A FRAMEWORK FOR IGNITION PROBABILITY OF FLAMMABLE GAS CLOUDS

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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 safety assessments. 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, including their area density, whether they are intermittent or continuous and whether they are enclosed in buildings.

Keywords: Ignition probability, flammable gas clouds, risk assessment

INTRODUCTION

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. Current risk analyses generally use simple models 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. Current modelling tends to be based on extrapolation of limited incident data or, in many cases, on the judgement of those conducting the safety assessment. Spencer & Rew (1) provide a detailed review of current methodologies for ignition probability modelling and discuss availability of data on both accidents and potential ignition sources. This paper summarises this review and outlines the framework for a proposed ignition probability model.

There is a large variation in the properties of ignition sources found in industrial, urban or rural areas, relating to their strength, activity or intermittency, and their area density, i.e. the number of sources per unit area. A statistical framework for calculating ignition probability has been developed which accounts for this variation in ignition source characteristics. 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. Thus the model is able to differentiate between edge and central ignition of a gas cloud and accounts for the time dependency of ignition, for example, whether ignition occurs before the gas cloud has reached its maximum size. Results from a preliminary implementation of the model are used to illustrate the sensitivity of ignition probability, and thus risk calculations, to variations in ignition source properties.

IGNITION DATA

Ignition has been defined by Williams (2) as the process whereby a material capable of reacting exothermically is brought to a state of rapid combustion. At atmospheric temperatures and pressures, flammable mixtures of hydrocarbons and air will not ignite unless a source of energy is provided. Ignition may occur due to the production of low voltage inductive break sparks or high voltage capacitance sparks from electrical equipment, as well as due to heat produced by resistive heating of wires. Other heat sources capable of causing ignition of flammable gases are hot gases, surfaces, mechanical friction sparks and thermal radiation. Open flames are a strong source of ignition due both to supply of heat and free radicals. Energy capable of igniting flammable gases may be released by electrostatic discharge. Ignition may also result from a variety of less common processes, such as compression and shock waves and stray currents produced by electromagnetic radiation. Many authors have discussed the wide range of energy sources that are capable of igniting flammable gas clouds. For example, Eckhoff & Thomassen (3) provide a comprehensive review of sources on offshore installations and discuss the processes by which ignition can occur. CCPS (4) provide a similar review for onshore process installations.

Many experiments have been conducted to characterise the properties of flammable gases in order to estimate how 'easily' or how 'quickly' they can be ignited. Some of these characteristics include minimum ignition energy, minimum volume, autoignition temperature and ignition lag time. Data on these properties and discussions on different ignition processes are provided by Medard (5), Lees (6), Kuchta (7) and Dean et al (8), amongst many others.

Incident Data

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 such information. As well as identifying likely ignition sources, incident data have been used to estimate the proportion of ignitions that occur for different source types and, in many cases, have been used to provide estimates of probability of ignition for different release scenarios and sizes. A number of surveys have been conducted for the offshore industry which include information on ignition sources, for example by Forsth (9). Although these surveys are valuable in providing general information on ignition of flammable gas clouds, the range of ignition sources encountered in a controlled offshore environment bears little relation to those encountered onshore, especially where ignition occurs offsite. Therefore, the majority of incident data discussed below relates to onshore incidents only.

An example of the use of incident data to identify key ignition sources is that provided by Simmons (10), who 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. Further reviews of incident data are provided by Cox et al (11), who produced a study on ignition sources based on an analysis of a data bank of national incidents provided by the Health and Safety Executive, and Crowl & Louvar (12). Reports of incidents provide 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, many of the analyses include 'unknown' sources, which 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.

