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Ignition probability of flammable gases

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Ignition probability of flammable gases

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The calculation of the ignition probability of flammable gas clouds is a key step in the assessment of risk for installations where flammable liquids or gases are stored. The Health and Safety Executive currently use simple models, such as that contained within Flammables RISKAT (Clay et al, 1988), to calculate ignition probability. These simple models tend to assume that ignition probability is a function of release rate (or flammable gas cloud size) alone and tend not to consider location, density or types of individual ignition sources, although the HSE model does account for variation of ignition probability for releases dispersing over different land use types.

A review of data and methodologies relevant to the ignition of flammable gases has been undertaken with the primary objective of developing a model or methodology which will put the estimation of probability of ignition on a sounder footing than current, simple methods allow. The review confirmed that current modelling of ignition tends to be based on extrapolation of limited incident data or, in many cases, on the judgement of those conducting the safety assessment.

A framework for calculating ignition probability has been developed. The approach followed is to model the distribution of likely ignition sources in urban, rural and industrial locations and to calculate ignition probability by considering whether the flammable gas cloud will reach these sources. This model framework accounts for the different characteristics of ignition sources (their area density, and whether they are intermittent or continuous) and includes effects such as gas ingress into buildings. The nature of ignition sources and the effects of release location and type are considered.

A preliminary implementation of the model is used to illustrate the dependency of ignition probability on release mode (instantaneous or continuous), flammable cloud size and land use type, including the effect of mitigation measures, such as the control of ignition sources in the vicinity of the release. The model is then used to test the sensitivity of ignition probability, and thus risk calculations, to variations in the properties of ignition sources (eg intermittency and area density).

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1. INTRODUCTION

1.1 Background

The estimation of probability of ignition is a key step in the assessment of risk for installations where flammable liquids or gases are stored. The Health and Safety Executive currently use simple models, such as that contained within Flammables RISKAT (Clay et al, 1988), to calculate ignition probability. These simple models tend to assume that ignition probability is a function of release rate (or flammable gas cloud size) alone and do not consider location, density or type of ignition source.

The primary objective of this study is to develop a model or methodology which will put the estimation of probability of ignition on a sounder footing than current, simple methods allow. The model will consider the nature of ignition sources and the effects of release location and type and mitigation measures, such as the control of ignition sources in the vicinity of the release.

The results of the first phase of the study are described in this report. The first phase comprises a review of current ignition probability modelling and data on ignition sources and fire incidents. Based on this review, a framework for an ignition probability model is developed. The objectives and scope of work for the first phase are given below.

1.2 Objectives and scope of work

1.2.1 Objectives

The objective for the research programme is to develop a model, or methodology, for the estimation of the probability of ignition of flammable gas clouds, providing a more rigorous approach than current, simple methods allow. The intermediate objective of the first phase of the study is to provide a review of current methodologies and data and to define a framework for an improved ignition probability model. The study considers the sensitivity of ignition probability to the nature of the ignition source, the location and density of the ignition sources with respect to the release, and the nature of the release itself (for example, effect of fuel type and concentration).

1.2.2 Scope of work

The full scope of work for the initial phase of the study is given below.

i. *Identification of key modelling issues.* The key factors that may influence the ignition probability of flammable gases are identified in order to clarify the scope of the review.

ii. *Review of methodologies and data.* Current methodologies for the estimation of ignition are reviewed. Incident and experimental data relating to the ignition of flammable gases are collated.

iii. *Specification of model framework.* A proposed framework for an ignition probability model or methodology is defined.

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1.3 Methodology

Identification of key modelling issues

In order to clarify the scope of the first phase of the study, the key factors that may influence the ignition of flammable gases are identified.

Nature of ignition source:
- continuous or intermittent;
- strength;
- design (for example, intrinsically safe);
- type (for example, hot work, flare, electrical faults, static etc.);
- location (onsite or offsite);
- density of sources per unit area of land.

Release location:
- enclosed or open;
- distance to ignition sources (delayed or immediate ignition).

Release type:
- fuel type (minimum ignition energy);
- concentration of gas release (flammable limits, mean and intermittent);
- self-generation of ignition (for example, static or mechanical sparks).

Literature search

A formal literature search has been undertaken to identify appropriate information relating to the key features of the ignition of flammable gases identified above.

Review of current methodologies

Current methodologies for the prediction of the probability of ignition of flammable gases are reviewed. These methodologies include that used in Flammables RISKAT, and simple models based upon release rate only, such as those given by Cox et al (1990).

Data review

There is a reasonable amount of data available relating to characteristics of ignition sources and the effects of release type and location. These are reviewed in order to ascertain their value in the development of an ignition model.

For example, Jeffreys et al (1982) attempted to develop a database for ignition sources of LNG vapour clouds in urban areas. Cox et al (1990) discuss the limited nature of available incident data but have produced analyses of ignition source types for various industry sectors. Ignition data from the offshore sector, for example as given by Forsth (1983), is examined and its relevance to onshore scenarios, where off-site ignition must be considered, is assessed.

Laboratory data, such as that described by Gibbs (1991), is used to define the characteristics and energies of different types of ignition sources including flame,

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spark, arc, hot gas, impact and thermal radiation. Guidance on types of electrical equipment and their potential to cause ignition is given in hazardous area classification codes such as BS 5345 1976 Pt 1&2.

Sensitivity of risk assessment to modelling

Assessment is made of the relative importance of the features of the ignition of flammable gases with respect to risk assessment modelling. Consideration is given to the likely differences in risk assessment conclusions that may result from using a model which is more advanced than current simple models.

Specification of model/methodology framework

A proposed framework for an ignition probability model or methodology is defined, based upon the results of the tasks described above. Consideration is given to how the various factors which influence ignition can be incorporated into a model which is capable of being implemented into risk assessment programs such as Flammables RISKAT.

1.4 Report outline

The report presents the full results of the first phase of the study and covers each of the items given in the methodology outlined in Section 1.3. The report contents are outlined below.

Section 2 discusses the physical processes involved in the ignition of a flammable gas mixture and summarises the range of ignition sources that can be found in industrial sites and urban and rural areas.

Section 3 summarises data on ignition which is of value in developing an ignition probability model. Thus it considers the distribution and properties of ignition sources and identifies relevant statistical studies on fire incidents.

Section 4 reviews current modelling of ignition of flammable gases and compares a range of simple models presently used to determine ignition probability.

Section 5 presents the framework for the proposed ignition probability model. It discusses the information required for its eventual calibration and details the statistical techniques used in its development. The assembly of the model and its implementation into a risk assessment program (or methodology) is outlined and its limitations are discussed.

Section 6 gives the results of a sensitivity study using a preliminary implementation of the ignition probability model. The sensitivity of ignition probability, and thus risk calculations, to variations in the properties of ignition sources is tested. The dependency of ignition probability on release mode (instantaneous or continuous), flammable gas cloud size and land use type is also illustrated.

Section 7 presents the conclusions of the study. It summarises the results of the review and discusses the value of using improved ignition probability modelling within risk assessment studies. It also outlines the range of information required for the development and calibration of the proposed model.

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2. PHENOMENOLOGY

2.1 Physics of ignition

2.1.1 General description

Ignition can be defined as the process whereby a material capable of reacting exothermically is brought to a state of rapid combustion (Williams, 1985). At atmospheric temperatures and pressures, flammable mixtures of hydrocarbons and air will not ignite unless a source of energy is provided. The source of energy could be heat, an electric spark, another chemical reaction or pressure. The external energy provided breaks the molecular bonds of the fuel and oxygen producing radicals. The fuel radicals then recombine with the oxygen radicals, releasing more energy. If this energy is sufficient to break further bonds then sustained ignition occurs. Although the theoretical amount of energy needed to break the bonds is known, predicting when ignition will occur under practical circumstances is fraught with difficulties. Experiments have found that apparently similar conditions sometimes produce ignition and sometimes do not and ignition is sensitive to the geometry of the experimental set-up (Laurendeau, 1982). Ignition has been found to be sensitive to temperature, fuel and oxygen concentrations, volume of flammable mixture, pressure, area and contact time of mixture with a heat source, geometry of mixture and surroundings and turbulence in the mixture.

Certain characteristics of fuel and oxidant mixtures can be defined and measured which give some indication of how "easily" or how "quickly" a particular mixture in a particular situation will ignite. Some of these characteristics are minimum volume, minimum energy, autoignition temperature and ignition lag time. For a particular mixture at a particular temperature and pressure there will be a minimum volume of flammable mixture 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. The auto-ignition temperature is defined as the lowest temperature to which an entire fuel and oxidant mixture must be raised before it spontaneously ignites (Powell, 1981). It is therefore highly dependent on volume, stoichiometry, pressure and the geometry of the gas mixture. The ignition lag time is the time taken for a flammable mixture in contact with a hot surface to ignite. It is therefore dependent on the heat transfer between the surface and the flammable mixture. These characteristics will be discussed further in the remainder of this section.

2.1.2 Ignition energy and activation energy

Ignition energy is less sensitive to experimental set-up than minimum ignition temperatures, which are highly dependent on factors such as the volume of flammable mixture raised to that temperature and the time it has been at that temperature. Therefore, ignition energy is usually the property used to characterise the ignitability of a gaseous fuel mixture.

Ignition energy can be measured for a particular fuel and oxygen or fuel and air mixture by finding the minimum energy required by an electrical spark to ignite the

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mixture (Lees, 1980). The ignition energy is dependent on the mixture temperature, pressure and composition and usually has a minimum when the mixture is close to or just below stoichiometry for a given set of conditions.

Williams (1985) argues that ignition will occur only if enough energy is added to the gas to heat a slab about as thick as a steadily propagating adiabatic laminar flame to the adiabatic flame temperature. The minimum ignition energy, H, is then related to the quenching distance, d, the average thermal conductivity, λ, the adiabatic flame temperature, T_∞, and the laminar burning speed, S_L by:

$$H = \frac{d^2\lambda(T_\infty - T_0)}{S_L} \qquad (2.1.)$$

where T_0 is the initial temperature. However, he notes that discrepancies between this equation and experiments exceed a factor of 2 or 3. For ignition between two parallel flat plates the quenching distance, d, is defined as the minimum plate separation for which flame propagation can be achieved. This is given by:

$$d = \frac{a\lambda}{c_p\rho_0 S_L} \qquad (2.2.)$$

where c_p is the average specific heat at constant pressure, ρ_0 is the density of the unburnt mixture and a is a constant which depends on geometry. For parallel flat plates, a is approximately 40.

Measurement of ignition energy may be affected by electrode design (pointed electrodes do not quench ignition as much as flanged electrodes), type of sparks (capacitive sparks are more effective in igniting gas mixtures than inductive sparks of the same energy), gas movement (tests are usually conducted using stagnant gas) and temperature and pressure. When measuring ignition energy, the electrode gap width must be set to a value greater than the quenching distance. If the gap width is too small then the energy released by the spark is partially absorbed by the electrodes, particularly for flanged designs, increasing the measured ignition energy. It should also be noted that, even under controlled experimental conditions, there may not be a sharp cut-off between energies that cause 100% probability of ignition and those which cause 0% probability of ignition. Thus, for example, in assessing spark ignition of propane-air mixtures, Ko et al (1991) choose to define the minimum ignition energy as that which causes 50% probability of ignition. As further discussed in Section 3.2.2, probabilities of as low as 10^{-7} ignitions/spark may be relevant to the design of intrinsically safe equipment.

Minimum ignition energies at atmospheric conditions taken from Lees (1980) and Medard (1989) for various hydrocarbons are given in Table 2.1. These are compared with those calculated from Equation (2.1.). The differences between the ignition energies given by Lees and Medard demonstrate the degree of variability between different experiments.

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Source	Minimum ignition energy (mJ)		
	Lees (1980)	Medard (1989)	Equation (2.1.)
Methane	0.29	0.47	0.23
Ethane	0.24	0.28	0.18
Propane	0.25	0.30	0.19
Butane	0.25		
Hexane	0.25		

Table 2.1 Minimum ignition energies taken from Lees (1980) and Medard(1989)

Methane has higher ignition energies than other alkanes as it contains only carbon-hydrogen bonds, which are stronger than carbon-carbon bonds and therefore require more energy to break. However, the addition of small amounts of higher alkanes to methane (such as occurs in natural gas) reduces the ignition energy disproportionately to the quantity of higher alkanes. This is because, where carbon-carbon bonds are present, even in small numbers, they break down at a lower energy. Then the heat release from the recombination of the higher alkanes can be sufficient to cause sustained ignition in the methane.

Westbrook (1978) performed an analytical study of the shock tube ignition of mixtures of methane and ethane. Although the study is largely concerned with detonation, overall activation energies are calculated. The overall activation energy is the energy required per mole of fuel oxidant mixture for a reaction to take place. The minimum ignition energy is therefore related to the activation energy via the minimum number of moles of mixture which are required to be given the activation energy for ignition to occur. Westbrook (1978) showed that a stoichiometric mixture of 80 % methane and 20 % ethane in fact has an overall activation energy less than that of both methane and ethane. The results from this study are shown in Figure 2.1.

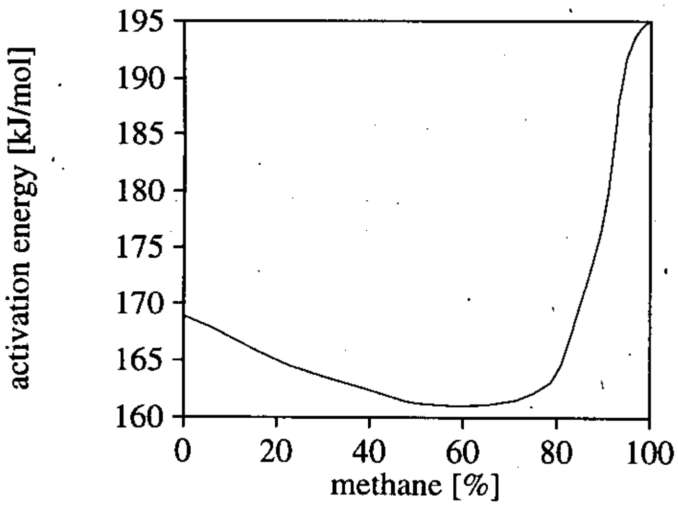

Figure 2.1 Effective overall activation energy for stoichiometric mixtures of methane and ethane taken from Westbrook (1978)

Ignition energy is highly dependent on stoichiometry (i.e. methane concentration in air) as shown in Figure 2.2, which is given by Lees (1980), for a methane/air mixture. The form of the variation could also be derived from Equation (2.1.).

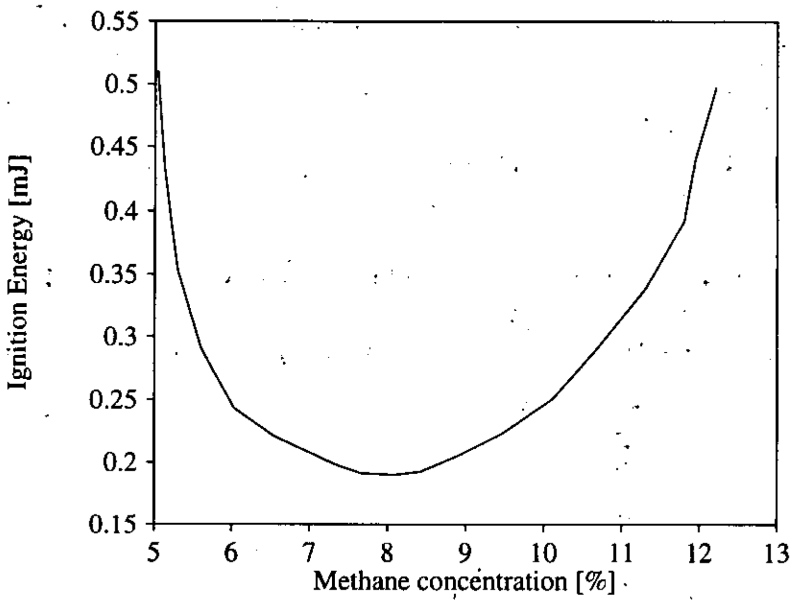

Figure 2.2 Effect of mixture composition on electrical ignition energy for a methane/air mixture, taken from Lees (1980)

2.1.3 Auto-ignition and the effect of volume

The auto-ignition temperature (or minimum ignition temperature) is defined as the lowest temperature to which an entire fuel and oxidant mixture must be raised before it (eventually) spontaneously ignites (Powell, 1981). The standard method for measuring this temperature involves uniformly heating the mixture in a 200ml flask. Results from this method for the first ten alkanes are shown in Table 2.2 as given by Lees (1980).

Fuel	A.I.T. (K)
Methane	810
Ethane	788
Propane	739
Butane	678
Pentane	531
Hexane	496
Heptane	496
Octane	493
Nonane	479
Decane	481

Table 2.2 Auto-ignition temperatures taken from Lees (1980)

However, it has been shown (Lewis, 1980) that this minimum temperature is strongly dependent on the volume of gas air mixture, as illustrated in Table 2.3.

Fuel	Standard AIT in 200 ml flask (K)	Spherical volume of 10 mm radius	Spherical volume of 1 m radius	Spherical volume of 2 m radius
Propane	743	836	624	605
Butane	638.	787	496	480
Pentane	558	612	459	449
Heptane	488	558	416	406

Table 2.3 Dependence of auto-ignition temperature on volume from Lewis (1980)

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Lewis (1980) suggested that the auto-ignition temperature, T, is related to the equivalent radius, R_0, by the equation:

$$\ln\left(\frac{T^2}{R_0}\right) + A = -\frac{B}{T-288} \tag{2.3.}$$

where A and B are constants depending on the fuel type. For propane, based on the values in Table 2.3, A is approximately -26 and B is 4383. Then the relationship between auto-ignition temperature and equivalent radius is as shown in Figure 2.3.

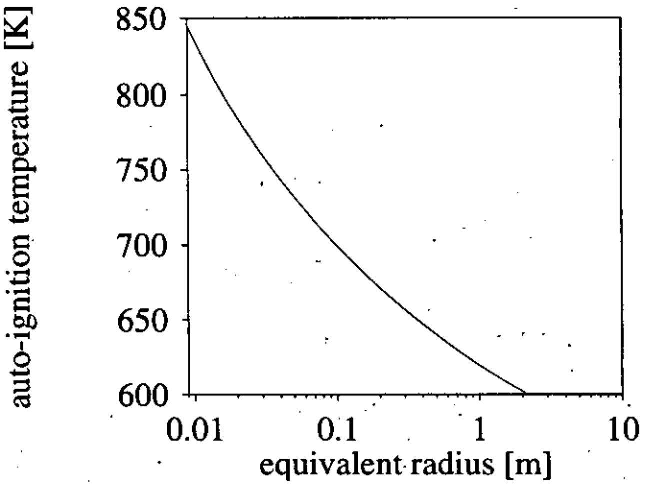

Figure 2.3 Effect of volume on auto-ignition temperature for propane, from Lewis (1980)

2.1.4 Ignition by hot surfaces and hot particles and ignition lag time

Determination of the temperature of a particle or surface required to ignite a flammable gas has not yet been achieved accurately. Attempts at this have been made as far back as the mid 1930's, when Silver (1937) made a study of ignition of gaseous mixtures by hot particles. Many experimental studies on ignition by hot particles and hot surfaces have been made since, most of which are reviewed by Laurendeau (1982) and Powell (1981). These show that the surface temperatures required for ignition are highly dependent on particular experimental set-ups, but are always significantly higher than the auto-ignition temperature. Laurendeau (1982) suggested the following correlations for ignition from hot surfaces for stagnant conditions, free convection and forced convection:

$$\begin{aligned} &\text{stagnant} && P^2L^2 \propto e^{\frac{E}{RT}} \\ &\text{free convection} && P\sqrt{L} \propto e^{\frac{E}{RT}} \\ &\text{forced convection} && \frac{PL}{u} \propto e^{\frac{E}{RT}} \end{aligned} \tag{2.4.}$$

where P is the pressure, L is a characteristic length scale of the surface or particle, E is the activation energy of the mixture, R is the universal gas constant, T is the temperature of the wall and u is the relative velocity between the gas mixture and the hot surface or particle.

