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Off-site ignition probability of flammable gases

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Abstract

A key step in the assessment of risk for installations where flammable liquids or gases are stored is the estimation of ignition probability. A review of current modelling and data confirmed that ignition probability values used in risk analyses tend to be based on extrapolation of limited incident data or, in many cases, on the judgement of those conducting the safety assessment. Existing models tend to assume that ignition probability is a function of release rate (or flammable gas cloud size) alone and they do not consider location, density or type of ignition source. An alternative mathematical framework for calculating ignition probability is outlined in which the approach used is to model the distribution of likely ignition sources and to calculate ignition probability by considering whether the flammable gas cloud will reach these sources. Data are collated on the properties of ignition sources within three generic land-use types: industrial, urban and rural. These data are then incorporated into a working model for ignition probability in a form capable of being implemented within risk analysis models. The sensitivity of the model results to assumptions made in deriving the ignition source properties is discussed and the model is compared with other available ignition probability methods. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ignition probability; Risk analysis; Flammable gas clouds

1. Introduction

Research was undertaken on behalf of the UK Health and Safety Executive with the purpose of improving the understanding of ignition probability modelling. This study involved two phases, the first phase of which [1,2] comprised a review of current methods and data used in risk assessments and resulted in the production of a statistical framework for calculating off-site ignition probability. The approach is to model the

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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 and release duration.

The second phase of the research [3] comprised the collation of ignition source data for a range of off-site land-use types which is used to produce a working model for ignition probability based on the framework developed in Phase 1 of the study. This paper outlines this working model and considers its sensitivity to assumptions made in deriving the generic ignition source properties. It then compares the model with other available methods and discusses requirements for future development.

2. Mathematical model for ignition probability

2.1. Background

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. In most cases, a suitable level of modelling is an intermediate position between these approaches such that ignition probability is calculated by considering the ignition sources found within a range of generic land-use types.

In the UK, ignition probability modelling may be used for Land Use Planning assessments or within the predictive elements of Safety Reports produced under the requirements of the Control of Major Accident Hazards regulations. In the latter case, considerable detail exists regarding the plant design and the land use within the surrounding area. However, in the former case, there may be little information known to the planning authority other than the hazardous substances involved and their respective quantities; any assessment undertaken must therefore be relatively robust against future design changes within the scope of any planning permission given.

The model described in this paper is designed to be ‘conservative best estimate’. Ignition probability is calculated by considering the likelihood of a drifting and/or growing flammable gas cloud encountering ignition sources and the following effects are incorporated:

- flammable cloud size and duration;
- multiple source types and variations in source properties;
- distribution of different types of ignition sources;
- variation in source densities between different land-use areas;
- time dependency of ignition due to source intermittency and gas ingress into buildings.

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 [4].

2.2. Model definition

The model predicts the probability of ignition as a function of time due to a flammable cloud spreading or drifting over an area of land. This area of land is divided up into a grid, with each grid square being allowed to contain a different land-use type (industrial, urban or rural) to adjacent squares. Each of the land-use types contains different ignition sources which are assumed to be randomly distributed.

Each ignition source in the solution domain can be characterised by four parameters.

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

(2) 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-dependent 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 a group of sources which do not always provide enough energy to cause ignition, for which p is set to less than 1. However, for a group of sources which contains a certain fraction that do not cause ignition initially, and will not cause ignition at a later point in time, the area density term, μ, should be reduced by this fraction rather than reducing p. An example of such a group is road traffic lights. Only certain types of traffic light (flashing electromechanical as opposed to solid state) could cause ignition and μ should be set to the area density of this type of traffic light, rather than the density for all traffic lights, with p set to 1.

(3) Parameter λ is the rate of activation of the source, as defined in Eq. (2) below, and is equivalent to the frequency with which the source becomes active.

(4) Parameter a is the proportion of time for which the source is active, as also defined in Eq. (2). Thus, for continuous sources, a is equal to one and for intermittent sources, a tends to zero.