Incident type	Data source	Size	Probability
General vehicle accidents	Rhoads (13)	all	0.24
LPG vehicle incidents	Croce (14)	all	0.24
LPG/LNG incidents	Simmons (10)	ignition model (see below)	
Gas pipeline releases, World-wide	Townsend & Fearnehough (15)	leaks	0.1
		ruptures	0.5
Gas pipeline releases, US	Jones (16)	ruptures	0.26
		all sizes	0.16
Gas pipeline releases, European	European Gas Pipeline Incident Data Group (17)	pinholes/cracks	0.02
		holes	0.03
		ruptures < 16 in.	0.05
		ruptures >= 16 in.	0.35
		all sizes	0.03
Offshore blowouts	Dahl et al (18)	gas	0.3
		oil	0.08
LPGITA survey	Blything & Reeves (19)	0.2 kg/s mean	0.11

Table 1 Ignition probabilities based on incident data

Various authors have collated incident data in order to estimate the probability of ignition of flammable gas clouds. The estimates usually give ignition probability for specific types of incident or quantity of flammables released. Table 1 summarises some of these probability estimates and indicates the type of incident and flammable materials involved. Note that all values given are inclusive of 'immediate', or event-initiated ignition, i.e. where the cause of release is also a strong ignition source. Event-initiated ignition tends to be more significant for transportation accidents than for storage or process plant incidents.

The variation in values of ignition probability given by the various authors above reflects the wide range of data sources used in their derivation. 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 studies, possibly due to the sparse nature of ignition data, or else due to the effect of variations in land use between different locations. Furthermore, use of historically based data does not allow consideration of improvements in equipment design (such as reduced use of electromechanical devices), or control of electrical ignition sources, on ignition probability.

Ignition Source Characterisation

If a model is to take 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 relating to ignition 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 or on the types of mechanical impact that can release sufficient energy to cause ignition. 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 ignition probability. However, this research is useful for eliminating ignition sources from consideration within an ignition model.

A more comprehensive study on ignition source characterisation is that by Jeffreys et al (20), 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. Characteristics for selected ignition sources are measured or estimated, including ignition potential (the probability that the ignition source will ignite the cloud given that the source is active and enveloped by the flammable mixture), activity and area density. Experiments performed in a 7 % methane/air mixture were used to define the ignition potentials of questionable ignition sources. For example, 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. 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.

The Jeffreys et al (20) study illustrates that the detailed quantification of the properties required to define all possible ignition sources for a range of land-use areas is a major task and it is likely to be more practicable to use a semi-quantitative ranking of ignition sources. The process of ranking ignition sources would draw data from studies such as that of Jeffreys et al (20) (in which sources are already classified as either 'strong', 'medium' or 'weak') 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'. Various experimental studies can be used to eliminate ignition sources from consideration within an ignition model, either on grounds of insufficient energy or low probability of occurring at the same time as a flammable release, forming a further category for those items with 'negligible' ignition potential. Britton (21) provides an example of the ranking of ignition sources based on consideration of their available energy in relation to the minimum ignition energy required for various flammable gas, mist or dust clouds. Figure 1 illustrates how a ranking of ignition sources might be developed, based on experimental studies, current industrial practice and engineering judgement.

CURRENT MODELLING

Current Approach

Current modelling of ignition probability is based on either sparse incident data or expert estimates. Expert estimates of ignition probability used in risk assessment methodologies are reviewed by Cox et al (11) and CCPS (22). For example, the HSE Canvey Island Report (23) 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.

In an HSC (24) report on the transportation of dangerous goods by rail, the ignition probabilities given in Table 2 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 2 Ignition probabilities for LPG transport by rail

Kletz (25) 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. Browning (26) 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 (19) 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.

In addition to the above, a number of simple correlations for ignition probability have been suggested based on historical data rather than site information. Three are reviewed here, two which relate ignition probability to cloud area and one which relates probability to release rate. Simmons (10) conducted a survey of 59 incidents of ignition of clouds of LNG or LPG resulting from accidental spills due to transportation. For these, the size of the cloud when ignition occurred was estimated and the probability of ignition as a function of cloud area fitted to an error function, where $P(A)$ is the cumulative probability of the cloud having ignited at or before it has covered a flammable area, A (m^2):

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

The current method used by HSE in Flammables RISKAT, as described by Clay et al (27), 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, P_f, equal to 0.999999, i.e. $1-10^{-6}$. For F2 conditions the RISKAT model assumes that P_f is equal to 0.9, reflecting the likely lower density of ignition sources when F2 conditions occur (generally at night). The probability that a drifting cloud has ignited is then related to P_f by:

$$P(A) = 1 - \left(1 - P_f\right)^{A/A_f} \tag{2.}$$

where A is the cloud area and A_f is the final area of a flammable cloud resulting from the 200 tonne release. Within the RISKAT model, the ignition probability is calculated on a grid by grid basis for industrial land and is then scaled by 0.8 for urban land and 0.04 for rural land. One disadvantage of the 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'.