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For flow past a hot surface, the required surface temperature for ignition is also dependent on the turbulence of the flow. Since turbulent flow increases heat transfer to the gas, the probability of ignition will be increased for a given surface temperature. This is partly included in Equation (2.4.) for the forced convection equation through modification of the relative velocity between the surface and the gas.

Ignition lag time is defined as the time taken for a flammable mixture in contact with a hot surface to ignite. It is closely related to the temperature of a hot surface. For a given experiment, if the temperature of a surface is being varied, the ignition lag time will drop as the surface temperature rises. Kuchta (1985) gives the following relationship for ignition lag time, τ:

$$\tau P^{n} \propto e^{\frac{E}{RT}} \qquad (2.5.)$$

where T is the temperature of the gas and n is the order of the reaction of the gaseous fuel with air.

Laurendeau (1982) also relates hot surface temperature to ignition lag time and suggests the following relationship between lag time and hot surface temperature T:

$$\tau P \propto \frac{(T - T_a)^2}{T} e^{\frac{E}{RT}} \qquad (2.6.)$$

where T_a is the ambient gas temperature.

Both Kuchta (1985) and Laurendeau (1982) report that the constants of proportionality for Equations (2.5.) and (2.6.) vary with hot surface temperature and experimental set-up. Thus these equations are of limited use for the prediction of ignition in practical plant situations.

2.1.5 Ignition due to electrical equipment and electrostatic discharge

Kuchta (1985) identifies three methods by which electricity can present an ignition source. These are thermal, due to the heating of wires carrying electricity, low voltage inductive break sparks and high voltage electrostatic capacitance sparks.

When a current, I, passes along a conducting material with resistance R, the rate of energy generation in the form of heat is given by I^2R. This energy will heat up the conducting material and the ambient atmosphere and thus the probability of ignition due to this source is now a problem of hot surface ignition, discussed in Section 2.1.4, and heat transfer.

When an electric circuit with negligible capacitance is broken, a low voltage, inductive break spark is produced. This has energy $E = \frac{1}{2} L I^2$ where L is the inductance of the circuit and I is the current. This energy can now be compared with the minimum ignition energy of its surroundings.

A high voltage electrostatic capacitance spark can be created by two objects with opposite charge coming close together and the medium between them breaking down, letting a spark pass between the objects. The energy of this spark is given by

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$E = \frac{1}{2} C V^2$ where V is the voltage difference between the two objects and C is the capacitance.

A comprehensive review on the physics of electrostatic ignition is given by Dean et al (1992). Charging processes of solids and liquids are described and a method of determining whether a charged object will discharge through a gaseous medium (generating a high voltage electrostatic spark) is given. The energy of this spark can then be determined and hence it can be compared with the minimum ignition energy of the gas mixture to estimate the likelihood of ignition.

Dean et al (1992) describe the process by which charge is generated whenever two dissimilar materials in contact are separated. Charges can be retained on one or both of the materials. Thus charges can be generated by rubbing, pouring, mixing, pumping or filtering. Plants handling powders, such as silos, represent a hazard as the powder particles rub against each other exchanging charge. Typically, the smaller particles accumulate a negative charge and the larger particles a positive charge. Then, if the powder settles, the larger particles will fall faster and charge separation occurs. Hence a spark can be generated between the top and bottom of the powder. Dean et al (1992) give charge densities generated by various plant operations on powders. The charge in a system, Q, can be calculated if the charge per unit time entering the system, I, and the effective relaxation time, τ, are known by the balance equation:

$$\frac{dQ}{dt} = I - \frac{Q}{\tau} \tag{2.7.}$$

The value given by Dean et al (1992) for the requirement of field breakdown in air is 3×10^6 V/m. However, this is sensitive to the angularity of surfaces, temperature, pressure, separation distances and humidity.

2.1.6 Further ignition processes

There are many other ignition processes in addition to those discussed above, including compression and shock waves, and electromagnetic radiation. Ignition may also be enhanced by catalysts and open flames (due to the supply of radicals).

Open flames produce hot gases, which can cause ignition by heating up cold flammable mixtures, and also contain free radicals which can break bonds in flammable mixtures causing sustained ignition. Flames and their reaction products are highly effective sources of ignition for flammable mixtures of gas.

Heat produced by mechanical impact or friction may also result in ignition. Eckhoff & Thomassen (1994) review the various events which may give rise to ignition by this process. Generally, the source of heat is either small hot particles released on impact or hot spots produced on one of the colliding bodies. In cases where alloys containing light metals such as aluminium or titanium are involved in impacts with rust, then thermite flashes may be produced due to exothermic transfer of oxygen from the rust to the alloy. It should be noted that impacts between chemically inert materials will not result in ignition, as the visible sparks produced are of insufficient temperature.

As has been noted in Section 2.1.4, ignition temperature is dependent on the ambient pressure. Thus compression waves, shock waves or other mechanisms which raise the pressure have a potential for causing ignition. Rises in pressure can also cause rises in

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temperature; thus enhancing the probability that a pressure rise will cause ignition. Compression has been discussed as a possible source of ignition in the Piper Alpha disaster (Richardson et al, 1990). However, compression ignition is unlikely to occur for releases into the atmosphere and is, therefore, not relevant to this study.

Eckhoff & Thomassen (1994) give electromagnetic radiation in the optical range as a possible source of ignition. For example, sunlight can cause ignition if focused onto a surface which will then become hot. A bottle can act as a lens for this purpose. High frequency electromagnetic waves produced by radio transmitters or industrial high frequency generators may produce ignition sources. Conductive equipment located in the radiation field may function as aerials, generating electric currents via electromagnetic induction. Thus thin wires may be heated up and sparks generated as conductive parts move apart. Also, energy produced by ultrasonic devices may be absorbed by objects which then heat up sufficiently to become potential sources of ignition.

2.2 Types of ignition source

2.2.1 General classification of ignition sources

There are many potential sources for ignition of flammable gas clouds. These can be divided into the theoretical types: heat, compression, chemical and electrical, as discussed in Section 2.1. Ignition due to heat includes autoignition, ignition by hot gases, surfaces, wires and mechanical sparks and thermal radiation. Ignition by open flames is due both to chemistry and heat. Other chemical sources include thermite reactions and catalysts. Exothermic reactions can lead to ignition due to heat, while catalysts may allow fuel and oxidant to react without so much initial available thermal energy. Electrical ignition is due to sparks or arcs and resistive heating of wires.

Sections 2.2.2 to 2.2.3 list typical ignition sources that may be encountered on industrial, urban and rural sites and Section 2.2.4 discusses the possibility of immediate ignition generated by the accident event.

2.2.2 Ignition sources on industrial sites

CCPS (1993) provide a comprehensive review of the most common ignition sources on industrial sites.

Ignition may occur due to flames, for example by gas fired equipment, burn pits, furnaces and flares. Hot work (welding, cutting and grinding) may also result in ignition due either to use of open flames (fuel-oxygen cutting equipment) or production of friction sparks by grinding.

Electrical equipment which is not manufactured to be intrinsically safe may produce sparks capable of causing ignition. Stray currents may flow along pipelines and other metal conductors and may be picked up from radiofrequency transmitters (as discussed in Section 2.1.6), from overhead high voltage lines and from cathodic protection systems.

An electrostatic charge is built up when two rough surfaces rub against each other and, when contact is lost, a spark can be produced. Such electrostatic charges can build up whenever pouring, mixing, pumping or filtering are carried out. Flammable dust clouds are particularly susceptible to this type of ignition as the dust particles rub against each other. Sources and the physics of this type of ignition are discussed by Dean et al (1992). Johnson (1980) has proposed that human electrostatic discharges are also capable of igniting hydrocarbon vapour mixtures.

Internal combustion engines comprise various ignition sources. Flammable vapour may enter the intake or exhaust lines and ignite and backfire. Electro-mechanical systems within vehicles, or loose electrical connections around engine blocks, may cause ignition.

Ignition may occur when two metal objects impact, due to production of hot spots by friction and surface compression, as well as production of frictional sparks. This impact can also form hot mechanical sparks due either simply to the force of the impact breaking the surface or, if the two surfaces are of different metals, these may react producing more heat than otherwise available. Impact of rusty iron with aluminium has been found to produce ignition far more frequently than impact with non-reacting pairs (Desy et al, 1975). This is due to the thermite reaction between iron oxide and aluminium, which produces iron and aluminium oxide and is exothermic.

2.2.3 Ignition sources in urban and rural areas

Many of the ignition sources in industrial areas may also be present in urban or rural areas. However, there are numerous other sources, mainly from traffic. Jeffreys et al (1982) performed a field survey of an LNG plant and an urban area. Greater Boston was chosen as the urban area, in which the most prevalent and potent ignition sources were found to be motor vehicles, smoking materials, traffic lights and open flames. Amongst other ignition sources identified are cigarette lighters, roof top unit heaters, gas fired heating equipment using outdoor air, camping, faulty electrical systems in cars, traffic lights, railways, clothes dryers and doorbells. The probability of ignition from each is estimated and the density given for Boston. This evidence is reviewed in Section 3.2.2. It is generally found that motor vehicles are found to cause ignition from back firing, catalytic converters, cigarette lighters and faulty wiring rather than from engine or exhaust heat.

Some ignition sources are to be found inside houses, such as ovens, heating and pilot lights. However a flammable cloud in an urban area may take some time to percolate into a closed building. This will cause a delay of ignition from indoor sources. Therefore, if there are sufficient outdoor sources, indoor ones may be insignificant. Alternatively, a cloud may have passed before the gas concentration can reach the lower flammability limit indoors. The ventilation rates required for flammable atmospheres to be present within buildings are discussed in Section 5.2.6 and Appendix B.

2.2.4 Immediate or incident generated ignition

Often, the cause of a release of a hydrocarbon will also be a strong ignition source. Therefore there may be a high conditional probability of immediate ignition, even if the probability of ignition at that point due to the sources listed above is low.

For example, if a metal container is broken by an impact, this impact event may be severe enough to cause a hot spot or frictional sparks, which could cause ignition. This is particularly true for releases from gas pipelines in rural areas where third party

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damage is often the cause of release as well as ignition Transportation incidents also include a high proportion of immediate ignition events.

Lightning is potentially a source of both release of fuel and its subsequent ignition in storage depots or industrial plants. It is unlikely to be a source of delayed ignition unless the release has been caused by a previous event during the same lightning storm. Runaway chemical reactions are another incident that may be a cause of both release and ignition of released material. Similarly, hot work ignition tends to be associated with both release and ignition, although in many cases the vapour ignited is that contained within drums or vessels which were expected to be inert.

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3. IGNITION DATA

3.1 Incident data

3.1.1 Ignition sources of previous accidents

Incident reports are of value in identifying the types of sources that have been known to cause ignition of flammable vapour clouds in the past, and a number of previous research studies have collated information on ignition sources. As well as identifying likely ignition sources, incident data has been used to estimate the proportion of ignitions that occur for different source types. A number of surveys have been conducted for the offshore industry which include information on ignition sources, for example by Forsth (1983). Currently, a joint industry project on ignition modelling is being run (DNV, 1996) with the aim of improving ignition probability models used within offshore quantified risk assessments. Although these surveys are valuable in providing general information on ignition of flammable gas clouds, the types of ignition source encountered in a controlled offshore environment bear little relation to those encountered onshore, especially where ignition occurs offsite. Therefore, the incident data discussed below relates to onshore incidents only.

Simmons (1974) collected information from 59 accidents involving spills of LPG and other flammable liquids in the open. The cause of the spill, ignition source (if known) and number of casualties is reported and the cloud area at ignition is estimated. The results of the study are summarised in Table 3.1, where it can be seen that, relative to other studies, the data includes a high proportion of sources which have resulted in immediate ignition. It should be noted that many of these immediate ignitions relate to transportation incidents and were due to collisions between vehicles or with storage vessels and pipelines.

Industrial		Non-Industrial	
Immediate	5	Immediate	7
Vehicles	5	Vehicles	6
Engine	1	Kitchens	6
Power house	1	Unknown inside buildings	6
Open flames	1	Restaurants	3
Boiler	1	Hot water heater	3
Furnace	1	Shops	2
Acetylene torch	1	Service station	1
Unknown	1	Electrical equipment	1
		Refuse burner	1
		Camp fire	1
		Kerosene switch lamp	1
		Unknown	1
Total	17	Total	39

Table 3.1 Ignition sources for accidents reported by Simmons (1974)

Cox et al (1990) have produced a study on ignition sources based on an analysis of a data bank of national incidents provided by the Health and Safety Executive. The study covers a one-year period from April 1987 to March 1988 and some of the results are summarised in Table 3.2. The analysis for the open and closed process plant given by Cox et al (1990), and repeated in Table 3.2, only includes incidents which relate to process plant and to situations where hazardous area classification appears

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applicable Thus the analysis represents only a small subset of the total available data, the total of 968 incidents covers a range of fuels, including solids and explosives, and offsite as well as onsite locations. It can also be seen that Cox et al (1990) have removed both hotwork and spontaneous ignition from the analysis. It was considered that, where hotwork appeared in the data, it was almost invariably the initiating event for the release as well as being the source of ignition. Spontaneous ignition covers runaway reactions, pyrophoric ignitions etc. which are not relevant to ignition by external sources.

Ignition source	Closed process plant		Open surface plant and activities		Total	
	No.	%	No.	%	No.	%
LPG fired equipment	2	2.3	2	1.4	24	2.5
Other flames	8	9.3	27	19.4	237	24.5
Hot surfaces	10	11.6	20	14.4	48	4.9
Friction	4	4.7	11	7.9	36	3.7
Electrical	8	9.3	29	21.0	70	7.2
Hot particles	3	3.5	-	-	20	2.1
Static electricity	6	7.0	10	7.2	19	2.0
Smoking	-	-	17	12.2	38	3.9
Autoignition	7	8.1	2	1.4	25	2.6
Other					5	0.5
Unknown	38	44.2	21	15.1	300	31.0
Spontaneous ignition					26	2.7
Hotwork					120	12.4
Total	86	100.0	139	100.0	968	100.0

Table 3.2 Survey of ignition sources by Cox et al (1990)

Crowl & Louvar (1990) present a list of sources considered to be those with the greatest probability of causing ignition, but also note that sources of ignition are too numerous to be individually identified. This list of sources is reproduced in Table 3.3. The data is for general fire accidents and, although the majority of these sources are still relevant to the ignition of flammable gases, the relative proportions of each are not applicable.

Ignition source	%
Electrical (wiring of motors)	23
Smoking	18
Friction (bearings or broken parts)	10
Overheated materials (abnormally high temperatures)	8
Hot surfaces (heat from boilers, lamps etc.)	7
Burner flames (improper use of torches etc.)	7
Combustion sparks (sparks and embers)	5
Spontaneous ignition (rubbish, etc.)	4
Cutting and welding (sparks, arcs, heat etc.)	4
Exposure (fires jumping into new areas)	3
Arson	3
Mechanical sparks (grinders, crushers etc.)	2
Molten substances (hot spills)	2
Chemical reactions (runaway reactions)	1
Static sparks	1
Lightning	1
Miscellaneous	1

Table 3.3 Ignition sources of major fires reported by Crowl & Louvar (1990)

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The information described above provides an indication of the key ignition source types that must be considered within an ignition probability model and the relative importance of each. However, this data requires careful interpretation in order to determine which sources are relevant to the ignition of large flammable gas clouds. For example, care is required in the use of data on ignition by static electricity, where static may have been blamed for ignition when more obvious sources were not found. Also, the number of unknown sources in the Cox et al (1990) data could suggest that many sources were either not reported, not identified or did not fit into the more typical ignition categories. These unknown sources may differ significantly from each other in property but still require consideration within a risk assessment as they comprise a high proportion of the total data.

3.1.2 Probability data derived from incident reports

Various authors have collated incident data in order to estimate the probability of ignition of flammable gas clouds. The estimates tend to be based on sparse accident data and usually give ignition probability for specific types of incident or quantity of flammables released. Note that the ignition probability data discussed below does not include values based on expert judgement; these are discussed in Section 4.1.

CCPS (1995) review data relating to the ignition of flammable liquids and gases within transportation incidents. They discuss studies by Rhoads (1978) and Croce (1982) which both suggest that there is an ignition probability of 0.24 for spills of flammable material during vehicle accidents. The Rhoads (1978) study covered a wide range of materials, whereas Croce (1982) considered only LPG vehicle incidents over a 10-year period, for which 12 out of 49 incidents resulted in ignition. It should be noted that both studies included immediate ignition and it was considered that immediate ignition was more significant for larger events, which tend to arise from accidents of higher energy.

As discussed in Section 3.1.1, Simmons (1974) collected information from 59 accidents involving spills of LPG and other flammable liquids in the open. As well as identifying types of ignition source, they developed a model for cumulative probability of ignition as a function of cloud area for LPG and LNG releases. Section 4.2 gives details of the model. It includes ‘immediate’ ignition, which was estimated by the authors to have a probability of approximately 0.5. This high value reflects the large proportion of transportation-related incidents included in the study and also the definition of immediate ignition, which included all ignitions occurring within an area of 30 m^2 around the leak source, only 2/3 of which were related to the initiating event.

Dahl et al (1983) give values for the probability of ignition of gas and oil blowouts, based on incident data for both offshore drilling rigs and production platforms. These values are summarised by Cox et al (1990) and repeated in Table 3.4 below.

Release phase	No. of blowouts	No. of ignitions	Probability of ignition
Gas	123	35	0.3
Oil	12	1	0.08

Table 3.4 Blowout ignition probability (Dahl et al, 1983)

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Blything & Reeves (1988) derive an ignition model and compare it against LPG incident data collected by LPGITA (now the LP Gas Association). An ignition probability of 0.11 was obtained from the LPGITA survey which covered 160 leaks over a 6½ year period. The average leak rate was approximately 0.2 kg/s, with a maximum observed rate of 1.3 kg/s.

Townsend & Fearnehough (1986) state that a review of world-wide failures suggests that the ignition probability for natural gas leaks from pipelines is approximately 0.5 for 'ruptures' and 0.1 for 'leaks'. However, no further detail is given regarding the source of the data. CCPS (1995) compare this data with other pipeline ignition data and this is repeated in Table 3.5. Care is required when comparing this data against that derived from industrial incidents as immediate ignition is included (which may be relatively high for pipeline releases where third party damage is common) and many of the pipeline releases may have occurred in rural areas.

Data source	Ignition probability	
World-wide, Townsend & Fearnehough (1986)	leaks	0.1
	ruptures	0.5
US Gas, Jones (1986)	ruptures	0.26
	all sizes	0.16
European Gas, European Gas Pipeline Incident Data Group (1988)	pinholes/cracks	0.02
	holes	0.03
	ruptures < 16 in.	0.05
	ruptures >= 16 in.	0.35
	all sizes	0.03

Table 3.5 Ignition probabilities for gas pipeline failures

The variation in values of ignition probability given by the various authors above reflects the wide range of data sources used in their derivation. The data may be based on offshore or onshore incidents, may be for transportation events or fixed sites and cover a wide range of release sizes. It would also appear that, even for well defined event categories, such as gas pipeline releases, the predicted probability of ignition may vary significantly between sources, possibly due to the sparse nature of ignition data, or else due to the effect of variations in land use between different countries.