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 assumed to be 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 simplified to Eq. (1), the full derivation of which is provided in Refs. [1,3]:

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

$$a = \frac{t_\mathrm{a}}{t_\mathrm{a} + t_i}, \qquad \lambda = \frac{1}{t_\mathrm{a} + t_i}, \tag{2}$$

where $Q_1(t)$ is the probability of nonignition, t_a is the average time for which the source is active and t_i is the average time between activations. 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 $t_i = 0$, and thus $a = 1$ and $\lambda = 0$.

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:

$$S_n = \frac{e^{-\mu A}(\mu A)^n}{n!} \tag{3}$$

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:

$$Q_A(t) = \sum_{n=0}^{\infty} S_n(1-ap)^n e^{-n\lambda pt}, \tag{4}$$

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

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:

$$Q_A = Q_{A1}Q_{A2}\dots Q_{AJ} = \prod_{j=1}^{J} Q_{Aj} = \prod_{j=1}^{J}\left\{\exp\left\{\mu_j A\left[(1-a_j p_j)e^{-\lambda_j p_j t} - 1\right]\right\}\right\} \tag{5}$$

The assembly and discretisation of the model within a two-dimensional grid system, as used in risk assessment codes such as Flammables RISKAT [4], is discussed in Ref. [3], which contains full details of modifications required to the formulation. The ground containing the release is divided up by a grid of I cells labelled from $i = 1, 2, \dots, I$ 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:

$$Q(t) = \prod_{i=1}^{I}\prod_{j=1}^{J} Q_{ji}(t), \tag{6}$$

where $Q_{ji}(t)$ is as defined in Eq. (5), noting that 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 ignition source has been enveloped above the lower flammable limit (LFL) within the dispersing cloud. Note that for sources enveloped within a building, there will be a delay before the internal concentration reaches the external concentration. Thus the duration for which the ignition sources are enveloped above LFL depends on this delay, which, in turn, depends on the ventilation rate of the building, Λ_j.

3. Ignition source data for generic off-site land-use types

3.1. Data requirements

The ignition sources found within each generic land-use type need to be predefined within the model. Section 2 defines the parameters required for each ignition source (or cluster of ignition sources); p, λ, μ and a. Values for these four parameters are required for each of the J ignition sources that may be found within a particular land-use type. In addition, it must be ascertained whether the ignition source is located inside a building or shelter. If the source, j, is inside, then the ventilation rate of that building enclosing it, Λ_j, must be defined. Note that the density and properties of ignition sources can vary diurnally and therefore separate values of ignition source parameters are required for day and night.

In deriving the data for industrial land-use (and for some properties found in urban areas such as restaurants), it was found that ignition sources tended to be clustered within industrial buildings rather than randomly distributed across an industrial area. Therefore, rather than consider individual ignition sources, the sources have been considered as groups of sources within separate industrial units.

Note that the following generic data is defined for the UK and may need to be modified if the model is to be used for risk analyses within other countries.

3.2. Urban and rural data

An urban area is defined to be one that contains mainly domestic dwellings consisting of a mixture of detached and terraced housing and flats. Other buildings which are assumed to form part of an urban land-use area are restaurants and public houses, shops, hospitals and offices. Each of these buildings will contain a variety of indoor ignition sources such as central heating pilot lights and cooking equipment and some may have balanced flue gas appliances (which use an external air supply and are effectively external sources). External sources in urban areas tend to be associated with transportation systems and include road vehicles, traffic lights and railways. Further external sources are open flames such as bonfires, campfires, barbecues and fireworks.

A rural area is assumed to contain a similar range of ignition sources to that found in an urban area. However, the level of housing is less dense and tends to be limited to single, sparsely spaced units. The proportion of housing containing balanced flue gas appliances is significantly lower than that found in urban areas and these appliances tend to use LPG rather than mains gas. It is assumed that other external sources are as found in urban areas but with a significantly lower density. It is also assumed that there may be a small number of shops and public houses in a rural area, but no offices or hospitals.

The choice of significant ignition sources contained within urban and rural areas, and their probability of igniting a flammable cloud given that they are active, is based on information provided by Jeffreys et al. [5] and Simmons [6]. The densities and frequencies of activation of significant ignition sources in urban and rural areas during the day and night are estimated using published statistics, for example, those published by the UK Office for National Statistics (ONS) [7,8] and UK Department of Transport [9–11].