Cox et al (11) 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, based on 'observed' data is approximately given by:

$$P = 0.017\dot{m}^{0.74} \tag{3.}$$

In deriving this correlation, 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 (18), and that the probability of ignition for a 'minor' 0.5 kg/s leak is 0.01, based on estimates provided by Kletz (25).

Model Comparison

Figure 2 compares the formula given by Simmons (10), based on historical data, with the probabilities of ignition for industrial, urban and rural areas given by Equation (2). For the purposes of comparison, the ground level area swept by a cloud concentration above LFL has been calculated using the HEGABOX model (Post, 28), giving $A_f = 540,000$ m^2 for 5D conditions. The figure shows that, for all land use types, the probability of ignition of clouds of area less than 10^5 m^2 is significantly underestimated by the HSE model in comparison to the Simmons model.

Probabilities calculated using the Cox et al (11) model are also shown in Figure 2. The cloud area for a particular gas flow rate is calculated using the HEGADAS steady state dense gas dispersion model, Post (28), for D5 conditions. It can be seen that the model predicts slightly lower ignition probabilities than the HSE curves for industrial or urban areas. However, it should be noted that the Cox et al (11) curve is plotted against the maximum, steady-state area that the cloud would have reached had ignition not occurred. However, the Simmons (10) 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 (11) curve is underestimated in Figure 2, and is not directly comparable to the other curves.

Figure 2 illustrates the wide range of ignition probabilities that can result from different interpretations of incident data or expert judgement. Many of the models or values based on expert judgement 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.

MODEL FRAMEWORK

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 would be a compromise between these approaches. 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, using pre-defined source distributions for urban, rural and industrial locations, and considers the following effects:

- flammable cloud size and concentration dependence;
- multiple source types and variations in source properties;

- distribution of ignition sources (assumed to be random);
- variation in source densities between different land use areas;
- time dependency of ignition due to source intermittency and gas ingress into buildings.

Each ignition source in the solution domain can be characterised by four parameters. 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. 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 a source not always causing ignition when activated, for example because it is not enclosed in flammable vapour at the particular time it sparks or is turned on. Alternatively, it can be used to account for sources which produce insufficient energy always to guarantee ignition. However, it does not account for the fraction of particular types of ignition source 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.

Parameter λ is the rate of activation of the source, as defined in Equation (5), and is equivalent to the frequency with which the source becomes active. Parameter **a** is the proportion of time for which the source is active, as defined in Equation (5). Thus, for continuous sources, a is equal to one and for intermittent sources, a is zero. 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.

The probability that an ignition 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 λp, given that the source was not initially active. Thus the cumulative probability that a cloud, with a single generalised ignition source, has not ignited at a time t is given by:

$$Q_1(t) = (1 - ap)e^{-\lambda p t} \tag{4.}$$

$$a = \frac{t_a}{t_a + t_i}, \quad \lambda = \frac{1}{t_a + t_i} \quad \text{for } t_i > 0$$
$$a = 1, \quad \lambda = \infty \quad \text{for } t_i = 0 \tag{5.}$$

where $Q_1(t)$ is the probability of non-ignition and the parameters describing the ignition source are as given below. Intermittent sources are a special type of the generalised intermittent source with $t_a = 0$, and thus a = 0, and continuous sources are a special case with a = 1 and $\lambda = \infty$.

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 can be assumed to follow a Poisson distribution with mean and variance μA. Using the Poisson distribution, the probability of finding exactly n sources of a particular type in the flammable cloud is given by:

$$S_n = \frac{e^{-\mu A}(\mu A)^n}{n!} \tag{6.}$$

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

$$Q_A(t) = \sum_{n=0}^{\infty} S_n (1-ap)^n e^{-n\lambda pt}$$

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

(7.)