It should further be noted that the use of historically based data does not allow consideration of improvements in equipment design (such as reduced use of electromechanical devices) or plant layout, on ignition probability. Mitigation, such as control of electrical ignition sources through hazardous area classification or use of more stringent work permit systems, may have an impact on the likelihood of flammable gas cloud ignition, especially in the near field.

3.2 Ignition source characterisation

3.2.1 Source definition

If a model is to be formulated which takes into account the characteristics of individual ignition sources within a flammable gas cloud, it is necessary to gather information on the properties and distribution of different sources in different land use areas. A large amount of research effort has been conducted in the area of ignition

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source characterisation and mainly consists of experiments to ascertain whether plant items are suitable for installation in potentially flammable atmospheres. Thus, for example, a large amount of work has been directed at the design of intrinsically safe electrical equipment. In addition, a study by Jeffreys et al (1982) has been identified which gives detailed information on the characteristics of typical ignition sources found in both industrial and urban areas.

The detailed data requirements for characterisation of an ignition source are given in Section 5.3.1 and include its ignition potential, activity and intermittency. Information is also required regarding the area density of different sources for a range of land use types. Sections 3.2.2 to 3.2.5 discuss the availability of data for characterisation of ignition sources.

3.2.2 Ignition potential of a source

'Ignition potential' is defined as the probability that the ignition source will ignite the cloud given that the source is active and enveloped by the flammable mixture. There are a number of stochastic effects which result in the ignition potential of a source being less that one. For example, a particular item of equipment may be enclosed in a casing, reducing the likelihood of a flammable atmosphere reaching it. Alternatively, the energy released by the source may not be sufficient to guarantee ignition, as discussed in Section 2.1.2.

For a large number of sources an ignition potential of unity can be assigned (i.e. certain ignition), reflecting the fact that these sources are always able to release energies significantly higher than the minimum ignition energies for flammable gases given in Section 2.1.2. Examples of these sources include open flames and furnaces. At the other end of the scale are items of equipment which are designed to be used within potentially flammable atmospheres. Even for these sources it can be argued that there is still a finite probability of ignition, although the ignition potential is unlikely to be significant enough for inclusion in a risk assessment model. For example, Cawley (1988) discusses the probabilistic nature of spark ignition in intrinsically safe circuits. For circuits representative of those which might be used in the design of monitoring equipment for gassy, underground mines, the probability of ignition (ignitions per spark) was of the order of 10^{-2} to 10^{-7}.

There is a large amount of research relating to the assessment of potential ignition sources, much of it discussed by authors such as Eckhoff and Thomassen (1994) and reviewed in Section 2.1. However, it should be noted that most of this research is concerned with defining whether sources are capable of causing ignition, rather than providing data on probability of ignition. Thus, although this research is useful for eliminating ignition sources from consideration within an ignition model, it is of limited value in quantifying the ignition potential of a particular source.

There are certain exceptions, for example various studies on the probability of ignition due to mechanical sparks. One such study is that completed by Komai et al (1994) who conducted drop tests, of light alloys onto rusted steel plates, to determine the likelihood of ignition of methane air mixtures by thermite flashes. They found that probability of ignition was related to drop height, sample weight, impact angle and alloy material composition, allowing improved design of industrial equipment to be used in potentially flammable atmospheres. Use of such data in an ignition

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probability model would require information on the type, location and likelihood of impact of materials likely to be found in typical industrial areas. Bearing in mind that ignition by thermite flashes represents a small fraction of potential mechanical spark ignition sources, it is unlikely to be practicable to use such data within an ignition probability model.

James et al (1987) present an analysis of the probabilistic factors involved in the radio frequency ignition of flammable gaseous mixtures. They suggest that their results can be used to argue a substantial reduction in the size of hazard zones around transmitters as predicted by current British Standards. They cite the example of a large crane in a methane handling plant about 3 km from a transmitter radiating 100 kW at 1 MHz where their methodology suggests a probability of ignition of order of 10^{-6}, compared to a worst case prediction of ignition probability of one. The value of this, or similar studies, in the production an ignition probability is likely to be limited to the elimination of insignificant ignition sources.

A more comprehensive study is that conducted by Jeffreys et al (1982), who identified over 150 potential ignition sources in urban and industrial areas. The urban ignition source data was based on a survey of the Boston area and the industrial data was based on an LNG facility. It should be noted that the land-use categories used by Jeffreys et al (1982) differ from those defined for the HSE Flammables RISKAT model (see Section 4.2.1), where 'industrial' corresponds to general industrial areas, rather than gas processing facilities, and 'urban' corresponds to residential areas. Tables 3.6 and 3.7 give characteristics for selected ignition sources which include, amongst other information, the estimated ignition potential for each source type. Experiments performed in a 7 % methane/air mixture were used to define the ignition potentials of questionable ignition sources. It was found that, under normal operation, electrical systems in cars were not an ignition source, although ignition was observed for loose starter wires and broken ignition wires. Traffic light relays, as found in the Boston area, were found to be a potential source of ignition if they had a switching energy of 600 W or more. Smouldering cigarettes were found not to cause ignition, although the process of lighting them with a match or cigarette lighter was found to be a strong source of ignition. A hot source such as a car cigar lighter did not cause ignition. It should be noted that these probabilities are fuel dependent and will be slightly higher for fuels such as propane, butane and natural gas than for methane, as the minimum ignition energies are lower.

It can be seen that, for many of the sources given in Tables 3.6 and 3.7, only a qualitative description of ignition potential is given. A semi-quantitative ranking of ignition sources is discussed in Section 3.2.5.

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Ignition sources	Ignition potential	Rate of activity (minutes)		Density (no. per km^2)
		on time	off time	
Outdoors in Boston				
Electromechanical flashing traffic lights	1	0.02	1	2 (f)
Non-flashing or solid state traffic lights	0	0.02	1	3 (f)
Cigarette	0	5	30	m
Cigarette lighter	1	5	30	m
Accidental fires	1	90 (if)	1 day	s
Decorative gas lights	1	if	0	14 (f)
Doorbell	1	i		d
Car electrical system	0.06	i		d
Diesel exhaust	m	c		d
Cars lorries and busses	m	f		d
Motorcycles and mopeds	m	f		s
Public telephones	m	i		m
Indoors in Boston				
Gas fired heaters	1	10	30	88
Gas heater pilot lights	1	c	0	23 (f)
Clothes dryer	1	45	1.5 days	d
Electric appliances	w	f		d
Electric switches	s	i		d
Televisions	w	f		d
Electric tools	s	f		d
Faulty wiring	s	c		s
Fireplaces	s	f		d
Hair dryers	m	if		d
Toasters	m	if		d
Office machinery	m	i		d
Lifts	m	f		m
Slide projectors	s	f		s
Pinball machines	s	f		s
Arcades	s	c		s

Key:

Ignition potential column	s	strong	> 0.5
	m	medium	0.05 - 0.5
	w	weak	< 0.05
Rate of activity column	c	continuous	
	f	frequent	6-12 hours a day
	if	infrequent	1-6 hours a day
	i	intermittent	
Density column	d	dense	> 2 /km^2
	m	medium	
	s	sparse	

Table 3.6 Selected results for urban sources from Jeffreys et al (1982)

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Ignition sources	Ignition potential	Rate of activity (minutes)		Density (no. per km^2)
		on time	off time	
Industrial				
Material handling equipment (e.g. conveyors & fork lift trucks)	m	f		s
Furnaces and boilers	s	f		m
Thermal processing of metals, glass and refractory materials	s	f		s
Coking plants	s	c		s
Incinerators	s	f		s
Refineries	s	c		s
Machine tools	s	f		s
Curing heaters and ovens	s	f		s
Electric motors and controls	s	f		m
Flares	s	c		s
Electrostatic precipitators	w	c		s
Food preparation	s	f		d
Hot ash disposal	s	f		d
Welding	m	if		s

Key: see Table 3.6

Table 3.7 Selected results for industrial sources from Jeffreys et al (1982)

3.2.3 Source activity and intermittency

Many ignition sources are only active for a very short duration, especially electrical items which cause ignition by producing sparks; they are intermittent sources. Other ignition sources are continuously active, for example pilot lights. Other sources can be characterised as semi-continuous, such as intentional or accidental fires in the open, which may occur once per day and last for an hour, say. Jeffreys et al (1982) estimated the active and inactive times of the sources they investigated and these are also given in Tables 3.6 and 3.7.

Further data on the activity of controlled ignition sources, such as electrical equipment designed for use within areas subjected to hazardous area classification or hot work controlled by work permit systems, may be available from operational manuals.

It should be noted that the activity of some ignition sources may vary during the day. This variation may be significant when conducting a risk assessment for a particular area, as the dispersion of a flammable cloud is usually subject to different conditions at night compared with those experienced during the day.

3.2.4 Source density

Although a detailed site survey is necessary to identify the density of all ignition sources, average values can be estimated for various land use types. Jeffreys et al (1982) performed a survey of Greater Boston and an LNG plant in order to determine the density of ignition sources in urban and industrial areas and some of the results of this survey have been presented in Tables 3.6 and 3.7. As is true for source activity, source density may vary between night and day, particularly for sources connected with vehicle operations.

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3.2.5 Ranking of ignition sources

As discussed above, the detailed quantification of the properties required to define all possible ignition sources in industrial, urban and rural areas is a major task. It may be more practicable to use a semi-quantitative approach in which ignition sources are ranked in terms of ignition potential. Once ranked, the ignition sources could be placed in bands of ignition potential. This is an approach used by Jeffreys et al (1982) who categorised the majority of sources which they identified as either strong (ignition potential greater than 0.5), medium (ignition potential between 0.5 and 0.05) or weak (ignition potential less than 0.05).

The process of ranking ignition sources would draw data from studies such as that of Jeffreys et al (1982) and from experimental studies concerned with the characterisation of specific ignition sources. From operational experience and current working practices, some sources are known to be highly probable ignition sources, for example, hot work is prohibited in areas where flammable atmospheres may occur and most forms of hotwork would be classified as either strong or medium sources. Other items of process equipment are known always to cause ignition, such as open flares, and warrant a further category of ignition potential, for example 'certain'. As discussed in Section 3.2.2, various experimental studies can be used to eliminate ignition sources from consideration within an ignition model, forming a further category for those items with 'negligible' ignition potential. For example, the work of James et al (1987) could be used to eliminate radio frequency sources from the ignition probability model. Furthermore, some ignition sources are only relevant to immediate ignition. For example, it is highly unlikely that lightning would be a source of ignition unless it was also the cause of the release of the flammable material.

Britton (1992) provides an example of the ranking of ignition sources based on a consideration of their available energy in relation to the minimum ignition energy required for various flammable gas, mist or dust clouds. This ranking is repeated in Table 3.8, which indicates which sources produce sufficient energy to be of particular significance to the ignition of flammable gases. It also illustrates how ignition potential is fuel, as well as source, dependent.

Table 3.9 illustrates how a ranking of ignition sources might be developed, based on experimental studies, current industrial practice and engineering judgement. It should be noted that, as well as ranking ignition sources by their potential, estimates of source density and activity are required for each individual source or source type and this could also be undertaken on a semi-quantitative basis.

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Ignition energy (mJ)	Explosive mixture	Examples of explosive gas and dust mixtures	Ignition source
100-1000	coarse dusts and mists, very insensitive gases	methylene chloride, ammonia	flames, chemical sources, large hot spots, propagating brushes
10-100	typical sub-200 mesh dusts, typical mists, insensitive gases	lycopodium	personnel spark limit, bulking brush limit
1-10	sensitive dusts, fine mists, some gases in air	acetone	brush limit
0.1-1	typical gases in air, very sensitive dusts, very fine mists	methane, methanol	mechanical sparks, stray current sparks, ungrounded conductors, small hot spots
0.01-0.1	sensitive gases, primary explosives, oxygen enriched air	ethylene, hydrogen	discharges from textiles, weak inductive coupling, weak radio-frequency pick-up

Table 3.8 Illustration of ignition energy ranges (from Britton, 1992)

Category	Examples of ignition sources	Ignition potential
Certain	pilot light open flare	$p = 1$
Strong	electric motors hot work	$p > 0.5$
Medium	vehicles faulty wiring	$0.5 > p > 0.05$
Weak	electrical appliances mechanical sparks	$p < 0.05$
Negligible	intrinsically safe equipment radio frequency sources	p = negligible

Table 3.9 Framework for ranking of ignition sources

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4. REVIEW OF CURRENT MODELLING

4.1 Current approach

Modelling of ignition probability tends to be based on either sparse incident data or expert estimates. Many quantified risk assessments have used expert estimates of ignition probability rather than historical data, as reviewed by both Cox et al (1990) and CCPS (1995).

The Canvey Island Report (HSE, 1981) used onsite ignition probabilities of 0.1 for areas with 'no' ignition sources, 0.2 for 'very few' ignition sources, 0.5 for 'few' ignition sources and 0.9 for 'many' ignition sources. Conditional probabilities were also given for delayed ignition over population areas (conditional on the cloud not having previously ignited). Thus 'edge/edge' ignition, where ignition occurs when the cloud edge reaches the edge of the population area, is assigned a conditional probability of 0.7. A conditional probability of 0.2 is assigned to 'central' ignition, where the cloud is over the population area, leaving a conditional probability of 0.1 for no ignition over the population area.

In a report on the transportation of dangerous goods by rail (HSC, 1991), the following ignition probabilities for LPG releases during rail incidents were used, based on both incident data (although it is noted that large release values were based on releases from static storage facilities) and engineering judgement.

Spill size	Immediate	Delayed	None
Small	0.1	0	0.9
Large	0.2	0.5	0.3

Table 4.1 Ignition probabilities for LPG transport by rail

Kletz (1977) argued that the probability of ignition increases with size of leak and is certainly greater than 0.1 for large leaks (10 ton or more) and may be as high as 0.5. Kletz also states that 1 in 10,000 small leaks in polyethylene plants ignites and that 1 in 30 small to major leaks on plants handling hydrogen and hydrocarbons at 250 bar ignites. Browning (1969) suggests that, for massive LPG leaks into areas with no obvious source of ignition, and explosion proof equipment, the probability of ignition is only 0.1.

Blything & Reeves (1988) suggested that 70% of 'large' LPG releases (where no pool was formed) would ignite, defining a large release as one which would travel approximately 60m before being diluted to below LFL. It was then assumed that ignition probability was proportional to distance travelled for other release sizes. Ignition probability was reduced by a factor of 10 for cases where the releases did not reach the nearest identifiable ignition source. As discussed in Section 3.1.2, this model was compared against LPGITA data and was found to underpredict by a factor of 10 for small releases, possibly due to non-consideration of temporary ignition sources.

It can be seen that there is a wide variation in the values of ignition probabilities given by the various authors quoted above and the use of such expert judgement requires considerable care. Many of the values are case specific and, while they may be reasonable estimates of ignition for certain plants or types of release, they may not be directly applicable to more general studies. Furthermore, interpretation of terms such as 'massive' or 'minor' is not straightforward. Section 4.2 discusses a selection of more generalised models for ignition probability. These models tend to be based on both historical data and expert judgement and relate ignition probability to mass release rate of flammable gas or to the cloud area.

4.2 Ignition probability models

4.2.1 Model overview

A number of simple correlations for ignition probability have been suggested based on historical data rather than site information. Three are reviewed here, two based on cloud area (Clay et al, 1988, Simmons, 1974) and one on release rate (Cox et al, 1990).

Simmons (1974) conducted a survey of 59 incidents of ignition of clouds of LNG or LPG resulting from accidental spills due to transportation. For these he estimated the size of the cloud when ignition occurred and fitted the probability of ignition as a function of cloud area to an error function. For incidents in which only the distance from the source of the ignition point, x, was reported, the cloud area, A, was estimated using the following correlation:

$$A = 0.175x^2 \qquad (4.8.)$$

Then the probability of ignition, inclusive of immediate and delayed, P(A), as a function of area is given by:

$$P(A) = \frac{1}{2}\left\{1 + \operatorname{erf}\left(\frac{\log_{10} A - 1.38021}{2.45318}\right)\right\} \qquad (4.9.)$$

where the area, A, is given in m^2.

The current method used by HSE in Flammables RISKAT (Clay et al, 1988) for delayed ignition is based on the assumption that a large release of LPG over industrial land has a probability of ignition of almost unity. The probability of ignition of a smaller cloud is then calculated in terms of the large release. Thus it is assumed that a large instantaneous release of 200 tonnes of LPG which has drifted downwind over industrial land in D5 weather conditions has a probability of ignition of 0.999999, i.e. $1\text{-}10^{-6}$. If this probability is denoted by P_f, then, for a cloud which has drifted a distance x downwind, the probability that it has ignited is:

$$P(A) = 1 - \left(1 - P_f\right)^{A/A_f} \qquad (4.10.)$$

where A is the cloud area and A_f is the area swept by the flammable cloud if it disperses to its full size. Within the RISKAT model, the ignition probability is calculated on a grid by grid basis. Thus for industrial land, the ignition probability per grid, P_I, is calculated as follows:

$$P_I = 1 - \left(1 - P_f\right)^{1/N_f} \qquad (4.11.)$$

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giving

$$P(A) = 1 - \left(1 - P_l\right)^N \qquad (4.12.)$$

where N is the number of grid squares encompassed by the release being modelled and N_f is the number of grid squares encompassed by the reference release of 200 tonnes of LPG. The ignition probability per grid is then scaled by 0.8 for urban land and 0.04 for rural land. Thus it should be noted that, for urban and rural land use types, the probability of ignition is dependent on the size of the grid, although the effect is small for grid sizes typically used in RISKAT (50m square). It should also be noted that, for F2 weather conditions, although the cloud area will be higher than for D5 conditions, the RISKAT model assumes that the cumulative probability of ignition, P_f, is lower and is equal to 0.9. This reflects the likely lower density of ignition sources when F2 conditions occur (generally at night).

For the purposes of comparison within this study, the area swept by an instantaneous release of LPG has been calculated using the HEGABOX model in the HGSYSTEM suite (Post, 1994). For a 200 tonne release of propane, HEGABOX gives the final cloud area above the LFL as 540,000 m^2. It is assumed that, due to the small cloud drift in comparison to the radial growth (or slumping) for a release of this size, the area swept, A_f, is approximately equal to the final cloud area and the calculations presented below are based on this figure.

One disadvantage of this HSE model is that, for clouds in industrial areas significantly smaller than A_f, the probability of ignition is highly dependent on the choice of P_f, i.e. 'an ignition probability of almost unity'. For example, for a cloud of area 20,000 m^2, using $P_f = (1\text{-}10^{-6})$ gives a probability of ignition of 0.4 whereas if $P_f = (1\text{-}10^{-4})$ had been used the probability would be 0.3 and if $P_f = (1\text{-}10^{-8})$ had been used the probability would be 0.5. This is illustrated in Figure 4.1 which shows the variation of probability of ignition with cloud area for these values of P_f. It would be preferable if the model was sensitive to parameters over which more certainty could be attached.

