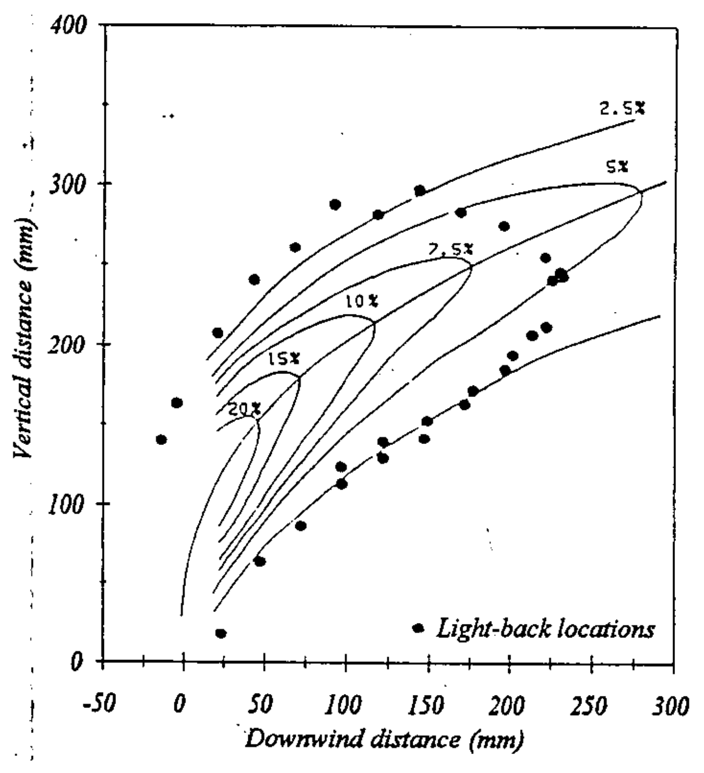

Figure 6.3 Light-back locations compared to mean concentrations for a natural gas jet (Birch et al(1989))

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At small downwind distances, light-back occurs at low mean concentrations (2.5% by volume of natural gas, approximately ½ the lower flammable limit). Further downwind light-back occurs at higher mean concentrations until light-back occurs at the gas jet axis, at a mean concentration of 6 to 7% by volume. These results are consistent with the idea of intermittency of concentration within a turbulent jet. At the edges of the jet, close to the source, a probability density function of concentration would show that there is a large probability that the concentration of gas is almost zero but also a finite probability that the concentration will be above the lower flammable limit of the gas, despite the mean concentration being below the lower flammable limit. The finite probability of the concentration being above the lower flammable limit is associated with turbulent jet contributions. As the distance away from the source increases, the turbulent contribution to the concentration p.d.f. decreases and with it the probability of obtaining a flammable mixture. The light-back locations move to regions of relatively high mean concentration. In general it was found that the maximum downwind location of light-back tended to occur on the jet axis and was within the mean lower flammable limit. The location of the light-back critical surface was found to depend on both jet exit velocity and wind velocity due to their effect on mixing and on the generation of turbulence.

Evans & Puttock[(1986)] describe ignition and flame propagation studies on dense gas clouds produced from pools of evaporating propane, the objective being to predict the fraction of the predicted mean lower flammable limit for which the cloud is flammable. The experimental procedure was similar to that used by Smith et al[(1986)] and Birch et al [(1989)], except that a pilot flame was used for ignition rather than a spark system. Ignition was categorised as either producing 'small flames', 'large flames' or 'sustained flames'. 'Small flames' produced zones of hot gas between 4 and 16m in diameter and 'large flames' over 16m. 'Sustained flames' were those that burned back to the spill source ie. equivalent to the 'light-back' criterion of Smith et al[(1986)] and Birch et al[(1989)]. Analysis of data produced in this experiment, together with additional information from the Maplin Sands experiments (Colenbrander[(1980)]), showed that sustained ignition occurred at a mean concentration of approximately 1.9% by volume of propane compared to the lower flammable limit of 2.1%. Thus sustained ignition can occur at mean concentrations of 0.9 LFL. Similarly 'small flames' occurred at 0.6 LFL.