The ignition source parameters estimated for all ignition sources considered to be significant in urban and rural areas are given in Table 1. Each line within the table corresponds to a single ignition source type j. Thus, for example, for urban day time ignition, data for all sources corresponding to day time conditions in urban areas must be entered in the model.

Table 1
Ignition sources in urban and rural areas during the day and night

Source	Location	Λ_j [ach]	Land-use	Time	μ_j [ha^{-1}]	p_j	λ_j [min^{-1}]	a_j
Road vehicles	Outdoor	∞	Urban	Day	0.51	0.1	0	1
				Night	0.13	0.1	0	1
			Rural	Day	0.027	0.1	0	1
				Night	0.0068	0.1	0	1
Traffic lights	Outdoor	∞	Urban	Day	0.004	1	0.02–1	0
				Night	0.004	1	0–0.1	0
Trains	Outdoor	∞	Urban	Day	2.1×10^{-4}	0.5	0	1
				Night	7.4×10^{-5}	0.5	0	1
			Rural	Day	2.6×10^{-5}	0.5	0	1
				Night	9.2×10^{-6}	0.5	0	1
Balanced flue gas appliances	Outdoor	∞	Urban	Day	2.33	1	0	0.05
				Night	2.33	1	0	0.125
			Rural	Day	1.7×10^{-3}	1	0	0.05
				Night	1.7×10^{-3}	1	0	0.125
Occasional fires	Outdoor	∞	Urban	Day	8.28	1	2.2×10^{-5}	2.6×10^{-3}
				Night	8.28	1	3.4×10^{-6}	4.1×10^{-4}
			Rural	Day	0.20	1	2.5×10^{-4}	3.0×10^{-2}
				Night	0.20	1	5.7×10^{-6}	6.8×10^{-4}
Households	Indoor	2	Urban	Day	8.28	1	0	0.5
				Night	8.28	1	0	0.5
			Rural	Day	0.20	1	0	0.5
				Night	0.20	1	0	0.5
Restaurants and public houses	Indoor	2	Urban	Day	0.034	1	0	0.5
				Night	0.034	1	0	0.3
			Rural	Day	9×10^{-4}	1	0	0.5
				Night	9×10^{-4}	1	0	0.3
Shops	Indoor	2	Urban	Day	0.27	1	0	0.75
			Rural	Day	0.007	1	0	0.75
Hospitals	Indoor	2	Urban	Both	9×10^{-4}	1	0	1
Offices	Indoor	2	Urban	Day	0.16	1	0	0.75

Table 1 shows that the most significant external sources in urban areas are balanced flue gas appliances. When operating, these appliances draw in air directly from outside the house and therefore are classified as external ignition sources with an ignition potential p of 1. It is estimated that approximately 30% of urban homes use such an appliance and that this proportion is growing. Road vehicles are also important ignition sources, for both urban and rural areas, and it should be noted that there is much uncertainty in the value used for their ignition potential p of 0.1. Other external sources, such as occasional fires, traffic lights and railways, have a relatively small impact on ignition probability.

It can be seen from Table 1 that domestic housing is far more significant in terms of the density of indoor ignition sources than all other types of building. It can also be seen that if a flammable cloud encloses a building for a long duration producing a flammable concentration inside, then indoor ignition sources become more significant than external sources, especially in rural areas, where there is less use of balanced flue gas appliances than in urban areas. Thus for long duration releases, ignition probability will be sensitive to assumptions made in defining the proportion of active time a and activation rate λ of indoor sources and the ventilation rate of the building.

3.3. Industrial data

An industrial area is assumed to comprise a mixture of manufacturing plants, wholesalers, retail outlets, vehicle repair workshops, storage facilities and offices. Note that the industrial land-use type relates to areas beyond the boundary of a site storing or processing flammable gases (where there is assumed to be above average control of ignition sources).