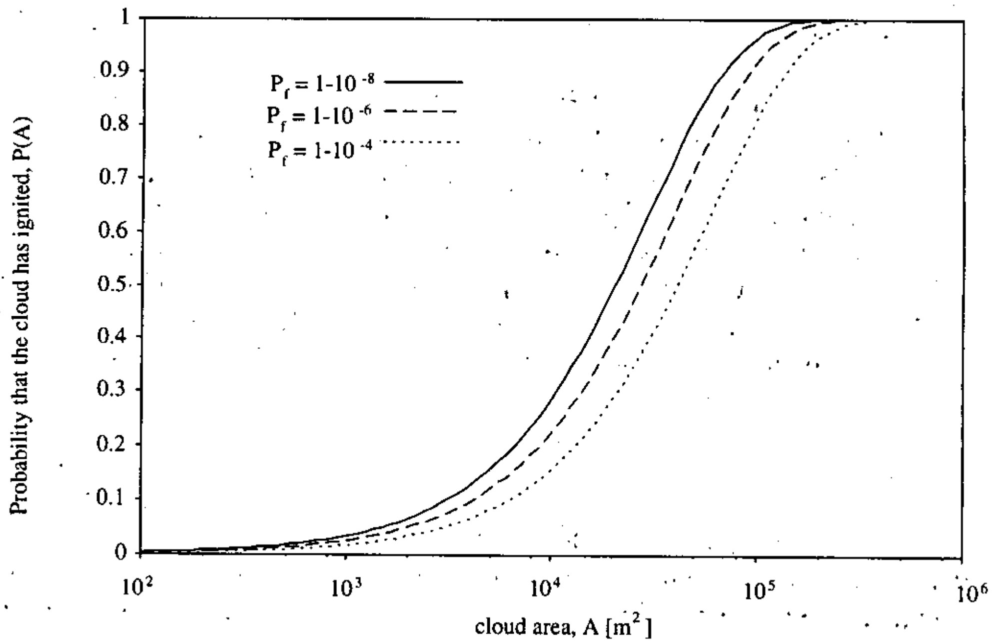

Figure 4.1 Sensitivity of current HSE model to value of P_f chosen.

Cox et al (1990) suggested a correlation for the probability of ignition based on mass flow rate, i.e. for continuous rather than instantaneous releases. It is assumed that the probability of ignition is proportional to a power of the mass flow rate. The constant of proportionality and the power are then set from a few data points. If the mass flow rate is denoted by $\dot{m}$ (kg/s), then the probability of ignition (immediate and delayed) for a particular scenario is approximately given by:

$$P = a\dot{m}^{b} \qquad (4.13.)$$

Values of the coefficients a and b are estimated for a few scenarios and are given in Table 4.2, noting that the 'observed' coefficients are based on both incident data and expert judgement. It is assumed that the probability of ignition for a 'massive' 50 kg/s release is 0.3, based on data for blowouts given by Dahl et al (1983) (see Section 3.1.2), and that the probability of ignition for a 'minor' 0.5 kg/s leak is 0.01, derived from the estimates of Kletz (1977) (see Section 4.1). Values of a and b for the other scenarios are based on the judgement of Cox et al (1990). It should be noted that the model is not intended for very high mass release rates, where it gives a probability of greater than 1.

Scenario	a	b
Observed	0.017	0.74
Control of ignition sources	0.006	0.77
Self Ignition	0.003	0.28
No control of ignition sources	0.074	0.57

Table 4.2 Coefficients for model suggested by Cox et al (1990)

4.2.2 Model comparison

This section compares the three models for ignition probability described in Section 4.2.1 above. Figure 4.2 compares the formula given by Simmons (1974), based on historical data, with the probabilities of ignition for industrial, urban and rural areas given by Equation (4.10.), as used by the HSE (A_f = 540,000 m^2). For the urban and rural curves, a grid size of 50m by 50m has been used. The figure shows that, for all land use types, the probability of ignition of clouds with areas less than 10^5 m^2 is significantly underestimated by the HSE model in comparison to the Simmons correlation. The shapes of the curves are also different, which is possibly due to the Simmons correlation being averaged over many different ignition source densities, whereas Equation (4.10.) assumes that the ignition source density is constant and known for a particular incident.

Probabilities calculated using the Cox et al (1990) model are also shown in Figure 4.2. The values of the coefficients used are those for the 'observed' ignition probability (a = 0.017, b = 0.74). The cloud area for a particular gas flow rate is calculated using Shell's HEGADAS steady state dense gas dispersion model (Post, 1994) for a wind speed of 5 m/s in stability class D. This gives the ground area over which the concentration is above the lower flammability limit as approximately 330 m^2 per kg/s of leak mass flow rate. It can be seen that the model predicts slightly lower ignition probabilities than the HSE curves for industrial or urban ignition sources. However, it should be noted that the Cox et al (1990) curve is plotted against the maximum, steady-state area that the cloud would have reached had ignition not occurred.

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However, the Simmons (1974) and HSE models relate probability of ignition to the area that the flammable cloud has reached when ignition occurs, which is likely to be significantly less than the maximum area of the cloud in most instances. Thus the Cox et al (1990) curve is underestimated in Figure 4.2, and is not directly comparable to the other curves.

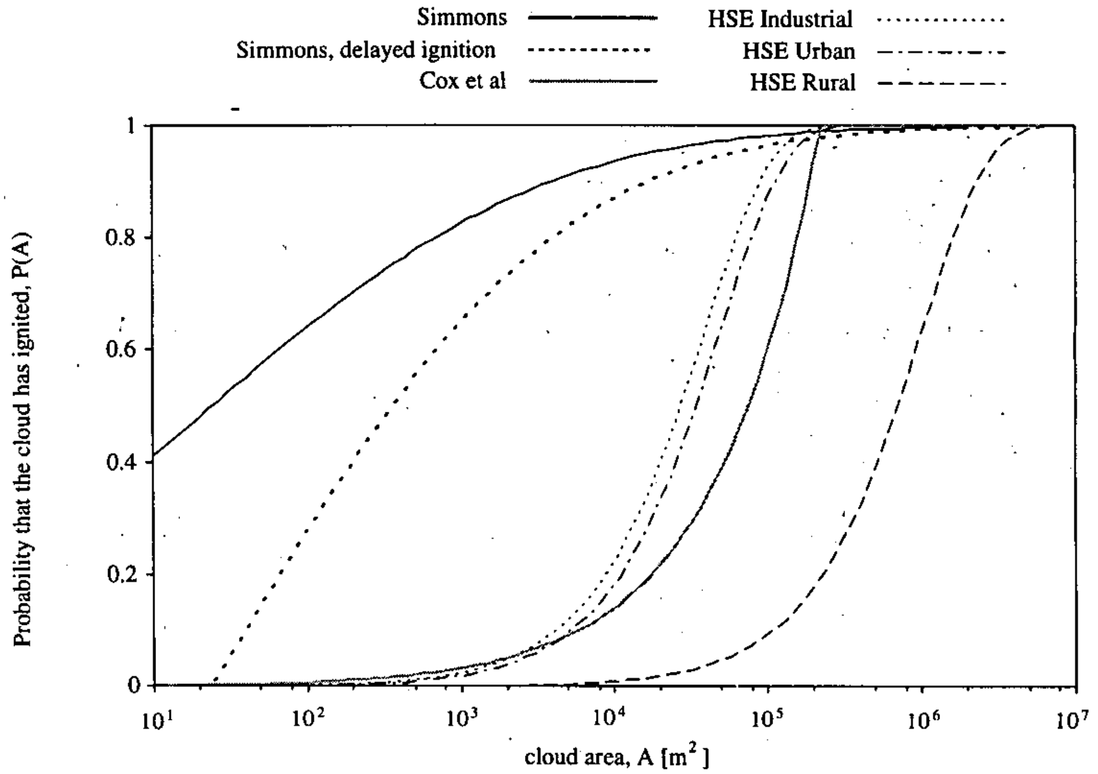

Figure 4.2 Comparison of historical data and model currently used by HSE

Figure 4.2 illustrates the wide range of ignition probabilities that can result from different interpretations of incident data or expert judgement. The effects of this variation on the results of a risk assessment are discussed in Section 6.3.4, where it is noted that overprediction of ignition probability with cloud size is not necessarily conservative and may underestimate offsite risk, because the cloud will be assumed to have already ignited before leaving the site, whereas in practice there is a finite probability that it ignites beyond the site boundary. This would suggest that the HSE ignition model may be pessimistic if used to calculate offsite risk for certain site and release sizes.

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5. FRAMEWORK FOR PROPOSED MODEL

5.1 Model requirements

5.1.1 General requirements and model outline

An ignition probability model is likely to fall into one of three categories. The first category is a simple ignition model which relates ignition probability to size of gas cloud or release rate. At the other end of the spectrum, ignition probability would be based on a site visit, where individual ignition sources and release locations would be identified.. However, it is likely that the most suitable level of modelling for implementation in a risk assessment tool, such as Flammables RISKAT, would be a compromise between these approaches. Different industrial or urban locations can be categorised with respect to type and density of ignition source, rather than each individual source being considered.

A statistical framework for calculating ignition probability is described below. Ignition probability is calculated by considering the likelihood of the flammable gas cloud meeting ignition sources for a range of generic land use types. The likelihood of ignition occurring will depend on the distribution of different types of ignition source within the area enclosed in the flammable gas cloud. The source distributions can be pre-defined for urban, rural and industrial locations. Consideration is given to how the characteristics of ignition sources (their area density, strength and whether they are intermittent or continuous) affect when and whether ignition will occur. The model also includes effects such as gas ingress into buildings. The detailed requirements of the model are outlined in Section 5.1.2.

As described by Clay et al (1988), Flammables RISKAT divides the area to be assessed into a Cartesian grid, with grid dimensions of 25m by 25m or larger. For each time step as the flammable gas cloud develops, ignition probability is calculated at each grid, depending on the land use type defined for that grid. Section 5.3.1 describes how the proposed ignition model can be applied to such a grid system. However, it should be noted that the model is designed to stand alone and can be used to calculate ignition probability independently of risk assessment tools such as RISKAT.

5.1.2 Detailed requirements

Cloud size and concentration dependence

The most obvious requirement is that the probability of ignition should be dependent on the size of a flammable cloud and the concentrations within that cloud. These are both incorporated in the proposed model by including the area of gas at ground level within the flammability limits. However, the model is not dependent on the exact concentration within the flammability limits, as discussed further in Section 5.4.

Uniform or random distribution of ignition sources

Usually the exact location of the ignition sources and cloud are not known. In the proposed model, ignition sources are assumed to be randomly distributed with respect to the cloud. This covers the possibilities of ignition sources being randomly

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distributed with respect to the ground, or the exact location of a flammable cloud or plume being unknown.

Time dependence

If a flammable gas cloud contains intermittent sources or large hot surfaces, the probability of ignition will be dependent on the duration of the cloud. For example, if a continuous, steady state plume with a roughly constant area within the flammability limits contains an ignition source with a rate of activity of once per 5 minutes, then the cumulative probability of ignition tends to one with increasing time although the cloud area does not change. A less frequently occurring example is that of a large hot surface parallel to the wind direction. The temperature of this surface may not be sufficient to ignite the cloud if the exposure time were low, but, if the cloud flows along the surface, and its concentration remains above LFL, the exposure time for a "gas parcel" may be significant, depending on the size of the surface and the wind speed.

Multiple source types

The model must be able to handle many source types at once. For example, a cloud may have a low probability of containing a strong ignition source and a high probability of containing many weak ignition sources and intermittent sources. The probability of ignition of the cloud may therefore have significant contributions from sources with different characteristics.

Effect of gas ingress into buildings

Many ignition sources in urban areas, such as gas fired central heating, are found predominantly indoors. However, flammable gas passing over an area may take some time to percolate into the building. Thus the concentration inside a building may reach the lower flammability limit some time after the outside concentration has reached this level. Once the cloud reaches the lower flammability limit inside the building, the external cloud may be much larger than when the cloud first reached the building. If ignition then occurs, this represents a greater hazard. Alternatively, the internal concentration may never reach the lower flammability limit before the cloud has passed. It is therefore necessary to model gas ingress into buildings and its effect on the probability of ignition.

Intermittent and continuous ignition sources

Some ignition sources are active 24 hours a day, others are continuous when they are active, but are only active for a fraction of the day and some are active for very short periods a number of times a day, i.e. they are intermittent and have a rate of activity.

Variable source types in different regions

It is necessary to be able to specify different ignition probabilities and source densities in different regions. For example, it may be known that there is a flare in a particular location on a plant or that a flammable gas cloud is likely to spread over an industrial and urban region. Alternatively, it may be known that there is a high probability of

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immediate ignition for the site under consideration and it may therefore be necessary to specify a high probability of ignition in the region surrounding the fuel release.

5.2 Description of mathematical model

5.2.1 Background theory

Throughout this section, p or P denotes the probability of an event occurring and q or Q denote the probability of an event not occurring (where capitals are used for cumulative probabilities). Therefore $Q = 1 - P$ and $q = 1 - p$. Given two events with probabilities of occurring of P_1 and P_2, the probability of one or the other or both occurring is equal to 1 minus the probability of neither occurring. The probability of neither occurring is equal to the product of the probabilities of each not occurring:

$$\text{Probability}\left[1 \text{ or } 2 \text{ or both}\right] = 1 - Q_1 Q_2 = P_1 + P_2 - P_1 P_2 \tag{5.14.}$$

5.2.2 Intermittent and continuous ignition sources

A continuous source is assumed to be present 24 hours a day, 365 days a year and has a probability less than or equal to one of igniting a flammable cloud surrounding it. The uncertainty is due, for example, to uncertainties in the energy of the source or uncertainties in whether such an energy would ignite a cloud. The probability of ignition from one continuous source is denoted by p and the probability of no ignition by $q = 1 - p$. If it is known that there are n such sources in a cloud, the probability of ignition, P_n is given by:

$$\begin{aligned} 1 - P_n &= Q_n = q^n = (1-p)^n \\ \Rightarrow P_n &= 1 - (1-p)^n \end{aligned} \tag{5.15.}$$

Throughout the analysis, $Q_x = 1 - P_x$ where x denotes any subscript.

An entirely intermittent source is active for a fraction of a second and has an average rate of activation denoted by λ (s^{-1}), such that the mean time between activations is $1/\lambda$. If the activations are randomly distributed then their standard deviation is equal to $\sqrt{1/\lambda}$ and the activations follow an exponential distribution with parameter λ and probability density function, f(t):

$$f(t) = \lambda e^{-\lambda t} \tag{5.16.}$$

Thus the probability that the ignition source has been active by time t is given by the cumulative distribution function:

$$F(t) = \int_0^t \lambda e^{-\lambda t'} dt' = 1 - e^{-\lambda t} \tag{5.17.}$$

If there are exactly n such ignition sources in a cloud, the rate of activation is $n\lambda$ and the activations follow an exponential distribution with parameter $n\lambda$. Such intermittent sources may not always cause ignition when they are active and inside the flammable cloud. If this is the case, the activation rate needs to be scaled by the fraction of activations which cause ignition, denoted by p. Thus, if there are n ignition

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sources in a flammable cloud, each with activation rate λ and probability of causing ignition when active of p, then the rate of ignition is exponentially distributed with parameter nλp. For a fixed size cloud containing exactly n intermittent sources with rate λp, the probability that the cloud has ignited after a time t is therefore given by:

$$\begin{aligned} P_n(t) &= 1 - e^{-n\lambda pt} \\ \text{or } Q_n(t) &= e^{-n\lambda pt} \end{aligned} \qquad (5.18.)$$

Most sources will be neither wholly continuous nor intermittent but will be active for a certain proportion of the time. These can be considered as a generalisation of the intermittent source. For example, an outdoor fire in a residential area may occur on average once a day and last for one hour. Thus the probability that the source is active as the cloud first reaches it is equal to the proportion of time for which the source is active. Subsequently, the probability that the source becomes active is exponentially distributed with parameter equal to the rate of activation, given that the source was not initially active. The probability that the source is initially active is denoted by a and the rate at which the source becomes active is denoted by λ. These are given by:

$$\begin{aligned} &a = \frac{t_a}{t_a + t_i}, \quad \lambda = \frac{1}{t_a + t_i} \quad \text{for } t_i > 0 \\ &a = 1, \qquad\quad \lambda = \infty \qquad \text{for } t_i = 0 \end{aligned} \qquad (5.19.)$$

where t_a is the average time for which the source is active and t_i, the average time between activations. Then the cumulative probability that a cloud, with one such ignition source, has ignited at a time t is given by:

$$\begin{aligned} P_1(t) &= ap + (1 - ap)\left(1 - e^{-\lambda pt}\right) \\ &= 1 - (1 - ap)e^{-\lambda pt} \\ \text{or } Q_1(t) &= (1 - ap)e^{-\lambda pt} \\ &= Q_C Q_T \end{aligned} \qquad (5.20.)$$

where Q_C represents the continuous part (1-ap) and Q_T represents the intermittent part ($e^{-\lambda pt}$). This assumes that, when such an activated ignition source is in contact with the flammable cloud, ignition will occur immediately if it occurs at all. (Intermittent sources are a special type of this generalised intermittent source with $t_a = 0$, and thus $a = 0$ and continuous sources are a special case with $a = 1$ and $\lambda = \infty$.) For a cloud with n generalised ignition sources, the cumulative probability of ignition is given by:

$$\begin{aligned} P_n(t) &= 1 - (1 - ap)^n e^{-n\lambda pt} \\ Q_n(t) &= (1 - ap)^n e^{-n\lambda pt} \\ &= Q_{Cn} Q_{Tn} \end{aligned} \qquad (5.21.)$$

5.2.3 Cloud containing a variable number of ignition sources

If a cloud is changing size or shape then the number of ignition sources in it may change with time. In this case, the time dependent equations of Section 5.2.2 are not valid since the exponential distribution assumes that the rate of activation remains constant with time. However the number of ignition sources per unit area on the ground may not be changing. In this case the ground can be subdivided into a number

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of small regions (or cells) For each small region the probability of no ignition is given by Equation (5.21.), with n being the number of ignition sources in the small region and t being the duration for which the flammable cloud has covered the small region. Then, the probability of no ignition for the whole cloud is given by the product of the probabilities of no ignition for all the small regions covered by the flammable cloud.

To calculate the probability of no ignition at time t, the ground is divided into I cells labelled from i = 1, 2,...,I, each with area A_i. For each cell the probability of ignition is dependent on the duration, d_i, for which the concentration of the gas in that cell has been between the flammability limits. If the probability of no ignition for each cell is denoted by $Q_i(d_i)$, then the probability of non-ignition for the whole cloud is given by:

$$\begin{aligned} Q(t) &= \prod_{i=1}^{I} Q_i(d_i) \\ \Rightarrow \ln\{Q(t)\} &= \sum_{i=1}^{I} \ln(Q_i(d_i)) \end{aligned} \qquad (5.22.)$$

5.2.4 Uniformly or randomly distributed ignition sources

The previous section dealt with the probability of ignition from a generalised ignition source with a varying, but known, number of ignition sources in the flammable cloud or plume. However, in most cases, although the average number of ignition sources per unit area may be known, the exact number of ignition sources in a cloud of a certain size will not be known, since the exact position of ignition sources and cloud are not known. Thus the expected number of ignition sources in a cloud of a certain size is known and the probability of finding a certain number of ignition sources in a cloud can be evaluated.

There are two possibilities for evaluating the probability of a number of ignition sources being in a cloud. Firstly, it could be assumed that the ignition sources are uniformly distributed in a grid shape and a circular cloud passes over this uniform distribution. Appendix A gives the probability of finding a certain number of uniformly distributed ignition sources in a circular cloud. Secondly, it could be assumed that the ignition sources are randomly distributed with respect to the cloud, so that, for any size flammable cloud, there is always a finite probability of finding any number of ignition sources. It is this assumption that is used within the proposed ignition model, as discussed below.

If the ignition sources are randomly distributed with respect to the cloud with, on average, μ sources per unit area, then the number of ignition sources in the cloud of area A follows a Poisson distribution with mean and variance μA. The Poisson distribution is chosen because, if there were a number of ignition sources randomly distributed over an area, a subset of which was flammable, then the probability of finding a particular number of ignition source in the flammable region is binomially distributed. As the total number of ignition sources gets larger and the total area gets larger (but the average number of ignition sources per unit area remains the same) the binomial distribution tends to a Poisson distribution. Thus, using the Poisson distribution, the probability of finding exactly n sources of a particular type in the flammable cloud is given by:

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$$S_n = \frac{e^{-\mu A}(\mu A)^n}{n!} \tag{5.23.}$$

When μA is large (greater than about 5 or 6) the Poisson distribution becomes expensive to compute and prone to numerical rounding errors. However, as μA becomes large, the Poisson distribution tends to the normal distribution with mean and variance μA. These two distributions are compared in Appendix A. Therefore, for large μA, the normal distribution can be used instead of the Poisson distribution.