Burgess et al[(1974)] also discuss the experimental results of a study into the ignitability of weak mixtures. Ignition was found to occur, after a delay of 3½ minutes, at a continuous ignition source, 25m downwind of an LNG release, release, at which location the mean concentration was 0.57%. The peak concentration recorded during that time was around 5%, but this apparently occurred 2½ minutes prior to ignition.

Hirst[(1986)] discusses the flammability of high pressure two-phase releases of propane. Experiments with both vertical and horizontal (downwind) release orientations were assessed. One of the purposes of the test programme was to compare the downwind travel of the flame (ignited close to the release point) with predicted mean LFL contours calculated using a modified heavy gas dispersion model. It was found that the flame travelled to approximately 75% of the predicted distance to mean LFL for horizontal releases and to 50% of the predicted distance for downward releases.

Maurer et al[(1977)] discusses the effect of the unmixedness of releases of propylene produced by the bursting of liquefied gas vessels. It was observed that lack of micro-mixing of the gas (ie. intermittency) produced a period of yellowish, luminous

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afterburning of the cloud after the bluish premixed deflagrative flame has passed through. It was estimated that no more than 30% of the discharged gas would be involved in the premixed burning stage.

The above studies show that there was a variation in mean concentration at the light-back locations with respect to the mean lower flammability limit, which suggested that the probability density function for concentration is dependent on both position within the cloud and the type of release.

6.5 Small Scale Fire Data

Small-scale experiments enable many fire phenomena to be investigated economically. However, problems may occur when attempts are made to interpret data from scaled-down experiments.

Aslanov et al[1991] investigates flame propagation in a diesel oil droplet cloud. A dispersed cloud was created by superheating the fuel in an aerosol generator. Remote ignition occurred and a practically spherical flame front was observed. The speed of flame propagation in droplet mixtures was found to be higher than in gas mixtures. The explanation postulated for this is that radiation from the flame front heats the droplets and increases reaction rates. Large particles decrease the flame speed at higher concentrations, but as turbulence increases these have a lower effect.

In experiments described in Maurer et al[1977], droplet/vapour clouds were formed by superheating propylene in a sealed tank until the tank burst. Turbulent entrainment was observed and the pressure amplitude was determined for propylene flashing at different preheat temperatures. The propagation velocity of the vapour cloud boundary was recorded for different tank sizes and rapid dilution by entrainment was a consequence of the very intense turbulent motion resulting from flash expansion. The burning of the cloud after the passage of the pressure wave had no contribution to the pressure amplitude. The proportion of hydrocarbon vapour reacting during deflagration was found to be only 30%. The rest burns as a yellowish flame covering the whole cloud after deflagration. High speed film was used to determine the flame speed over the flame front envelope and was found to increase from 10 to 43m/s as the tank size increased. The tendency of the flame speed and peak overpressure to increase with increasing mass release for larger experiments was questioned within this paper since there was a tendency for the curve to flatten towards the top end of the range. This suggests that there may be an upper limit to the flame speed for large clouds.

Small scale experiments to investigate turbulence in 5.66% propane in air mixtures are described in Urtiew[1981]. The velocity of the flame front was measured under various conditions both with, and without, obstacles. It was found that, in the absence of obstacles, the flame propagation velocity (V) was 2-3m/s, but increased five-fold when the chamber roof spacing was halved. All obstacles increased the flame velocity, but smaller obstacles had a greater effect on flame velocities than larger ones, raising V to 6 rather than 4m/s. If the obstacles are raised slightly from the floor then the flame propagation velocity increases still further up to a maximum of 20m/s when all obstacles are raised. This is due to gas from the previous 'cell' being able to flow under the obstacles and disturb the gas in the next cell, thus leading to a faster burning rate. However, the final velocity was reached near the first obstacles and no evidence of further acceleration was obtained.

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In addition to the above tests, a large amount of experimental data has been obtained on flammability limits of hydrocarbon gas mixtures and on the effect of turbulence on burning rates. The use of this data has been discussed in Section 4.1

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7. APPLICATION OF THEORY TO FLASH FIRE MODELLING

7.1 Features to be included

In Sections 2.2 and 2.3, the features of cloud dispersion and flame propagation that were expected to affect the modelling of flash fires were listed. Thus any simple model proposed for the calculation of the effects of flash fires must account for each of these features. This section discusses simple models for flame propagation through a dispersed gas cloud, including examples of simple modelling given in the literature and proposals for simple modelling based on the review of Sections 4.1 to 4.3.