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:

$$Q_A = Q_{A1}Q_{A2}...Q_{AJ} = \prod_{j=1}^{J} Q_{Aj} = \prod_{j=1}^{J}\left\{\exp\left\{\mu_j A\left[(1-a_j p_j)e^{-\lambda_j p_j t} - 1\right]\right\}\right\}$$

(8.)

The assembly and discretisation of the model within a two-dimensional grid system, as used in risk assessment codes such as Flammables RISKAT, is detailed by Spencer & Rew (1). The ground containing the release is divided up by a grid of I cells labelled from i = 1, 2,....,I and each cell is assigned a land use type. The probability of ignition in each cell due to each ignition source type is then calculated. Thus, at time t, the probability of the cloud not having ignited is given by:

$$Q(t) = \prod_{i=1}^{I}\prod_{j=1}^{J} Q_{ji}(t)$$

(9.)

where $Q_{ji}(t)$ is as defined in Equation (8.), noting a number of modifications are required to cope with drifting clouds or clouds changing in shape or size. The cell area is used rather than the cloud area, A, and the time, t, is replaced by the duration for which each cell has been enclosed within the flammable cloud.

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.

IMPLICATIONS FOR RISK ASSESSMENT

Figure 3 shows the variation in cumulative probability of ignition with gas cloud area, for an instantaneous 200 tonne release of LPG. Curves for five values of source density, μ, are plotted, noting that all sources are assumed to be strong and continuous (p=1, $\lambda=\infty$). The release is assumed to occur from a 1 hectare industrial site, spreading into the surrounding area which is assumed to have an ignition source density of one tenth of the industrial area. As the cloud reaches the site boundary, the rate of growth of probability of ignition reduces.

Figure 4 shows the effect of ignition source density on risk. In producing this figure it has been assumed that risk, for a particular release, is proportional to the probability of ignition of the cloud at a certain area multiplied by the number of fatalities. It is further assumed that the number of fatalities is proportional to the cloud area at ignition, as may be true for flash fire events. 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. Figure 4 illustrates the high sensitivity of predicted risk levels to the assumed source density. Whether an 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 relative value of source densities used in the model to those found on the site being studied. It should also be noted that ignition probability, and thus risk calculations, are also sensitive to the intermittency of ignition sources. Highly intermittent sources are more likely than continuous sources to cause ignition of a cloud once it has reached its maximum size.

CONCLUSIONS AND FUTURE DEVELOPMENT

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. The three models compared above 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 was found to underpredict in comparison to the model of Simmons (10), which was fitted to data from approximately 60 incidents. However, underprediction of ignition probability with respect to cloud area is not necessarily non-conservative, as ignition may be delayed until the cloud has grown to cover offsite areas, hence producing more severe consequences. 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. Thus the model requires information on the types and distribution of sources encountered in these areas. For each source type, properties relating to their strength, activity and intermittency must be defined. Prediction of risk was found to be highly sensitive to source density and intermittency.

Many useful data on ignition source characteristics have been identified. However, it is clear that a significant amount of further data would be required to define the properties of every ignition source encountered for the different land use types listed above. The model framework described above is therefore being further developed to define the distributions and properties for ignition sources found in industrial, urban and rural land-use types. In order to do this, ignition sources will be ranked and those which have a negligible effect on ignition probability eliminated. The ranking will be undertaken on a semi-quantitative basis, using information on current industrial practice and engineering judgement, as well as relevant experimental or incident data.