If the probability of ignition of a cloud containing exactly n ignition sources is P_n, the probability of ignition of a cloud containing randomly distributed ignition sources with mean μA is given by:

$$\begin{aligned} P_A &= \sum_{n=0}^{\infty} S_n P_n = \sum_{n=0}^{\infty} S_n(1-Q_n) = \sum_{n=0}^{\infty} S_n - \sum_{n=0}^{\infty} S_n Q_n = 1 - \sum_{n=0}^{\infty} S_n Q_n \\ \Rightarrow Q_A &= \sum_{n=0}^{\infty} S_n Q_n \end{aligned} \tag{5.24.}$$

Thus, for a fixed size flammable cloud containing generalised intermittent sources with parameters λ, p and a, the probability of no ignition at time t is given by:

$$\begin{aligned} Q_A(t) &= \sum_{n=0}^{\infty} S_n (1-ap)^n e^{-n\lambda pt} \\ &= \sum_{n=0}^{\infty} \frac{e^{-\mu A}(\mu A)^n}{n!}(1-ap)^n e^{-n\lambda pt} \\ &= e^{-\mu A} \sum_{n=0}^{\infty} \frac{\left(\mu A(1-ap)e^{-\lambda pt}\right)^n}{n!} \\ &= e^{-\mu A} \exp\left\{\mu A(1-ap)e^{-\lambda pt}\right\} \end{aligned} \tag{5.25.}$$

$$\Rightarrow \ln\{Q_A(t)\} = -\mu A\left[1-(1-ap)e^{-\lambda pt}\right]$$

5.2.5 Extension to allow for different source types

Any ignition source can be characterised by the parameters p, λ, a and μ, where p is the probability of ignition from that source given that it is active and enclosed in the cloud, λ is the rate of activation of the source, a is the proportion of time for which the source is active and μ is the average number of ignition sources per unit area. If an area of land contains J different ignition source types each with parameters p_j, λ_j, a_j and μ_j, then for a cloud of fixed area A, the probability of no ignition from source type j is denoted by Q_{Aj} and is evaluated using the methods presented above. Then the probability of no ignition of the cloud by any ignition source type is denoted by Q_A and is given by:

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$$
\begin{aligned}
Q_A \qquad & Q_{A1}Q_{A2} \quad Q_{AJ} \quad \prod_{j=1}^{J} Q_{Aj} \\
& = \prod_{j=1}^{J} \left\{ \exp\left\{ \mu_j A\left[\left(1 - a_j p_j\right) e^{-\lambda_j p_j t} - 1 \right] \right\} \right\} \qquad (5.26.) \\
\Rightarrow \ln\{Q_A\} & = \sum_{j=1}^{J} \mu_j A\left[\left(1 - a_j p_j\right) e^{-\lambda_j p_j t} - 1 \right]
\end{aligned}
$$

Similar arguments can be applied to different ignition source types in different areas.

5.2.6 Incorporation of gas ingress

Over urban areas, many ignition sources are indoors. It is therefore necessary to take into account the effects of gas ingress into buildings. When a flammable cloud passes over a region containing a building, the indoor concentration will initially be less than the outdoor concentration, since the flammable gas takes time to ventilate into the building. This time is dependent on the ventilation rate of the building, which is dependent on the size of openings such as open windows or gaps around doors. Thus, if there is a strong ignition source inside a building, this will only ignite the cloud once the gas has ventilated into the building. As the cloud then drifts away from the building, the gas concentration inside the building will take time to drop to below the lower flammability limit, while the gas ventilates out of the building. If ignition inside the building occurs once the external cloud has moved on, ignition of the whole cloud will not occur, just ignition inside that building.

A method of including the effects of gas ingress on the probability of ignition is given here and Appendix B presents a method for calculating the concentration inside a building of a given size and ventilation rate. It is assumed that the probability of ignition is required over an area in which all buildings have the same ventilation rate. However, if this is not the case, the region can be divided into smaller areas, in all of which the buildings have the same ventilation rate. Alternatively, a method of obtaining the probability of ignition over an area containing buildings of different ventilation rates is given in Appendix B.

To find the probability of ignition over an area containing buildings with the same ventilation rate, it is necessary to solve for two different concentration fields everywhere in the domain. A method of doing this is given in Appendix B. The outside concentration is denoted by C_o and the concentration inside buildings by C_b. It is then possible to define two cloud areas, A_o and A_b. A_o is the area in which the outside concentration is between the flammability limits and A_b is the area which encloses all buildings in which the indoor concentration is between the flammability limits. For example, the instantaneous relationship between A_o and A_b could be similar to one of those shown in Figure 5.1.

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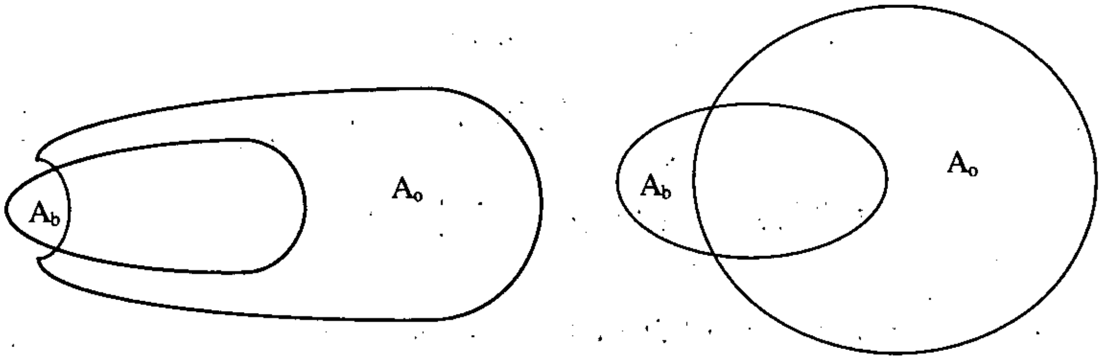

Continous fuel source

Instantanous fuel source

Figure 5.1 Relationship between areas enclosing outdoor and indoor concentrations between the flammability limits

All ignition sources are classified as either indoor or outdoor and have parameters p, λ, a and μ. It is therefore possible to find the probability of no ignition from indoor and outdoor sources separately. These are denoted by Q_{Ab} and Q_{Ao}. The probability of no ignition of the whole cloud is then given by:

$$Q_A = Q_{Ab}Q_{Ao} \tag{5.27.}$$

However, if ignition is caused by an indoor source and the gas concentration outdoors is not within the flammability limits, a fire or explosion will be caused in the building (which may spread to other buildings depending on their proximity) but the outdoor cloud will not be ignited. Thus a full scale vapour cloud explosion or flash fire will not occur. Therefore, if the probability of ignition of the cloud only is required, rather than the probability of ignition of the cloud or a building, then A_b should be redefined to be the intersection of A_o and A_b.

5.3 Model assembly and discretisation

5.3.1 Ignition source definition

Each ignition source in the solution domain is characterised by five parameters, p, λ, a, h and μ.

Parameter **p** is the probability of ignition from a source given that it is active and enclosed in the cloud. It is equivalent to the 'ignition potential' of a source, as discussed in Section 3.2.2. The probability of ignition will depend on the energy available from the source in comparison to the energy required for ignition of the fuel, and so is both source- and fuel-dependent. Thus **p** can be used to account for sources which produce insufficient energy always to guarantee ignition. Alternatively it can be used to account for a source not always causing ignition when activated, for example because it is not enclosed in a flammable vapour at the particular time it sparks or is turned on. However, it does not account for the fraction of certain ignition source types which, when caught within a flammable gas cloud, do not cause ignition initially and will not cause ignition at a later point in time. This effect can be accounted for within the source density term of the ignition source.

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Parameter λ is the rate of activation of the source, as defined in Equation (5 19), and is equivalent to the frequency with which the source becomes active. For continuous sources, λ is infinite.

Parameter **a** is the proportion of time for which the source is active, as defined in Equation (5.19.). Thus, for continuous sources, a is equal to one and for intermittent sources, a is zero.

Parameter **h** is a flag which denotes whether the source is indoors or outdoors, and is equal to b if the ignition source is inside a building and o if it is outside.

Parameter μ is the average number of ignition sources per unit area. It should be noted that many items may only be potential ignition sources when faulty, particularly electrical equipment. For these items, μ is the number of faulty items per unit area.

Table 5.1 gives the definition of a selection of typical ignition sources, noting that the numbers given are illustrative only. The availability of experimental or accident data which can be used to define p, λ, a, h and μ has been discussed in Section 3.

Source type	Example	p	λ (min^{-1})	a	h	μ (km^{-2})
Continuous	flare	1	∞	1	o	<1
Semi-continuous	gas fired equipment	1	∞	0.25	b	90
Intermittent	car electrics	0.06	2	0	o	20

Table 5.1 Ignition Source Definition

5.3.2 Data required for generic land use types

As discussed in Section 5.1.1, practical implementation of the proposed ignition model in a risk assessment tool requires that the distribution of ignition sources is pre-determined for a range of generic land use types. The land use types presently used within Flammables RISKAT (Clay et al, 1988) are industrial, urban, rural and special. The special category allows calculation of risk for areas of the environment not adequately described by the other categories.

Ideally, the parameters for each source type within a generic land use area would be fully defined. In practice, it may not be realistic to define fully every type of ignition source found in each of the land use areas and a more qualitative approach may be necessary. This would involve assigning values for each of the ignition source parameters based on a ranking of sources as discussed in Section 3.2.5. Such a qualitative approach is likely to require calibration against incident data.

It should be noted that immediate, or event-initiated, ignition has not been explicitly considered in the model framework described above. In many risk assessment methodologies, immediate ignition is considered separately from delayed ignition and this is the approach followed in Flammables RISKAT. Incorporation of event-initiated ignition within the model framework would require definition of a special land-use type for the grid where the flammable release occurs.

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5.3.3 Application to a two-dimensional grid

It is assumed that there are K land use types, $L_1,...L_K$, each with indoor and outdoor ignition sources, labelled, $j = 1,...,J$. Each ignition source has parameters h_j, p_j, λ_j and a_j. The mean source density for each source, μ_j, is dependent on land use type. The indoor and outdoor cloud areas at time t are denoted by $A_b(t)$ and $A_o(t)$ and are split up into $A_{1h},...,A_{Kh}$ depending on the land use region into which each area falls. Ignition source j has a density μ_{jk} in land use region k.

- The ground containing the release is divided up by a grid of I cells labelled from $i = 1, 2,...,I$ each with area A_i. Each cell is assigned a land use type, L_k.
- It is then necessary to solve for the indoor and outdoor concentration as a function of time in every cell. These are denoted by $C_{ih}(t)$. Typically the outdoor concentration at each grid point will be given by a gas dispersion model.
- The duration for which each cell has been within the flammability limits indoors and outdoors is calculated as a function of time. These are denoted by d_{ih}.
- Next it is necessary to calculate the probability of ignition in each cell indoors and outdoors due to each ignition source type. The probability of no ignition at time t, due to ignition source j, in cell i, indoors or outdoors (depending on the value of h) is given by:

$$\ln\{Q_{jih}(t)\} = \mu_j A_i\left[(1-a_j p_j)e^{-\lambda_j p_j d_{ih}} - 1\right] \qquad (5.28.)$$

- Then, at time t, the probability of the cloud not having ignited is given by:

$$\begin{aligned} Q(t) &= \prod_{i=1}^{I}\prod_{j=1}^{J} Q_{jih}(t) \\ \Rightarrow \ln\{Q(t)\} &= \sum_{i=1}^{I}\sum_{j=1}^{J} \ln\{Q_{jih}(t)\} \\ &= \sum_{j=1}^{J}\sum_{i=1}^{I} \mu_j A_i\left[(1-a_j p_j)e^{-\lambda_j p_j d_{ih}} - 1\right] \end{aligned} \qquad (5.29.)$$

5.4 Model limitations

5.4.1 Variation of probability of ignition with concentration

As can be seen in Figure 2.2, ignition energy of a hydrocarbon air mixture varies with its concentration. Therefore it is expected that probability of ignition should also vary with concentration. However, the form of this variation is not known and the data available on probability of ignition is not given in terms of concentration. In practice, due to concentration fluctuations within a flammable cloud or plume, any ignition source within a cloud will experience a range of concentrations, further complicating the effects of concentration on ignition probability. Full-scale experiments on the ignitability of flammable gas clouds, for example those of Birch et al (1989), on natural gas jets, and Evans & Puttock (1986), on dense gas clouds, have shown that the probability of ignition varies with position within a cloud, an hence with concentration. Thus the ignition potential of a source would vary with position within the flammable envelope.

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5 4 2 Effect of ignition lag time

When a flammable mixture is in contact with a hot surface capable of causing ignition, there will be a delay before ignition occurs. This corresponds to the time taken for the surface to heat up a sufficient quantity of mixture to a high enough temperature. This effect is not included in the current model; it is assumed that an active ignition source in contact with the flammable cloud will ignite the cloud immediately, if at all. This is reasonable if the wind speed is sufficient and the ignition source is small since, in this case, the time taken for a parcel of flammable mixture to pass over the ignition source is small in comparison to the time of the simulations.

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6. SENSITIVITY OF RISK ASSESSMENT TO MODELLING

6.1 Model calibration

6.1.1 Calibration against HSE model

If it is assumed that ignition is always due to strong, continuous sources ($p = 1$, $a = 1$, $\lambda = \infty$), then the proposed ignition model, described in Section 5, will have the same form as the HSE model used in Flammables RISKAT (Clay et al, 1988). The probability of no ignition is equal to the probability of there being no ignition sources in the cloud. Thus, from Equation (5.24) in Section 5.2.4, the probability of no ignition, Q(A), is given by:

$$Q(A) = e^{-\mu A} \qquad (6.30.)$$

As discussed in Section 4.2, the HSE model gives the probability of no ignition for a cloud of area A as:

$$Q(A) = \left(Q_f\right)^{A/A_f} \qquad (6.31.)$$

where A_f is the maximum area swept by the flammable cloud due to a 200 tonne release of propane and Q_f is the probability that this cloud has not ignited. Equating these two expressions to find the average ignition source density, μ, gives:

$$\Rightarrow \mu = \frac{-1}{A_f}\ln\left(Q_f\right) \qquad (6.32.)$$

Table 6.1 gives source densities for different land use types. Note that the value of A_f used (540,000 m^2) is that used in the comparison of ignition models discussed in Section 4.2.2 and is calculated using the Shell HEGABOX model (Post, 1994). The value of Q_f for an industrial site is 10^{-6}. The values of Q_f for urban and rural land use types are found by scaling P_I for an industrial site by factors of 0.8 and 0.04 respectively, based on a 50m by 50m grid.

Land use type	Q_f	μ [per hectare]
Industrial	$1\mathrm{x}10^{-6}$	0.26
Urban	$2\mathrm{x}10^{-5}$	0.20
Rural	0.6	0.01

Table 6.1 Ignition source densities based on HSE model

6.1.2 Calibration against Simmons (1974) model

A similar analysis can be undertaken to calculate the source density required to match the proposed ignition probability model to the Simmons (1974) model (without immediate ignition), as described in Section 4.2.1. If it is assumed that all ignition sources are strong and continuous, then the source density required to match that model can be shown to reduce with cloud area at ignition, equivalent to distance of the source from the point of release. This variation of μ with cloud area at ignition is shown in Figure 6.1.

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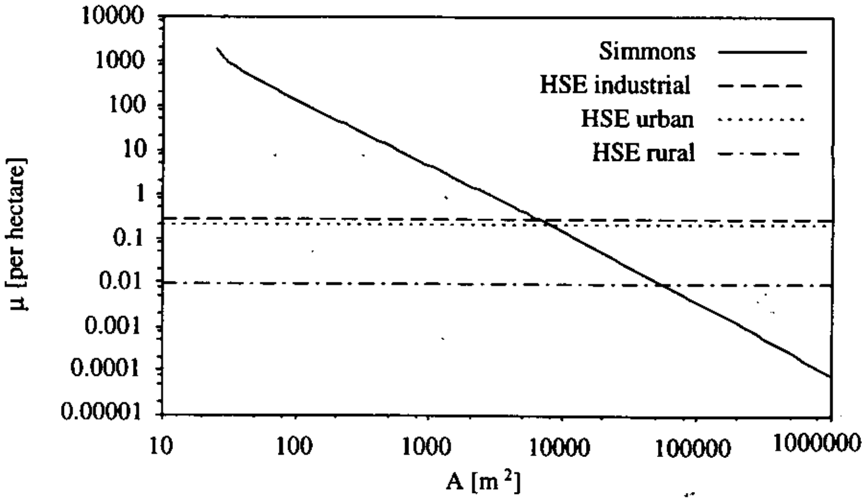

Figure 6.1 Variation of source density with cloud area for the Simmons (1974) model

At values of A less than approximately 5000m^2, the source density is higher than that for the HSE model for industrial areas (for A_f = 540,000m^2). However, the source density is significantly lower than the HSE model for rural areas at values of A higher than 50,000m^2. The Simmons model is fitted to incident data and the variation of source density with distance from the release location is likely to reflect the fact that, for the majority of incidents studied by Simmons, the release occurred within industrial areas before spreading into urban or rural areas. It should be noted that the HSE model would also give a variation of source density with cloud area if it was assumed that the grid locations close to the source were industrial, surrounded by urban and then rural grids.

6.2 Effect of source properties on ignition probability modelling

The probability of ignition within Flammables RISKAT is calculated on a grid by grid basis. Figures 6.2 to 6.4 illustrate the effect of changes in source parameters on the probability of ignition within a 25m by 25m grid continuously enveloped in a flammable gas cloud.

Figure 6.2 illustrates the effect of source density on ignition probability within the grid square, assuming that all the sources are strong and continuous. Thus it can be seen that the ignition probability varies as $(1-e^{-\mu A})$, asymptoting to 1.

Figure 6.3 shows how ignition probability varies with time for a grid square containing intermittent sources. It can be seen that, as time increases, the ignition probability tends to a steady value equal to that of a grid containing the same density of continuous sources. The higher the value of λ, the faster the probability tends to the steady value. Figure 6.4 shows similar behaviour of ignition probability with time for increasing values of a, except that in this case the initial ignition probability is not zero. The initial probability of ignition relates to the probability that the ignition source is already active when the flammable gas cloud arrives.

Figure 6.5 shows the variation of ignition probability for a gas cloud of constant area (equal to that of a 25m by 25m grid square) drifting over land with continuous ignition sources. The ignition probability is initially equal to approximately 0.4, which is the same as that for a single grid square. However, as the cloud drifts, the probability that

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it will come across other ignition sources gradually increases and the ignition probability tends to 1.