7.2 Examples of Simple Flame Propagation Modelling

One of the earliest models for the calculation of heat radiation to personnel outside a dispersed heavy gas cloud was proposed by Raj & Emmons(1975). The model requires the input of the flame propagation velocity and this is calculated using an empirical correlation based on data from a number of experiments involving spills of LNG or LPG. As discussed in Section 4.3, this correlation assumes that the flame propagation velocity through the cloud is proportional to the ambient wind velocity. Although the correlation appears to provide satisfactory predictions, it does not explicitly model dispersion effects such as ground roughness, heat transfer to the cloud and turbulence induced by the mode of release. Furthermore, being an empirical model, it is limited to ground-lying flammable vapour clouds for which it was developed and has no relevance to high momentum jet releases. It is only applicable to the diffusive burning stage of the cloud fire and therefore cannot be used in modelling pre-mixed flame propagation.

Wheatley & Webber(1984) also discuss flame propagation through heavy gas clouds with the aim of determining the likelihood of a vapour cloud explosion. Therefore the diffusion burning stage, which is limited by the rate of mixing and produces flame speeds of less than 10m/s, is not considered and a simple model for the turbulent pre-mixed flame propagation rate is developed. In order to calculate the flame speed, U_f, though the cloud, it is necessary to calculate the turbulent burning velocity and make assumptions regarding the effect of expansion of products behind the flame front. Wheatley & Webber(1984) assume that all the products of combustion are vented vertically from the gas cloud and therefore the flame speed is equal to the turbulent burning velocity. The following model is proposed for the turbulent burning velocity:

$$U_f = U_b = U_L + \alpha \ U_w$$

The effect of turbulence is modelled through the use of the final term. Thus it is assumed that the effect of turbulence is proportional to the cloud speed over the ground. The constant of proportionality, α, depends on ground roughness and is approximately equal to 1 for long grass and neutral stability. Therefore, the model is similar to the Raj & Emmons(1975) flame propagation model but with the flame speed being approximately equal to the wind speed, compared with approximately double the wind speed in Raj & Emmons(1975) (Note also that one predicts premixed and the other diffusive burning velocities). The model represents progress from that of Raj & Emmons(1975) in that dispersion effects of the cloud, such as surface roughness, can be accounted for.

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Wheatley & Martin[1990] extend the work of Wheatley & Webber[1984] by considering the effects of flame acceleration due to obstacles within the flammable gas cloud. The flame propagation model is as given by Wheatley & Martin[1990] except that the constant of proportionality is now a function of the obstruction-induced turbulence, and the wind velocity is replaced by the flow speed ahead of the flame. Wheatley & Martin[1990] also compare their flame speed model with alternative combustion models that are capable of coping with deviation from linearity of the burning rate at high turbulence intensities. They show that, at low levels of turbulence, their model is similar to the Abdel-Gayed & Bradley[1982] model as described in Section 4.2.3.

7.3 Proposals for Flame Propagation Modelling.

Review of Sections 2.2, 2.3 and 4.1 to 4.3 suggest that the following effects require consideration within a model for flame propagation:

1) Expansion of burnt gases
2) Turbulence within the cloud, resulting from atmospheric turbulence and ground and initial release effects.
3) Intermittency of concentration within the dispersed cloud
4) Connectivity of concentration and ignited regions of the cloud.
5) Fuel type.

In addition, the mode of combustion has a significant effect on the flame propagation speed and also changes the method of calculation. Diffusion flames are controlled by the rate of air entrainment to the fire due to buoyancy or turbulence effects whereas pre-mixed flames do not have this constraint. Therefore, possible models for premixed and diffusion flames are considered separately.