ACKNOWLEDGEMENT

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FIGURES

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

Figure 1 Framework for ranking of ignition sources
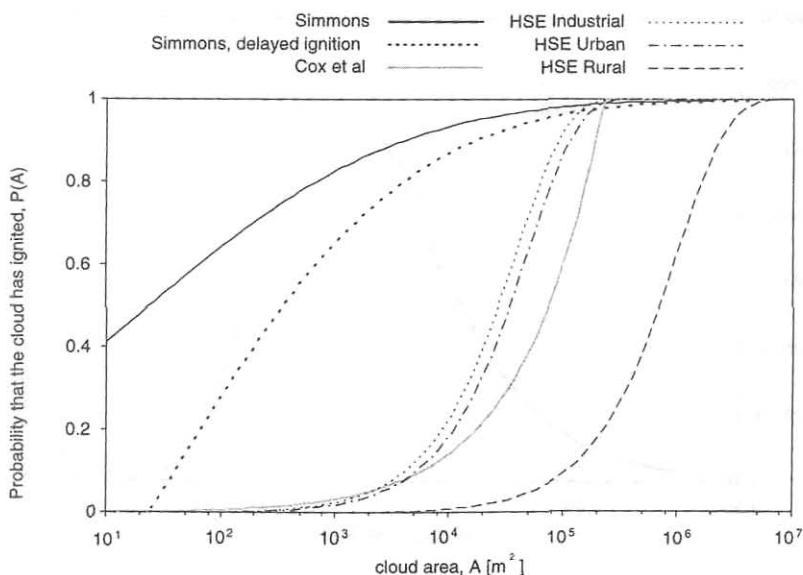

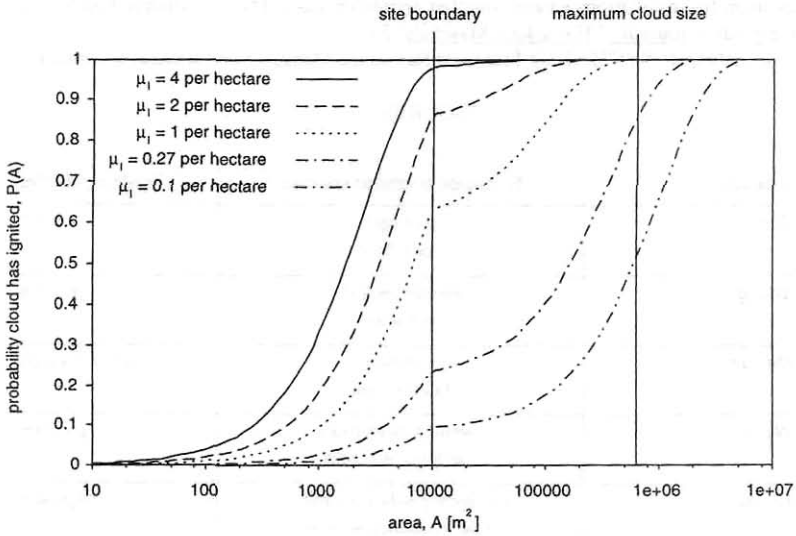Figure 2 Comparison of historical data and model currently used by HSE

Figure 3 Effect of ignition source density on the cumulative probability of ignition
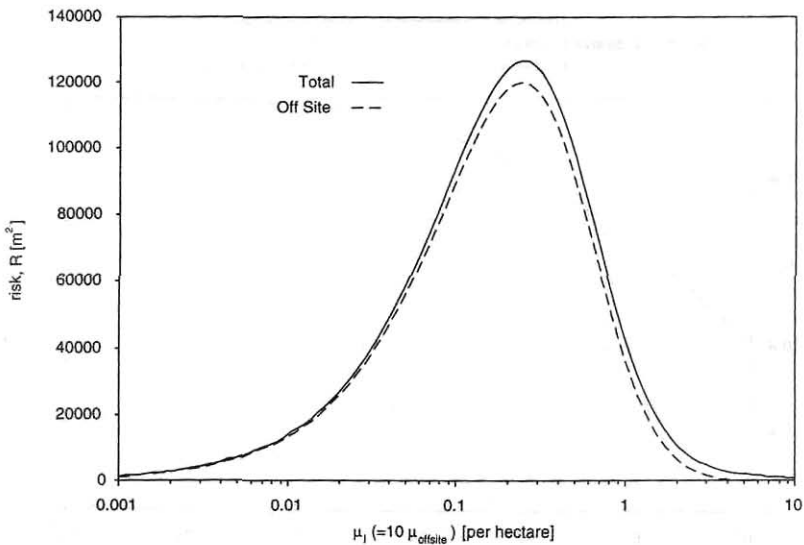

Figure 4 Variation of total and offsite risk with ignition source density