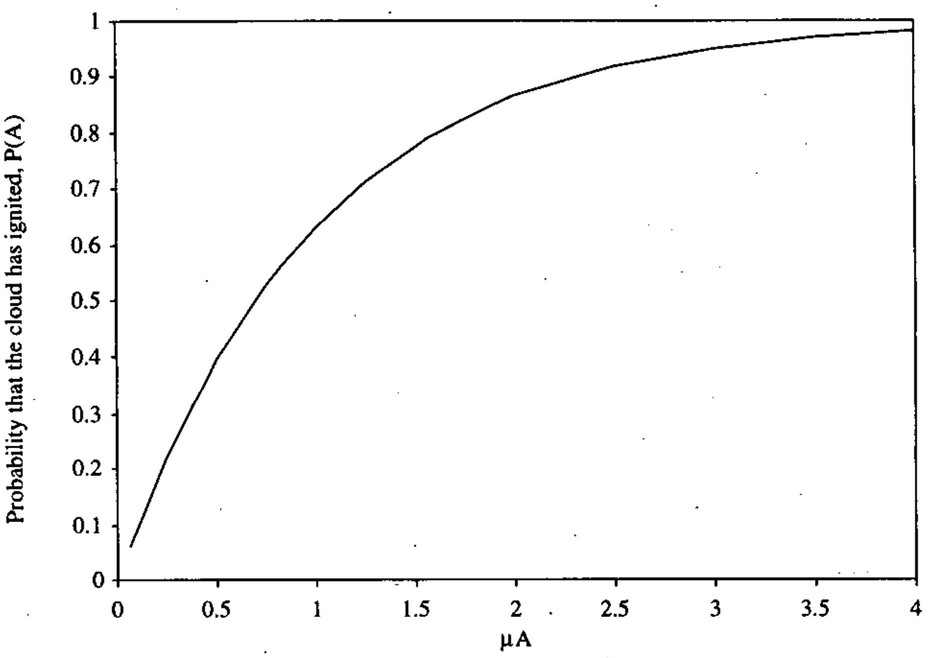

Figure 6.2 Variation of ignition probability with μA for strong continuous sources in a fixed area cloud (p=1, λ=∞, a=1)

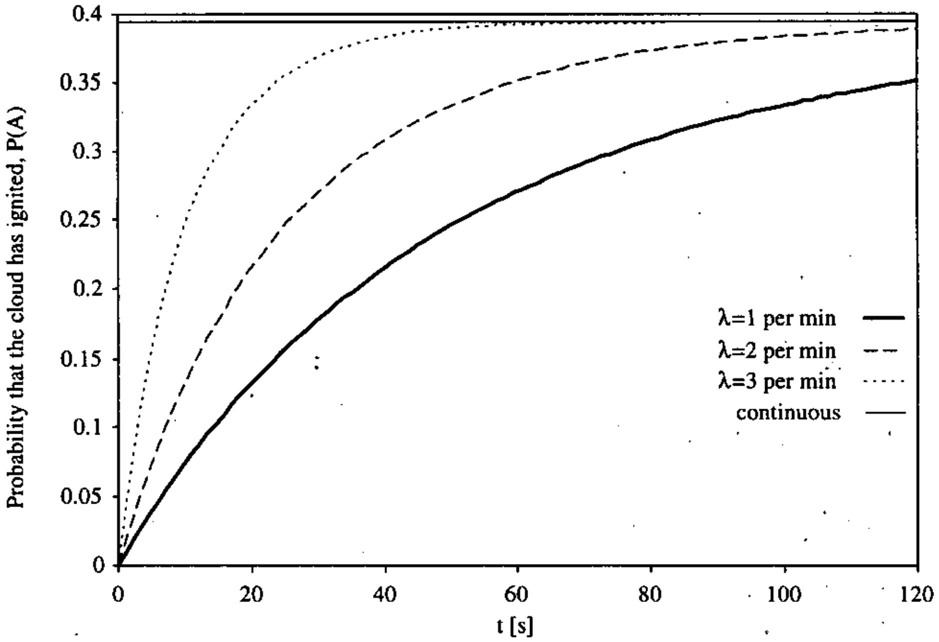

Figure 6.3 Variation of ignition probability with time for different source intermittency, λ ($A=625m^2$, μA=0.5, p=1, a=1)

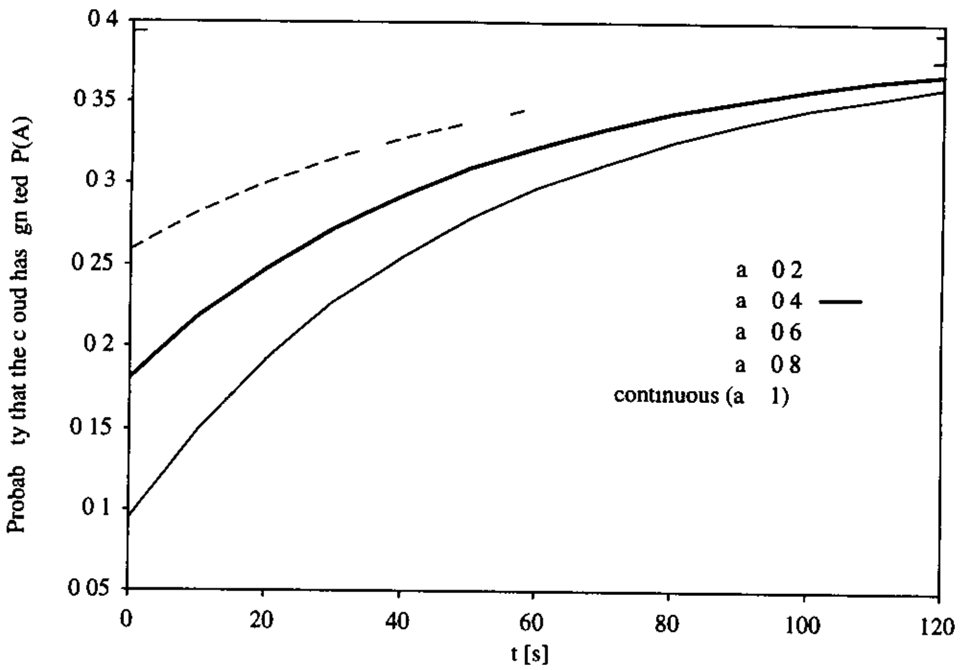

Figure 6.4 Variation of ignition probability with time for different source activity, a ($A=625m^2$, $\mu A=0.5$, $p=1$, $\lambda=1$/minute)

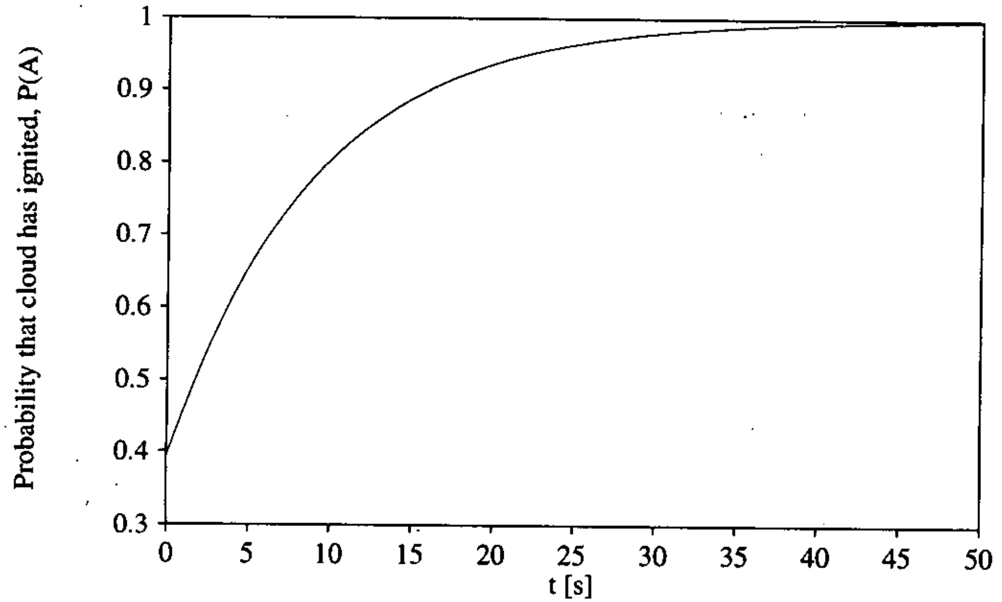

Figure 6.5 Ignition probability for a cloud of constant area drifting at 5 m/s. ($p=1$, $\lambda=\infty$, $a=1$, $A=625m^2$, $\mu A=0.5$)

6.3 Sensitivity of quantified risk assessment to modelling

6.3.1 Base case definition and methodology

The sensitivity analyses described below have been undertaken for a 200 tonne instantaneous release of LPG, from a 1 hectare site. The dispersion of the release has been modelled using the Shell HEGABOX model (Post, 1994) and the detailed definition of the release scenario is given in Table 6.2.

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Release parameter	Value
Initial aspect ratio	1
Initial diameter	48 m
Wind speed	5 m/s
Stability	D
Air and ground temperature	20°C
Ground roughness	0.1 m
Initial gas concentration	100%
Initial gas temperature	-42°C
Final cloud area at LFL	540,000 m^2
Area of industrial site around release	10,000 m^2 = 1 hectare

Table 6.2 Base case parameters

Throughout the sensitivity analyses, it is assumed that the area surrounding the industrial site comprises a mixture of land use types and has an ignition source density of one tenth of that of the site, i.e. $\mu = 0.1\mu_I$, where μ_I is the industrial source density. It is assumed that the release occurs at the centre of the industrial site.

In order to estimate the sensitivity of a risk assessment to ignition probability modelling, it is assumed that risk can be estimated by multiplying the probability of the event by the number of fatalities that are caused. It is also assumed that the number of fatalities caused is proportional to the area of the cloud at the time of ignition, as is usually assumed for flash fire events.

If P(A) is the cumulative probability that a cloud of area, A, has ignited, then the probability that the cloud will ignite between area A and A+δA, is δP(A). A density function, p(A), is then defined as follows:

$$p(A) = \frac{dP(A)}{dA} \tag{6.33.}$$

where:

$$\int_0^\infty p(A)dA = 1 \tag{6.34.}$$

The total risk during cloud growth can then be represented by a function, R, which has units of area and is calculated for a particular release as follows:

$$R = \int_0^{P_f} A\, dP(A) \; = \int_0^{A_f} Ap(A)\, dA \tag{6.35.}$$

where A_f is the maximum area that the cloud will reach if ignition does not occur and P_f is the cumulative probability of ignition at the maximum area. Similarly, offsite risk, R_o, can be estimated as follows:

$$R_o = \int_0^{A_f} (A - (A \cap A_S))p(A)dA \tag{6.36.}$$

where A_s is the area of the site.

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6.3.2. Effect of variation of source density

Figure 6.6 shows the variation in cumulative probability of ignition as the flammable gas cloud grows. Curves for three values of source density, μ, are plotted, noting that all sources are assumed to be strong and continuous ($p=1$, $a = 1$, $\lambda=\infty$). At an area of 10,000 m^2, the cloud reaches the site boundary and the rate of growth of probability of ignition reduces. At an area of 540,000 m^2, the cloud has reached its full size and the cumulative probability of ignition will have reached its maximum. It can be seen that, for lower source densities, there is a higher probability that ignition will be delayed until the cloud has had the opportunity to get closer to its maximum size (i.e. the rate of change of cumulative probability, P(A), is high as the cloud reaches its maximum size). This is further illustrated in Figure 6.7, which shows the effect of source density on the integrand, p(A)A, which represents the contribution to risk at each area. The area under the curve is the total risk. It can be seen that the contribution to offsite risk is higher for lower ignition source densities.

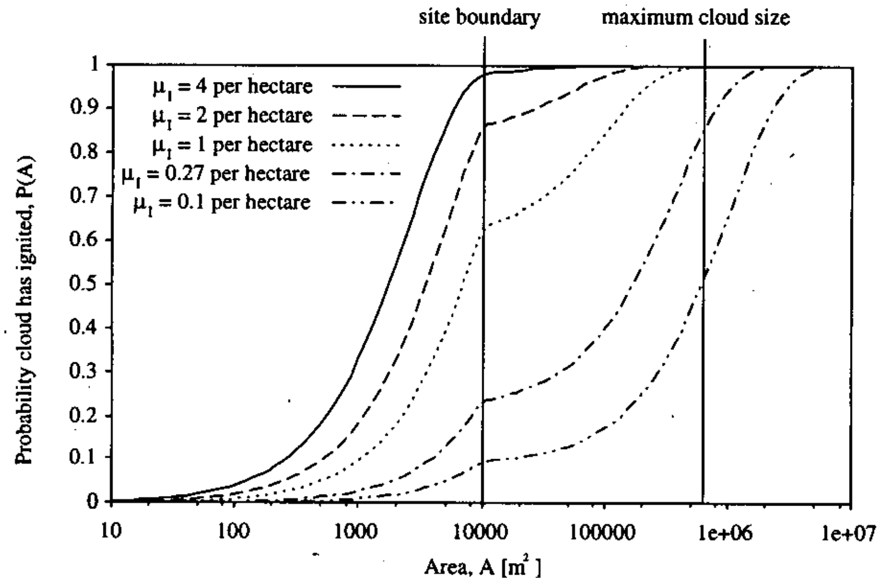

Figure 6.6 Effect of ignition source density on ignition

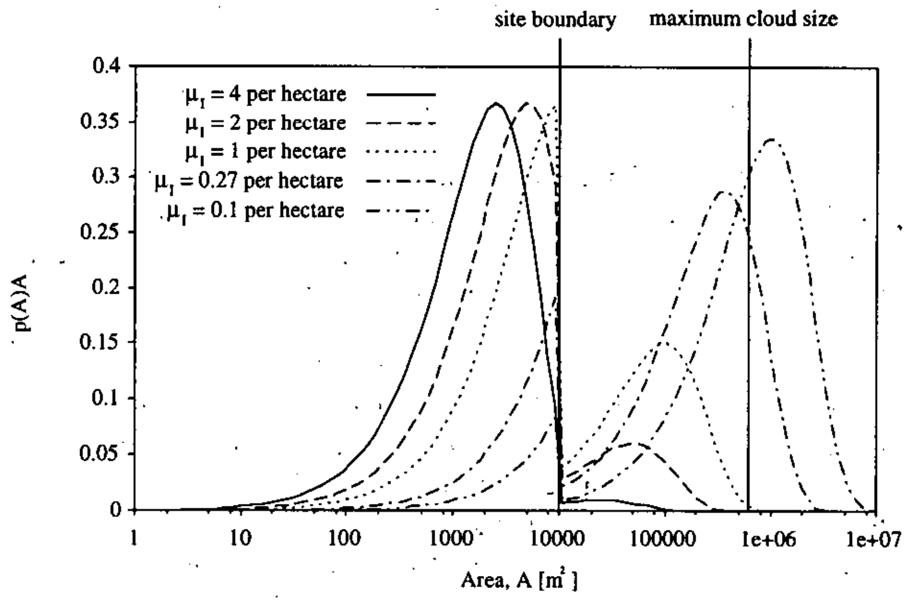

Figure 6.7 Variation of integrand, p(A)A, with ignition source density

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Figure 6.8 shows the effect of ignition source density on risk, with the total risk comprising mainly offsite risk due to the site area being small in comparison to the area of the flammable cloud. It can be seen that the risk peaks when μ_I is approximately equal to 0.27 ($\mu_{offsite} = 0.027$). The source densities which appear to give the highest level of risk are those for which the rate of growth of the cumulative probability of ignition is highest just as the cloud is reaching its maximum size, i.e. there is a high probability that the cloud is ignited close to its maximum size. For values of μ_I lower than 0.27, the cumulative probability of ignition has not reached 1 before the cloud reaches its maximum size and the risk is reduced significantly (although it should be noted that the μ_I axis is logarithmic). Eventually the risk comprises only offsite risk with the onsite risk becoming negligible. For values of μ_I greater than 0.27, the cumulative probability of ignition reaches 1 before the cloud reaches its maximum size and the offsite risk is reduced. It can also be seen that, for values of μ_I greater than 0.27, the onsite risk is approximately constant, and, at μ_I approximately equal to 5, the offsite risk is negligible.

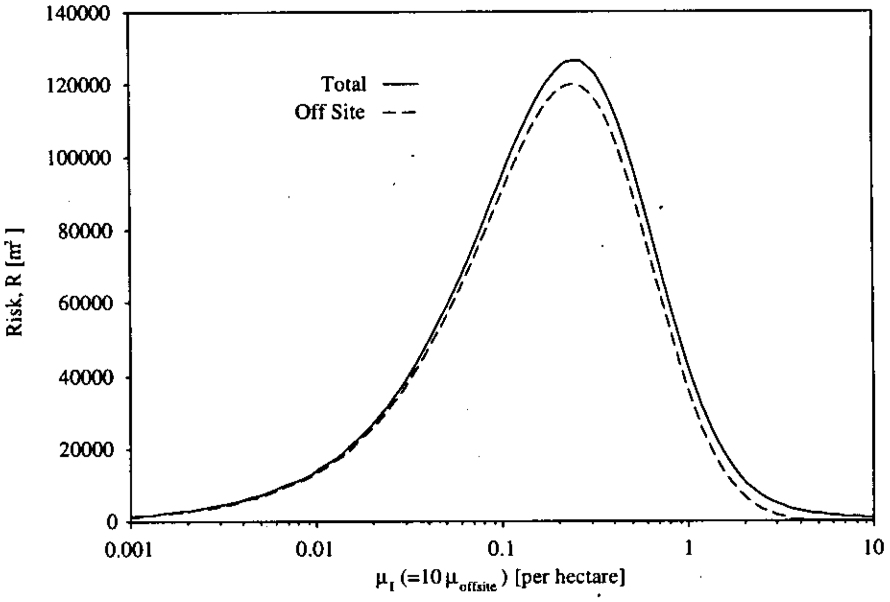

Figure 6.8 Variation of total and offsite risk with ignition source density

6.3.3 Effect of variation of source intermittency

Figure 6.9 shows the effect of ignition source intermittency on the cumulative probability of ignition, where all the curves are plotted for $\mu_I = 2$/hectare. It can be seen that, as the sources increase in intermittency, there is a higher probability that ignition will be delayed until the cloud has had the opportunity to get closer to its maximum size.

Figure 6.10 shows the effect of intermittency on risk for the 200 tonne LPG release. For very intermittent sources (low λ), the cumulative probability that the cloud ignites before it reaches its maximum size is low and there is a high probability that the cloud will disperse to below LFL without igniting. As the intermittency is reduced, i.e. λ increased, the risk levels increase until the risk is higher than for continuous sources of the same source density. As the intermittency is further reduced, the total risk and offsite risk tend to those of a continuous source. Thus it can be seen that

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intermittency may increase risk levels by increasing the probability that ignition will be delayed until the cloud has grown closer to its maximum size. However, this effect will depend on the size of release and the source density. If the source density is such that the risk is already at its peak, as illustrated in Figure 6.8, then intermittency can only reduce the risk by delaying activation of the ignition sources until after the cloud has dispersed.

It should be noted that the above analysis ignores the effect of the centre of the cloud being above the upper flammable limit, which would result in the reduced probability of sources causing ignition after the edge of the gas cloud has passed. Thus the significance of the effect of intermittency on risk is in practice rather less than has been demonstrated in Figures 6.9 and 6.10.