7.3.1 Premixed Flame Propagation

<u>Expansion of burnt gases</u> The first simplifying assumption that can be used in the modelling of premixed flame propagation is that the flame speed is approximately equal to the turbulent burning velocity. This assumption is used by Wheatley & Webber[1984] and is derived from observations of flash fire experiments and turbulent jet fire experiments where the combustion products appear to be vented normal to the flame direction, predominantly in the vertical direction due to buoyancy. Furthermore, the flame is seen to burn back to the original release point and not beyond it, which suggests that the unburnt gas is not pushed forward by expansion of burnt gas behind the flame front. Numerical studies by Taylor[1985] have calculated the flow field generated by the combustion of an elongated gas cloud which shows that venting tends to be almost completely lateral to the flame front. Experimental and theoretical analyses by Taylor[1985] back up this assumption by showing that vertical venting (and generally lack of confinement) reduces flame speeds significantly. Rodean & Hogan[1984] considers the effect of expansion of trapped burnt gases on the flame speed through a vapour cloud where ignition occurs within the flammable region and not at the edge. It is stated that the flame speed will tend to the turbulent burning velocity as the flame propagates away from the ignition point (where the effects of trapped combustion products may be important).

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Cloud turbulence. If it is assumed that the expansion of burnt gases does not propel the flame forwards then turbulence will be dominant in increasing flame speed above that of the laminar burning velocity of the fuel. The effect of turbulence already present in the cloud, before combustion occurs, can be seen to be significant; in turbulent jets, flame speeds of the order of 100m/s may be produced whereas in dense gas clouds turbulence may only produce flame speeds of the order of 10m/s. Turbulence in dense gas clouds is generated or suppressed via wind effects and interaction of the cloud with the ground, ie. boundary layer effects and reduction of turbulence due to slumping of the gas. As discussed in Section 4.2.2, models for turbulent flame propagation are dependent on the burning regime. The flame speeds for turbulent free jets are likely to be in the distributed regime whereas that of dense gas clouds are likely to be in either of the flamelet regimes. The choice between the range of turbulent flame correlations is discussed in Section 4.2.6. It should be noted that use of these correlations assumes that turbulence properties, such as turbulence intensity and integral and Gibson length scales will need to be predicted based on the review of relevant dispersion effects in Section 5.

Another input required to the turbulent flame speed model is the laminar burning velocity for the fuel. Variation of experimentally observed laminar burning velocity with equivalence ratio is described by Harris[(1983)], and Gottgens et al[(1992)] gives a model for calculating laminar burning velocities of fuel in lean concentrations. It should be noted that the effect of fuel type and equivalence ratio is not confined to its relationship with the laminar burning velocity but also is one of the parameters that determines the level of flame quenching at high turbulence intensities.

Concentration intermittency. The effects of intermittency of concentration within the gas cloud have not been considered in the simple models described in Section 4.4.1. However, local variations from the mean concentration are known to have a significant effect on the flame propagation as illustrated by experimental studies undertaken by Evans & Puttock[(1986)], Smith et al[(1986)] and Birch et al[(1989)] and discussed in Sections 4.1.3 and 6.4.1. It was found, in Birch et al[(1989)], that a critical surface existed for 'light-back' after ignition of the hydrocarbon cloud. Within the critical surface, the flame propagates back to the source whereas beyond the critical surface the flame pocket travels downstream until it is extinguished. This critical surface can be considered to be the surface at which the downstream gas velocity is equal to the upstream flame propagation velocity and is similar to the concept of lift-off of turbulent jets proposed by Kalgatghi[(1981)] and discussed in Section 4.3.2.

Consideration of the effect of intermittency on the turbulent flame speed could be accomplished using a probability density function (pdf) approach:

$$\overline{U_t} = \int_{LFL}^{UFL} p(c)\ U_t(c)\ dc$$

p(c) = pdf of concentration at a fixed location in the jet.

The turbulent burning velocity, U_t, is dependent on both the concentration of the mixture and the turbulence at the location of interest. The effect of mixture concentration on U_t is generally modelled via its effect on the laminar burning velocity (see Section 4.2.1). Note that the above equation assumes that the mixture

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concentration is independent of the turbulence intensity within the gas cloud, which is unlikely to be true. Thus a joint probability density function incorporating variables describing both the concentration and the effect of turbulence may be necessary.

A probability density function to model the intermittency of concentration within a dispersed jet has been used by Smith et al(1986), which calculated flammability factors (see Section 6.4.1) along the axis of hydrocarbon gas jets assuming a Gaussian pdf for concentration as illustrated in Figure 7.1a. Note that Birch et al(1989) discussed likely forms of concentration pdfs for locations in a natural gas jet away from the axis (see Section 6.4.1). It was thought that the pdfs would consist of two peaks, one being at zero concentration and another at a higher concentration due to a turbulence contribution as illustrated in Figure 7.1b. Therefore the applicability of pdfs to flame propagation within a dispersed cloud will depend on the availability of concentration measurements and predictions with respect to position throughout the cloud. Variations can be expected radially from the jet axis for turbulent jets and vertically for slumping heavy gas releases. It should be noted that the variations may exist for mean concentration as well as intermittency, causing the flame surface to deviate from the planar surface normally assumed.

A further assumption implicit in the above discussion is that the turbulence in the gas cloud is induced by atmospheric and release conditions alone. Thus it is assumed that the flame front does not induce turbulence in the unburnt gas ahead of it. This assumption will break down in the presence of confinement where turbulence is induced as the unburnt gas is pushed past obstacles in the flame path. However, for unconfined gas clouds, the assumption would seem to be reasonable. Peters(1986) notes a further weakness of this assumption, stating that experiments on turbulent jets at blow-off have shown that velocity fluctuations produced by quenching are of the same order as those produced by jet turbulence.

The simplest method of applying the mean turbulent burning velocity to flame propagation within the cloud is to assume that the flame moves perpendicular to the downstream flow of the cloud. Thus the flame velocity with respect to the release position, U, can be calculated as the difference between the mean flame propagation velocity and the downstream gas velocity. This is illustrated in Figure 7.2.

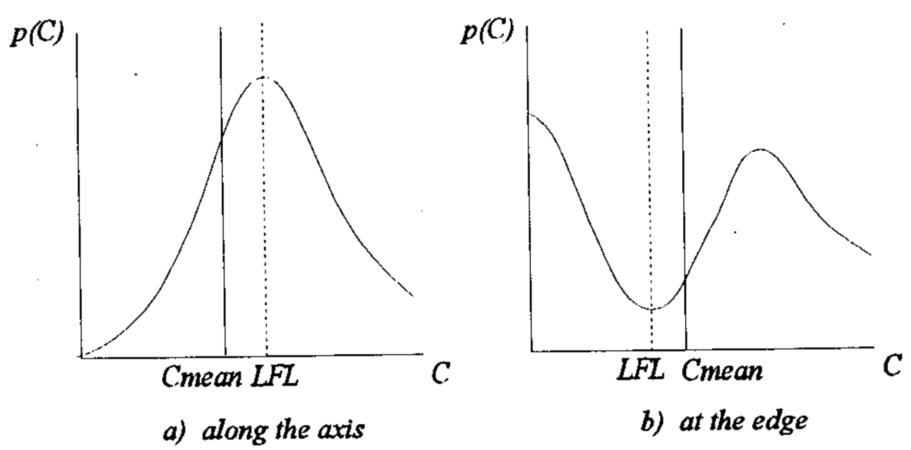

Figure 7.1 Concentration pdfs in the flammable region of a hydrocarbon jet

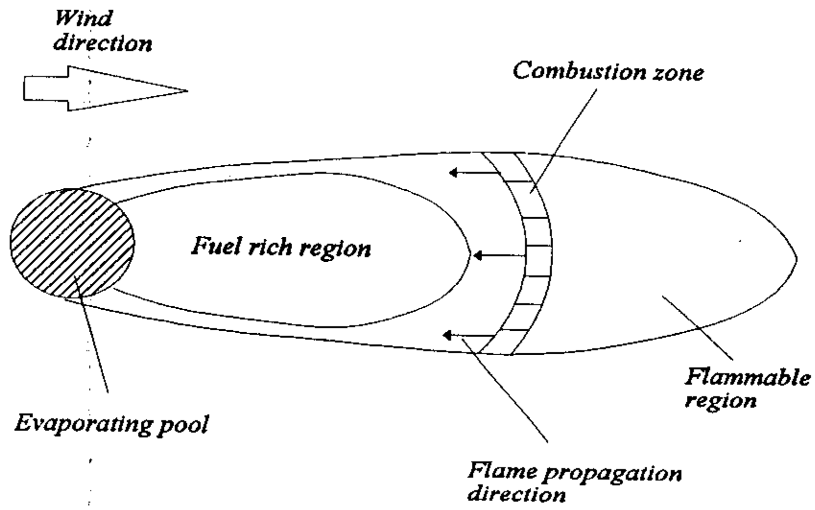

Figure 7.2 Assumed flame propagation path through a dispersed gas cloud

Concentration connectivity. The above simplification ignores the connectivity of the dispersed gas. The effect of connectivity on the flame speed is illustrated in Figure 7.3 which shows how patches of non-flammable gas effectively increase the travel distance of a flame front through the gas cloud. Note that the patches may result from gas concentrations below or above the flammable range or from high turbulence intensity causing extinction. As discussed in Section 4.3, percolation theory has been applied, by Peters(1986), to modelling the lack of connectivity due to local flamelet extinction near the nozzles of turbulent hydrocarbon jets. This enables successful prediction of lift-off heights. However, the difficulty in modelling the effect of connectivity on turbulent flame propagation is more likely to come from lack of experimental data describing connectivity rather than the mathematical techniques used to analyse it.

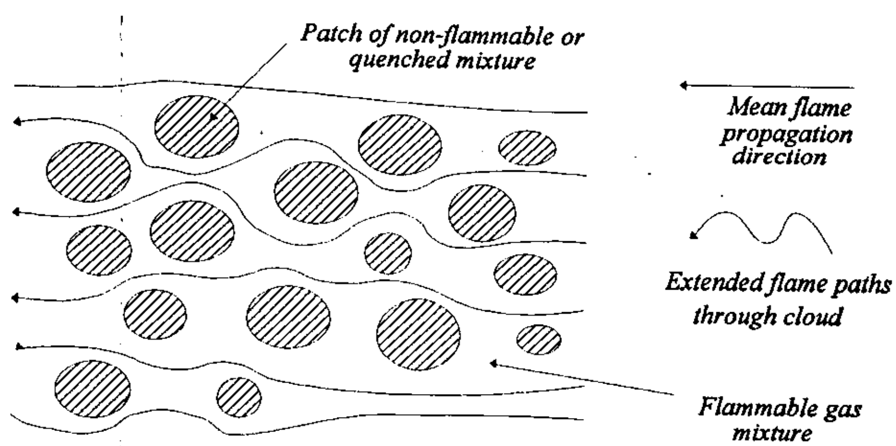

Figure 7.3 Effect of connectivity of gas concentration on the flame path through a gas mixture