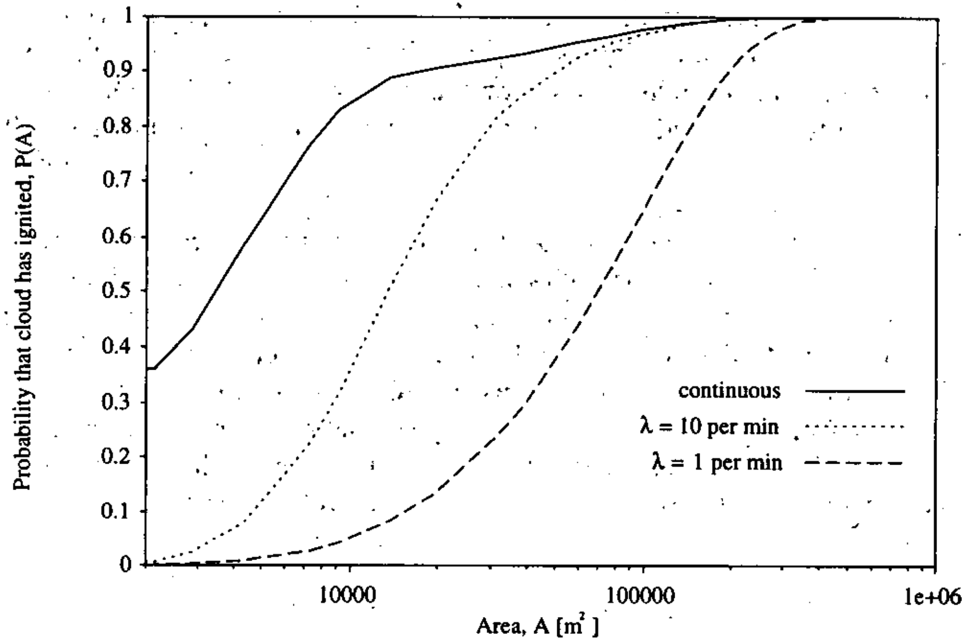

Figure 6.9 Effect of ignition source intermittency on ignition

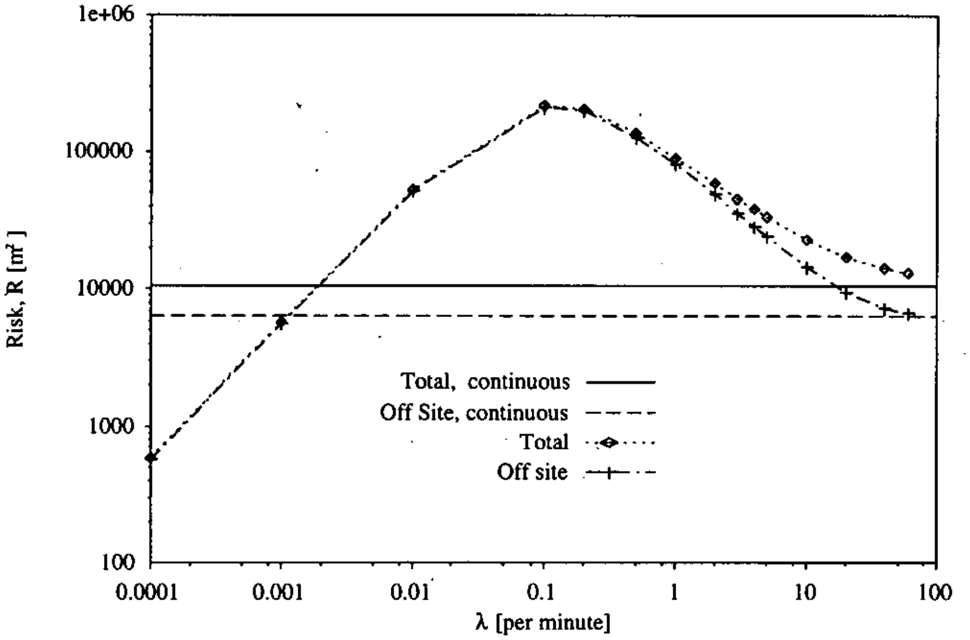

Figure 6.10 Variation of total and offsite risk with ignition source intermittency

6.3.4 Implications for risk assessment

One key conclusion that can be drawn from Figure 6.8 is that the HSE model for ignition probability will not necessarily be conservative, with predicted risk levels being sensitive to ignition source density. Whether the current HSE ignition model leads to underprediction or overprediction of risk will depend on the range and relative frequency of release sizes modelled in a risk assessment and on the value of source densities used in the model compared with those on the site being studied. Figures 6.6 to 6.8 show that risk is maximised when the rate of growth of the cumulative probability of ignition is highest just as the cloud is reaching its maximum size and there is a high probability that the cloud is ignited close to its maximum size. For the release size used to calibrate the ignition model, the offsite source density which produces maximum risk is 0.027 per hectare, which falls between the HSE rural and urban source densities (see Table 6.1). If ignition source densities close to the release point are as high as suggested by the model given by Simmons (1974), see Figure 6.1, then prediction of offsite risk by the HSE model is likely to be conservative for clouds which have maximum areas of the order of 100,000 m^2 or greater.

Another conclusion that could be drawn from the analysis is that, if the source density within an industrial site is high enough, then offsite risk can be reduced to negligible levels. However, the risk modelling used in the sensitivity analysis only considers fatalities due to delayed ignition from a flash fire type event. If ignition were always to occur on site, then the probability of fireball or BLEVE events would be increased due to event escalation. This would suggest that modelling of delayed ignition should be considered in tandem with modelling of immediate ignition and hence a consideration of the frequency of BLEVE and fireball events.

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7. CONCLUSIONS

7.1 Current modelling and ignition probability data

Current approaches to the modelling of ignition probability tend to be based on either expert judgement, extrapolation of limited incident data or a combination of both. Three models were compared in Section 4.2.2 and were found to give significantly different predictions of ignition probability with respect to cloud area. Of these, the model used by HSE within Flammables RISKAT (Clay et al, 1988), was found to underpredict in comparison to the model of Simmons (1974), which was fitted to data from approximately 60 incidents. However, as noted in Section 6.3.4, underprediction of ignition probability with respect to cloud area is not necessarily non-conservative as far as risk is concerned, since ignition is delayed until the cloud has grown to cover offsite areas.

The sensitivity analysis described in Section 6.3 showed that the prediction of risk was highly sensitive to the source density and intermittency used within the ignition model. Thus the results of Flammables RISKAT are likely to be sensitive to the calibration of its ignition model, which is based on the judgement that a 200 tonne release of LPG will have a probability of having ignited of close to 1 if it drifts over an industrial area. The sensitivity analysis also suggested that delayed ignition of a drifting cloud, leading to flash fire and explosion events, needs to be considered in conjunction with immediate (or near-field) ignition, which may result in fireball or BLEVE type events.

7.2 Proposed model framework and data requirements

The mathematical framework for an ignition probability model has been developed. The proposed ignition model differs from current approaches in that ignition probability is calculated by considering whether the flammable gas cloud will reach defined ignition sources within urban, rural or industrial locations, i.e. it is based on site information rather than on historical data. The model is able to distinguish between central and edge ignition of the cloud and accounts for the time dependency of ignition; for example, whether ignition occurs before the gas cloud has reached its maximum size. The model accounts for the different characteristics of ignition sources, including their area density, whether they are intermittent or continuous and whether they are enclosed in buildings.

In order for the model to be used within risk assessment, information on the types and distribution of sources encountered in industrial, urban and rural areas must be collated. For each source type, properties relating to their strength, activity and intermittency must be defined. The review outlined in Sections 2 and 3 has identified much useful data on ignition source characteristics. However, it is clear that a significant amount of further data would be required to define the properties of every ignition source encountered for each of the land use types listed above. In particular, there is a lack of data on densities of ignition sources.

Further development of the ignition probability model can be achieved by using a ranking of ignition sources, avoiding the need to define the properties of all possible ignition sources found in industrial, urban and rural sites; ranking of ignition sources has been discussed in Section 3.2.5. The ranking could be undertaken on a semi-quantitative basis, using information on current industrial practice and engineering

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judgement, as well as relevant experimental or incident data, allowing grouping of ignition sources in terms of ignition potential as either certain, strong, medium, weak or negligible. The process of collating ignition source data could then be simplified as follows. Firstly, based on the ranking, ignition sources which have a negligible effect on ignition probability would be eliminated. Data on those items which are known to be certain, or strong, sources of ignition would then be collated. Next, weaker sources would be examined and, where possible, eliminated from consideration within the model if their effect on ignition probability is negligible in comparison to the strong sources.

Having collated the ignition source data using the ranking process described above, the final model may still require calibration against available incident data discussed in Section 3.1.2, in particular, that reported by Simmons (1974). The model can also be assessed against more recent incident reports, checking whether it accommodates all the various factors which are known to have a significant influence on ignition.

The resulting model should provide significant improvement over present approaches, allowing consideration of the effect of individual source properties on ignition probability. The model framework accounts for specific site situations (such as control of ignition sources) and provides a more transparent and flexible methodology than current models based on incident data.

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REFERENCES

Birch, A.D., Brown, D.R., Fairweather, M., & Hargrave, G.K. (1989) 'An experimental study of a turbulent natural gas jet in a cross-flow', Combustion Science & Technology, Vol. 66.

Blything, K.W. & Reeves, A.B. (1988) 'An initial prediction of the BLEVE frequency of a 100 te butane storage vessel', SRD/HSE/R488.

Britton, L.G. (1992) 'Using Material Data in Static Hazard Assessment', Plant/Operations Progress, Vol. 11, No. 2, April.

Browning, R.L. (1969) 'Estimating Loss Probabilities', Chemical Engineering, 76, Dec., 135.

Cawley, J.C. (1988) 'Probability of Spark Ignition in Intrinsically Safe Circuits', Reports of Investigations - US department of the Interior Bureau of Mines .

CCPS (1993) 'Guidelines for Engineering Design for Process Safety', AIChE, New York.

CCPS (1995) 'Guidelines for Chemical Transportation Risk Analysis', AIChE, New York.

Clay, G.A., Fitzpatrick, R.D., Hurst, N.W., Carter, D.A. & Crossthwaite, P.J. (1988) 'Risk assessment for installations where liquefied petroleum gas (LPG) is stored in bulk vessels above ground', Journal of Hazardous Materials, 20.

Cox, A.W., Lees, F.P. & Ang, M.L. (1990) 'Classification of Hazardous Locations', IIGCHL, IChemE.

Croce, P.A. (1982) 'Feasibility Study of a Sealed Safety Monitor for Trucks Carrying LNG and other Hazardous Materials', Inc. for the US Department of Energy, Office of Operational Safety Programs, DOE/EV/10502-1.

Crowl, D.A. & Louvar, J.F. (1990) 'Chemical Process Safety: Fundamentals with Applications', Prentice-Hall International Series in Physics & Chemical Engineering Sciences.

Dahl, E., Bern, T.I., Golan, M. & Engen, G. (1983) 'Risk of oil and gas blowout on the Norwegian Continental Shelf.', SINTEF, Trondheim, Rep. STF 88A82062.

Davies, P.C. & Purdy, G. (1986) 'Toxic Gas Risk Assessments - The Effect of Being Indoors', Refinement of Estimates of the Consequences of Heavy Toxic Vapour Releases, Symposium Papers.

Dean, J.C., Hulburt, D.A., Matthews, A.L. & Williams, G. M. (1992) 'Quantitative Evaluation of Electrostatic Hazards', Intl. Conference on Hazard Identification and Risk Analysis, Human Factors and Human Reliability in Process Safety.

Desy, D.H., Neumeier, L.A. & Risbeck, J.S. (1975) 'Methane Ignition by Frictional Impact Between Aluminium Alloys and Rusted Steel', US Bureau of Mines Report of Investigations 8005, Bureau of Mines, Washington DC.

DNV (1996), 'JIP Ignition Modelling Work Group Meeting', Hovik, Norway.

Contents

Eckhoff, R.K. & Thomassen, O. (1994) 'Possible sources of ignition of potential explosive gas atmospheres on offshore process installations', Journal Loss Prevention Process Industries, Vol. 7, No. 4.

European Gas Pipeline Incident Data Group (1988) 'Gas Pipeline Incidents: A Report of the European Gas Pipeline Incident Data Group', Pipes and Pipelines International, 1970-1988.

Evans, A. Puttock, J.S. (1986) 'Experiments on the ignition of dense flammable gas clouds', 5th Intl. Symp. on Loss Prevention & Safety Promotion in the Process Industries, Cannes, Sept.

Forsth, L.R. (1983) 'Survey identifies causes of offshore fires and explosions', Oil and Gas Journal, 81, July 25, 154.

Gibbs, B.M. (1991) 'Fire Initiation I - Ignition', 16th Annual Short Course on Fire and Explosion', Leeds.

HSC (1991) 'Major hazard aspects of the transport of dangerous substances', Advisory Committee on Dangerous Substances, HMSO.

HSE (1981) 'Canvey: A Second Report: a review of potential hazards from operations in the Canvey Island/Thurrock area', HMSO.

James, R.A., Excell, P.S. & Keller, A.Z. (1987) 'Probabilistic Factors in Radio - Frequency Ignition and Detonation Hazards Analyses', Reliability Engineering, Elsevier Applied Science Publishers Ltd.

Jeffreys, D.T., Moussa, N.A., Caron, R.M. & Allan, D.S. (1982) 'Ignition sources of LNG vapour clouds', Gas Research Inst., GRI-80/0108.

Johnson, R.W. (1980) 'Ignition of Flammable Vapors by Human Electrostatic Discharges', 88th AIChE National Meeting.

Jones, D.J. (1986) 'An Analysis of Reportable Incidents for Natural Gas Transmission & Gathering Lines - 1970 through June 1984', American Gas Association, NG-18, Report No. 158.

Kletz, T.A. (1977) 'Unconfined vapour cloud explosions', Loss Prevention, Vol. 11, 50.

Ko, Y., Anderson, R.W. & Arpaci, V.S. (1991) 'Spark Ignition of Propane - Air Mixtures Near the Minimum Ignition Energy: Part I. An Experimental Study', Combustion and Flame 83: 75-87.

Komai, T., Uchida, S. & Umezu, M. (1994) 'Ignition of Methane - Air Mixture by Frictional Sparks from Light Alloys.', Elsevier Science B.V.

Kuchta, J.M. (1985) 'Investigation of Fire and Explosion Accidents in the Chemical, Mining and Fuel-Related Industries - A Manual', US Bureau of Mines Bulletin 680, Washington DC.

Laurendeau, N.M. (1982) 'Thermal Ignition of Methane-Air Mixtures by Hot Surfaces: A Critical Examination', Combustion and Flame, Vol. 46, pp. 29-49.

Contents

Lees, F.P. (1980) 'Loss Prevention in the Process Industries', Butterworths.

Lewis, D.J. (1980) 'Autoignition temperature determination & their relationship to other types of potential ignition sources & their application to practical situations', 7th International Symposium on Chemical Process Hazards, IChemE Symposium Series No. 58.

Medard, L.A. (1989) 'Accidental Explosions', 2 Volumes, John Wiley & Sons, New York.

Powell, F. (1981) 'Safety against Explosions', 9th Intl. Symp. on Prevention of Occupational Accidents and Diseases in the Chemical Industry, June.

Post, L. (1994) HGSYSTEM 3.0 Technical Reference Manual, Shell Research Limited.

Rhoads, R.E. (1978) 'An Assessment of the Risk of Transporting Gasoline by Truck', US Department of Energy, Contract No. EY-76-C-06-1830.

Richardson, S.M., Saville, G. & Griffiths, J.F. (1990) 'Autoignition - Occurrence and Effects', Transactions IChemE, Vol. 68, Part B, Nov.

Silver, R.S. (1937) Philos. Mag. Ser. 7, 23 (156 Suppl.), 633.

Simmons, J.A. (1974) 'Risk Assessment of Storage & Transport of Liquefied Natural Gas & LP-Gas', Final Report for Contract 68.01.2695 for US Environmental Protection Agency.

Townsend, N.A & Fearnehough, G.D. (1986) 'Control of Risk from UK Gas Transmission Pipelines', British Gas plc, Research and Development Division ERS E531.

Westbrook, C.K. (1978) 'An Analytical Study of the Shock Tube Ignition of Mixtures of Methane and Ethane', Combustion Science and Technology, 20.

Williams, F.A., 1985, Combustion Theory, 2nd Edition, Benjamin/Cumings Publishing Co.

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APPENDIX A IGNITION SOURCE DISTRIBUTIONS

A.1 Random distribution of ignition sources

Since the exact locations of the cloud and the ignition sources are not known in most cases, it is necessary to calculate the probability that a certain size cloud contains a certain number of randomly distributed ignition sources. There are three possible probability density functions; the binomial, normal and Poisson distributions. The application of these functions to the distribution of ignition sources is discussed below.

A.1.1 The binomial distribution

If a certain event has probability p of succeeding, and thus q = (1-p) of failing, and the event happens n times, the binomial distribution gives the probability of r successes as:

$$P(r\text{ successes}) = \binom{n}{r} p^r (1-p)^{n-r}$$

(A.1.)

$$\text{where } \binom{n}{r} = \frac{n!}{r!(n-r)!}$$

The mean number of successes is np and the variance is np(1-p).

If there is a flammable cloud of area A_f in a larger area A_l and there are n ignition sources randomly distributed over area A_l, then the probability of finding r ignition sources inside area A_f is binomially distributed with $p = A_f / A_l$.

A.1.2 The Poisson Distribution

As n and A_l tend to infinity and p tends to zero in the binomial distribution, with the mean, np, remaining constant, then the binomial distribution tends to the Poisson distribution. The Poisson distribution has a parameter λ = np and the probability of r successes is given by:

$$\mathrm{P(r\ successes)} = \frac{\lambda^r e^{-\lambda}}{r!} \qquad \text{(A.2.)}$$

The mean and variance of the number of successes are both equal to λ. The Poisson distribution is cheaper to compute than the binomial distribution. Note that when r becomes large the Poisson distribution becomes expensive to calculate.

If the exact number of ignition sources in an area is not known, but the average number in an area of that type is known, then the Poisson distribution is appropriate. In this case λ is equal to the average number of ignition sources in an area the size of the flammable cloud.

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A 1 3 The normal distribution

As n tends to infinity, the binomial distribution tends to the normal distribution. The normal distribution has parameters μ and σ and the probability of r successes is given by:

$$P(\text{r successes}) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(r-\mu)^2}{2\sigma^2}\right) \qquad \text{(A.3.)}$$

where μ and σ are the mean and standard deviation of the number of successes. If $\mu = \sigma^2$ and r is large, the normal distribution tends to the Poisson distribution.

A.1.4 Comparison

The normal, Poisson and binomial distributions are compared in Figure A.1 for $n = 20$, $p = 0.25$, $\lambda = \mu = 5$ and $\sigma = \sqrt{5}$,and it can be seen that they display similar behaviour. The binomial has a higher probability in the middle of the distribution and lower in the tails, becoming zero for the number of successes greater than $n = 20$, whereas both for the normal and Poisson distribution, as the number of successes increases, the probability tends to, but never reaches, zero.

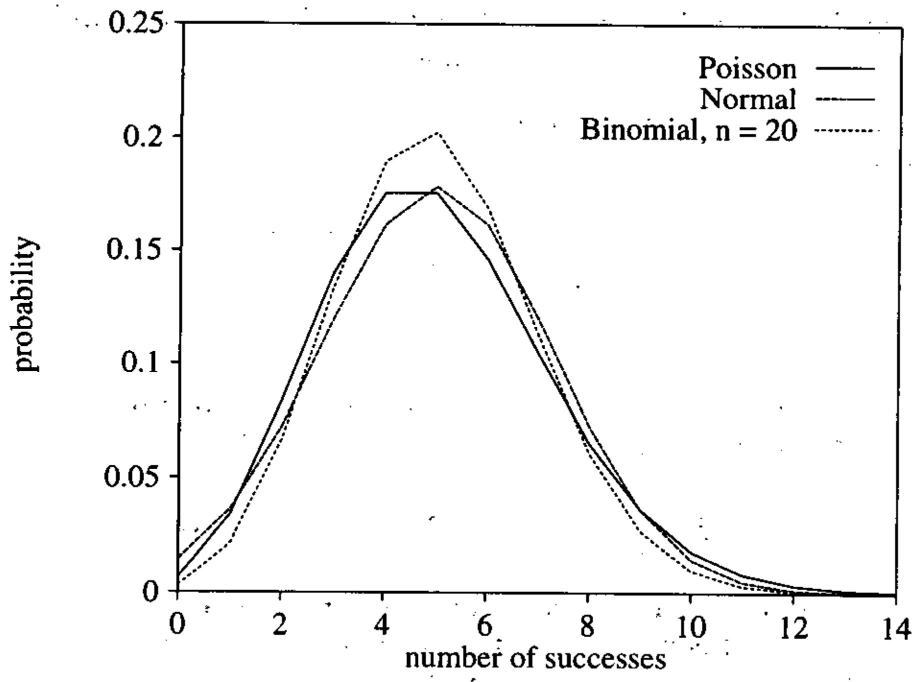

Figure A.1 Comparison of the normal, Poisson and binomial distributions for $n = 20$, $p = 0.25$, $\lambda = \mu = 5$ and $\sigma = \sqrt{5}$.