The experimental studies conducted by Birch et al[1989] suggest that the connectivity of the release is not important. At locations where the intermittent gas concentration is capable of supporting a mean flame speed greater than the gas velocity, the connectivity of the gas will not be sparse enough to isolate the flame front from the release point. This is partly due to the lateral spread of the flame at ignition producing a large flame front area for propagation. Connectivity can be assumed to affect the probability of flame propagation occurring rather than the rate of flame propagation if it does occur.

7.3.2 Non-Premixed Flame Propagation

The rate of flame propagation in the diffusion stage of the flash fire is dependent on the rate of air entrainment into the fire. The air entrainment may be due to buoyancy effects but is more likely to be due to turbulent mixing as a result of to release momentum or the effects of wind. The strong dependence of flame speed on wind speed, proposed by Raj & Emmons[1975] confirms this assumption. It may be feasible to model the diffusion flame propagation in a dispersed cloud using, for example, flamelet techniques, provided that predictions for entrainment could be made. Cook[1990] uses a similar approach for the modelling of turbulent jet diffusion flames within an integral model framework.

In Section 3.5, it is shown that sensitivity of risk to flash fire modelling is more dependent on escalation to other fire or explosion events rather than to fatalities caused by external radiation from the flash fire itself. The calculation of the diffusion flame speed will affect the external radiation generated but will have little effect on escalation. Therefore it may be sufficient to assume that the flame speed in the diffusion regime follows that in the premixed regime. This assumption is backed up by observations by Raj[1977] of the burning of spills of LNG or LPG where the flame front propagated through the cloud with a blue premixed flame at the top accompanied by a yellow diffusion flame below. Cowley & Johnson[1991] suggests that the premixed flame propagation is unsteady with the premixed flame racing ahead of the diffusion flame when there is sufficient premixed gas above the diffusion flame. The assumption that the premixed flame provides an ignition source for the diffusive flame is implicit in the calculation method for lift-off heights produced by Kalghatgi[1981] and others.

The above discussion assumes that the boundary between the diffusion and premixed stages of the flame is distinct. However, this assumption may be incorrect due to the effects of both gradual changes in mean concentration (between the stoichiometric concentration and the rich limit) and intermittent variations in local concentration. This might suggest that the 'premixed region' will burn as pockets of diffusion flamelets rather than as a truly premixed flame. Studies on partially premixed diffusion flames have been conducted by various authors for a range of flow configurations (Peters[1986]) and these may warrant further investigation.

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8. CONCLUSIONS

8.1 Flash Fire Incidents

Whilst it is clear that a number of flash fire incidents have taken place, conditions under which they were initiated are not always very well defined. The transient nature of the phenomenon makes it more difficult to determine the exact sequence of events, which in turn has led to a lack of data from such incidents.

It should also be noted that the immediate effects of flash fires may be relatively limited compared with those from vapour cloud explosions (VCEs). Far more emphasis has therefore been placed on obtaining data from incidents in which explosive overpressures have been observed. This has tended to exacerbate the lack of flash fire incident data.

8.2 Current Modelling of Flash Fire Consequences

The most frequently used model for determining the consequences of flash fires uses dispersion modelling to determine the LFL or ½LFL contour, then makes an assumption concerning the percentage of fatalities within that area (usually 100%). Some slight variants on this method have been produced which consider additional zones in which, for example, only 50% fatalities are expected. Such models have been shown to be generally adequate for estimation of immediate fatalities, but cannot be used for the determination of burn-back characteristics and hence prediction of escalation. Whilst there are only small differences between the flash fire models themselves, their dependence upon gas dispersion modelling makes the overall results susceptible to the variability which currently exists within that area.

In addition to these simple models, there are methods which have been developed to take account of the movement of the flame through the fuel-rich part of a gas cloud, in which a diffusion flame is present. Flame height and width correlations are also used to enable thermal radiation effects to be determined. Although such models have not been used extensively in risk assessments, they have been used to demonstrate that hazardous effects do not extend much beyond the edge of the cloud and hence justify the use of simpler models.

8.3 Current Modelling of Flash Fire Risks

In line with the general philosophy of most risk assessments, conservative assumptions are normally used when including flash fire effects. For example, it is assumed that a dispersing cloud will reach its fullest extent before igniting, ignition will take place at the centre of the cloud and that the whole cloud will be involved with the fire sufficiently rapidly that no escape is possible. A greater awareness of the location of potential ignition sources could therefore enable more realistic risk estimates to be made which include the possibility that only part of the maximum cloud size is involved.

The lack of currently available models which include flame propagation effects means that escalation probability is almost always overestimated. Improved modelling in this area for example, could identify cases where burn-back does not occur, or where it is sufficiently delayed that some mitigating action is possible. Such modelling would also allow a more realistic approach to be taken to the possibility of escape in the event of a slowly moving flame-front.

8.4 Flame Propagation Modelling

Currently, simple models of flame propagation have been used for the region of a dispersed gas cloud in which the concentration exceeds stoichiometric. These models are empirical correlations relating flame speed to wind velocity and are applicable only to dense gas LNG or LPG releases for a limited range of release conditions.

Extensive experimental and theoretical studies have been completed for the purpose of estimating flame speeds in turbulent homogenous mixtures of flammable gas. Small-scale data shows that turbulence length scale and turbulence intensity play an important part in the interaction between flame and turbulence. Section 4.4.3 discusses the application of this work to the study of flame propagation through the premixed regions of a dispersed hydrocarbon release. In particular, consideration has been given to the intermittency and connectivity of concentration within the gas cloud and its effect on the flame propagation rate.

8.5 Experimental Data

A number of large scale trials have been conducted which provide insight into the rate of flame propagation through dispersed gas clouds, as discussed in Section 6. Both the Shell Maplin Sands (1980) and the LLNL Coyote (1980) series trials provide extensive measurements of flame propagation velocities and flame paths through heavy gas LNG and LPG clouds. Further studies by British Gas, Shell and others have considered the effects of the concentration intermittency on the ignitability of gas clouds which result from both turbulent jets and evaporation of liquefied gas spills.

This data would be sufficient for an initial assessment of any proposed flame propagation model providing suitable models for gas concentration intermittency and cloud turbulence levels were available, for example those discussed in Section 5.4.

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