A.2 Uniform distribution of ignition sources

To calculate the probability that a certain size of cloud contains a certain number of uniformly distributed ignition sources, the following assumption are made:

- The flammable part of the cloud at ground level is circular with radius R.

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- The ignition sources are square packed (they lie on the vertices of a square grid) with squares of side length d.
- The centre of the circle lies a distance b from the nearest grid line in the y direction and a distance a from the nearest grid line in the x direction, where a and b are greater than zero and less than or equal to d. The square enclosing the centre of the circle is denoted by S.

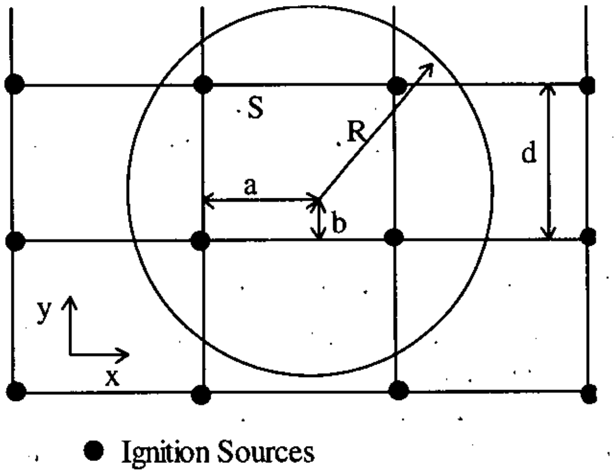

Figure A.2 A circular flammable cloud lying in a grid of uniformly distributed ignition sources

Therefore the number of ignition sources in the upper right hand quadrant of the circle is given by:

$$N_q(a,b)=\sum_{i=1}^{\mathrm{int}\left(\frac{R+a}{d}\right)} \mathrm{int}\left(\frac{b+\sqrt{R^2-(id-a)^2}}{d}\right) \qquad \text{(A.4.)}$$

Where the function "int" denotes the truncated integer part of a real number. Hence the number of ignition sources in the whole circle is given by:

$$N=N_q(a,b)+N_q(d-a,b)+N_q(a,d-b)+N_q(d-a,d-b) \qquad \text{(A.5.)}$$

To determine the probability of finding a particular number, n, of ignition sources in a cloud of radius R, it is necessary to find the proportion of the area of square S in which, if the circle centre lies in that portion, there are n ignition sources within the circle. This calculation is performed numerically by splitting the square up into a grid of smaller squares and finding the number ignition sources contained in the cloud when the circle centre is at the centre of each square of the finer grid.

The probabilities of numbers of ignition sources for the case when R = d = 100m are shown in Figure A.3 and are compared with the case of randomly distributed ignition sources with the same average density and cloud. The probabilities for the randomly distributed ignition sources are calculated using the Poisson distribution.

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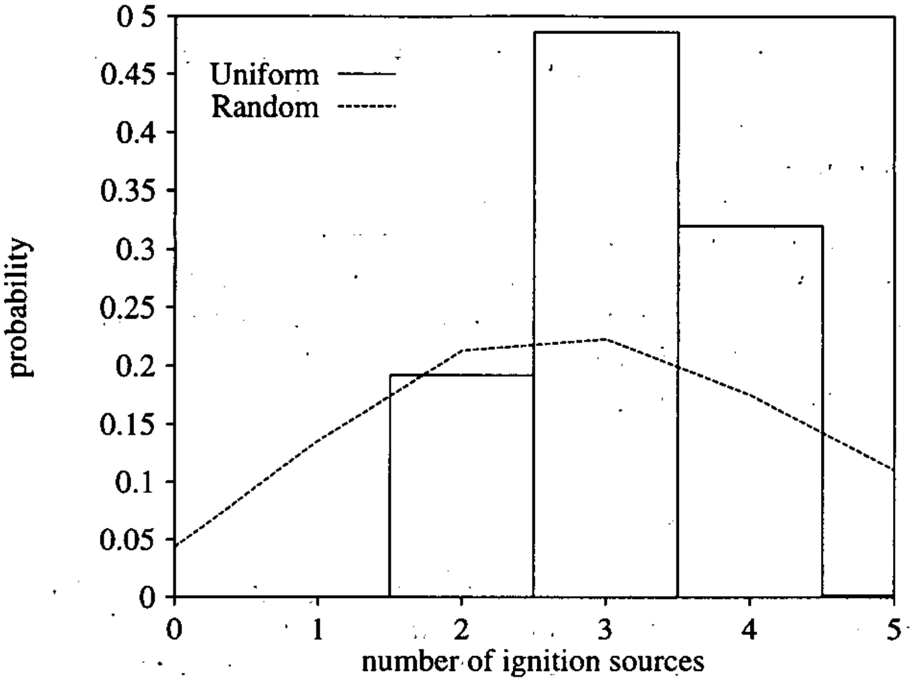

Figure A.3 Probabilities of finding certain numbers of ignition sources in a circular cloud of radius 100m and 1 ignition source per hectare

A.3 Conclusions

The uniform distribution defined in Section A.2 is only valid for a very limited set of conditions. It is also expensive to compute and is only applicable to a whole circular cloud. It is likely that the exact location of ignition sources will not be known, and therefore use of a probability distribution function which assumes that the ignition sources are randomly distributed seems more realistic. For the purpose of calculating the probability of finding an ignition source in each grid square of the cloud, it is necessary that the probability of finding an ignition source in each grid square is independent of every other grid square. The binomial distribution does not comply with this constraint and it is unlikely that enough information about a site would be known to allow use of the binomial distribution. Therefore the Poisson distribution will be used to calculate the probability of finding an ignition source in each grid square of the cloud.

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APPENDIX B GAS INGRESS INTO BUILDINGS

B.1 Simple modelling

A simple model for the prediction of gas ingress into buildings is given by Davies & Purdy (1986). It is assumed that the outdoor concentration, $C_o(t)$, is known as a function of time and space and the effective ventilation rate, λ in air changes per hour, is known for each building. Then, if the inside concentration is denoted by $C_b(t)$, the rate of change of $C_b(t)$ is given by:

$$\frac{dC_b}{dt} = \frac{\lambda}{3600}\left(C_o(t) - C_b(t)\right) \qquad \text{(B.1.)}$$

where time, t is in seconds. In general, for an arbitrary distribution of outside concentration as a function of time, this must be solved numerically for $C_b(t)$. Without resort to numerical approximation, Equation B.1. can be manipulated to give:

$$C_b(t) = \frac{\lambda}{3600} e^{\frac{-\lambda t}{3600}} \int_{t'=0}^{t} e^{\frac{\lambda t'}{3600}} C_o(t')\, dt' \qquad \text{(B.2.)}$$

Hence numerical integration can be used to find $C_b(t)$, once $C_o(t)$ is known.

$C_b(t)$ and $C_o(t)$ are calculated for a 200 tonne instantaneous release of LPG and a building close by with a ventilation rate of 2 ach. $C_o(t)$ is calculated using the HGSYSTEM HEGABOX model (Post, 1994). The inputs for HEGABOX are shown in Table B.1. Note that, although 5D conditions have been assumed, the size of the release is such that the dispersion is controlled by slumping of the cloud and thus 2F conditions give similar results.

Input	Value	Units
Release size	200	tonnes
Initial cloud height	48	m
Initial cloud diameter	48	m
Initial gas temperature	-42	°C
Air and ground temperature	20	°C
Ground roughness	0.1	m
Wind speed	5	m/s
Pasquill stability class	D	

Table B.1 Inputs for LPG HEGABOX calculation

The inside and outside concentrations at 100 m from the LPG source are shown in Figure B.1 for various ventilation rates, λ, of the building. This shows that a building must have a ventilation rate of at least 10 ach for the internal concentration to reach the lower flammability limit for this scenario. The inside and outside concentrations are shown in Figure B.2 for a building 24 m from the LPG source, i.e. at the downwind edge of the initial cloud, which will be the worst case position for build up of flammable vapour within the building. In this case the building needs a ventilation rate of just over 5 ach for the internal concentration to reach the lower flammability

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limit Thus, within residential buildings which are assumed to have a ventilation rate of approximately 2 ach, the likelihood of build-up of flammable vapour is small and ignition sources within these building types can be ignored.

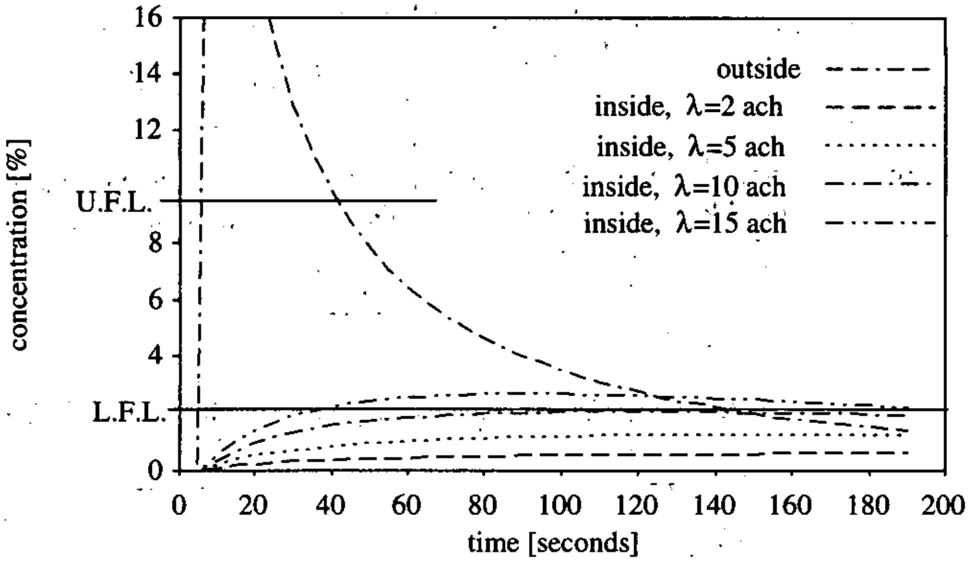

Figure B.1 Concentrations for a building 100 m from the LPG source

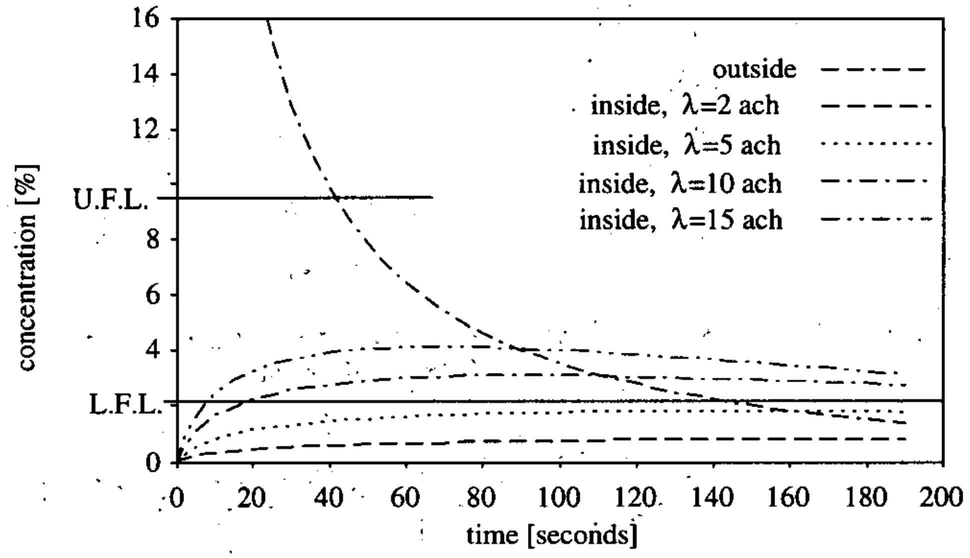

Figure B.2 Concentrations for a building 24 m from the LPG source

If the outside concentration is constant, say for a continuous release of LPG, it is possible to calculate the inside concentration exactly. For example, if $C_o(t)$ follows a top hat distribution, $C_b(t)$ is given by Equation B.3.

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$$C_o(t) = \begin{cases} C_0 \text{ (constant)} & \text{for } t_0 < t < t_c \\ 0 & \text{otherwise} \end{cases}$$

$$C_b(t) = \begin{cases} 0 & \text{for } t < t_0 \\ C_0\left(1 - e^{-\lambda(t-t_0)}\right) & \text{for } t_0 < t < t_c \\ C_0\left(1 - e^{-\lambda(t_c-t_0)}\right)e^{-\lambda(t-t_c)} & \text{for } t > t_c \end{cases} \qquad \text{(B.3.)}$$

For a continuous release which lasts for t_c hours, the outside concentration required to produce an inside concentration equal to the lower flammability, LFL, is given by:

$$C_o = \frac{LFL}{1 - e^{-\lambda t_c}} \qquad \text{(B.4.)}$$

This is shown in Figure B.3 and Table B.2, for t =30 minutes and LFL = 2.1 %.

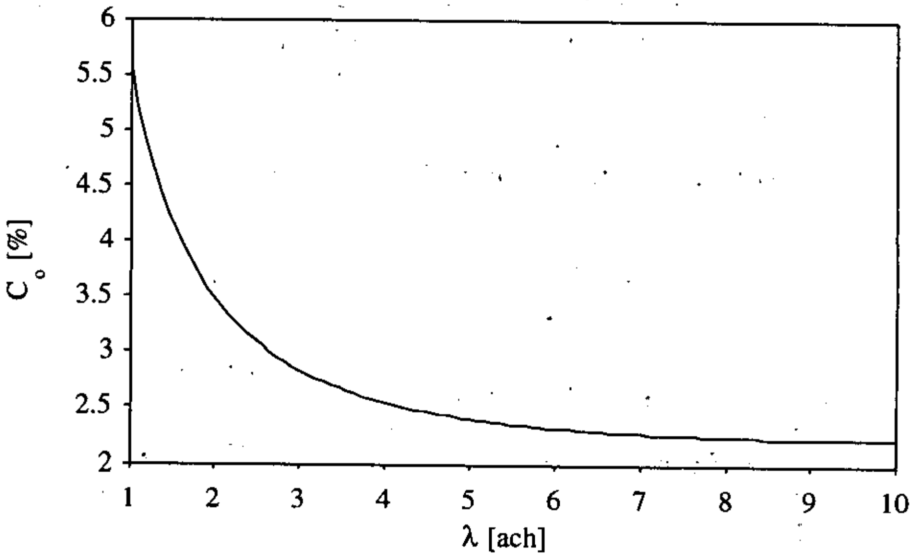

Figure B.3 Outside concentration required to produce an inside concentration of 2.1% after 30 minutes

Ventilation rate, λ	Outside concentration, C_o
2 ach	3.5 %
5 ach	2.4 %
10 ach	2.2 %

Table B.2 Outside concentrations required to produce an inside concentration of 2.1% after 30 minutes

Various steady state dispersion calculations have been undertaken in order to ascertain at what distance from the LPG source the concentrations stated in Table B.2 are achieved for various release rates. These calculations assume that the release is from an evaporating pool and the HGSYSTEM steady state dense gas dispersion model HEGADAS is used. Note that this form of release tends to produce greater hazard ranges than those from a hole in a pressurised vessel forming a high momentum jet. Release properties are given in Table B.3, where worst case 2F wind conditions are assumed.

Contents

Input	Value	Units
Initial gas temperature (HEGADAS)	-42	°C
Air and ground temperature	20	°C
Ground roughness	0.1	m
Wind speed	2	m/s
Pasquill stability class	F	

Table B.3 Inputs for LPG HEGADAS calculations

The distances at which external concentrations result in a flammable mixture inside a building for various ventilation rates are shown in Figure B.4. It is assumed that the building is on the centreline of the dispersing cloud and the gas enters the building at ground level. It can be seen that, as the building ventilation rate increases, the distance within which internal concentrations will be flammable increases. Residential buildings with a ventilation rate of 2 ach would need to be within 300 m of a continuous release of LPG before the cloud could be ignited by internal ignition sources.

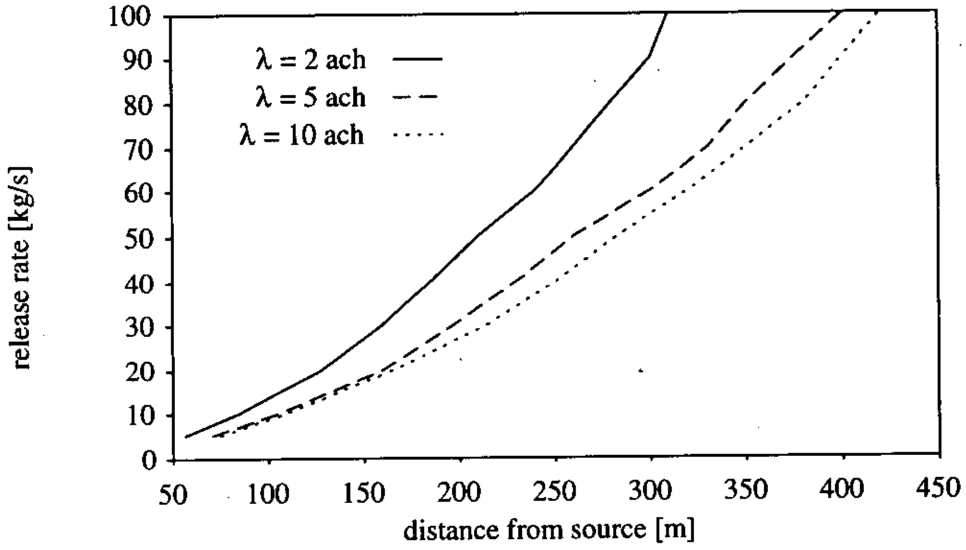

Figure B.4 Release rate giving external concentration resulting in flammable mixture inside a building using HEGADAS.

B.2 Probability of ignition in an area with buildings of different ventilation rates

It is initially assumed that, if two different buildings in a domain have different ventilation rates, then the solution grid will be defined so that these buildings fall into different grid cells. However, if buildings with different ventilation rates are mixed and dense, this may not be possible. It is therefore necessary to find the probability of ignition in a grid cell containing buildings with different ventilation rates.

As an example, it is assumed that an area contains 3 different types of buildings with ventilation rates λ_1, λ_2 and λ_3. Using the method given in Section B.1, it is possible to find the concentration field at every time step inside and outside all building types. These are denoted by $C_o(t,x)$, $C_{b1}(t,x)$, $C_{b2}(t,x)$ and $C_{b3}(t,x)$. It is then possible to define the areas in which the inside concentration in each building type is between the flammability limits. These are denoted by A_{b1}, A_{b2} and A_{b3}. All ignition sources are now classified as either outdoor, inside building type 1, inside building type 2 or

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inside building type 3. Now it is possible to find the probability of no ignition inside each building type using the method given in Section 5.2. Hence, the probability of no ignition is given by:

$$Q = Q_{A_o} Q_{A_{b1}} Q_{A_{b2}} Q_{A_{b3}} \qquad \text{(B.5.)}$$

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