Most of the key ignition sources that occur in industrial areas are located inside buildings. There is a wide range of strengths and densities of these sources within industrial buildings and there is also a wide range of different building types. Therefore the emphasis in evaluating ignition probability within an industrial area has been placed on distinguishing between the ignition potential of different building types. Note that as within urban areas, many industrial buildings may use either balanced flue gas appliances or boilers in external housings, both of which can be considered to be external ignition sources.

The external sources occurring in industrial areas have been assumed to be similar to those found in urban areas, except that occasional fires are not included. Thus the ignition source properties of road vehicles, traffic lights and trains are those given in Table 1. A further external ignition source considered in industrial areas is smoking.

The collation of data for the different types of industrial sites is based upon identifying groups of industries that can be represented by one set of ignition source parameters. Industries are classified using the UK Standard Industrial Classification (SIC) code [12]. It is assumed that all the manufacturing groups listed within the SIC code may occur within industrial areas, with the exception of ‘Coke, refined petroleum products and nuclear fuel manufacturing’. This group is considered to be a special case, as such sites either occur outside normal industrial areas or have controlled ignition sources due to the higher than usual risk of gas release. Industrial sites tend to be dominated by manufacturing industries, and the ignition sources within manufacturing plants are determined by the processes taking place, which are often similar for plants that produce similar products. Thus, from analysis of the most common processes involved, the wide range of different industrial building types have been placed into groups of industries which are judged to have similar ignition sources (e.g. manufacturers of electrical products, textile manufacturers). Further nonmanufacturing groups have also been considered such as vehicle repair workshops, warehouses, storage facilities and wholesale trade.

The typical ignition sources that occur within each of these groups have been identified and combined to produce a set of ignition source parameters to represent that ‘industry type’. The resulting industrial ignition source parameters are given in Table 2.

Table 2
Summary of industrial ignition source data
d = day, n = night.

Source	Location	Λ_j	p_j	λ_j [min^{-1}]	a_j	μ_j [ha^{-1}]	
						Day	Night
Food products	Indoor	15	0.25	0.056	0.99	0.097	0.015
	Outdoor	∞	1	0.0083	0.042	0.037	0.006
	Outdoor	∞	1	0.0083	0.281	0.059	0.009
Textiles	Indoor	15	0.15	0.056	0.99	0.163	0.016
	Outdoor	∞	1	0.0083	0.042	0.072	0.007
	Outdoor	∞	1	0.0083	0.281	0.091	0.009
Wood and paper	Indoor	15	0.3	0.035	0.98	0.113	0.008
	Outdoor	∞	1	0.0083	0.042	0.053	0.004
	Outdoor	∞	1	0.0083	0.281	0.059	0.004
Printing	Indoor	15	0.8	0.0277	0.883	0.265	0.066
	Outdoor	∞	1	0	0.125	0.127	0.032
Chemicals	Indoor	15	0.6	0.023	0.99	0.117	0.020
	Outdoor	∞	1	0	1	0.018	0.003
	Outdoor	∞	1	0	0.25	0.062	0.011
Nonmetal	Outdoor	∞	1	0	1	0.062	0.021
Basic metals	Outdoor	∞	1	0	1	0.028	0.009
Metal products	Indoor	15	1	0.039	0.692	0.271	0.068
	Outdoor	∞	1	0	0.125	0.143	0.036
Machinery	Indoor	15	1	0.022	0.584	0.140	0.035
	Outdoor	∞	1	0	0.125	0.081	0.020
Electrical	Indoor	15	0.4	0.0347	0.98	0.145	0.014
	Outdoor	∞	1	0.0083	0.042	0.065	0.006
	Outdoor	∞	1	0.0083	0.281	0.080	0.008
Transport	Indoor	15	1	0.022	0.584	0.051	0.013
	Outdoor	∞	1	0	0.125	0.029	0.007
Other	Indoor	15	0.6	0.037	0.862	0.170	0.026
	Outdoor	∞	1	0	0.25	0.077	0.012
Vehicle repair	Outdoor	∞	0.4	0.042	0.861	0.115	0
Wholesalers	Indoor	15	0.3	0.0167	0.25	0.564	0
	Outdoor	∞	1	0.033	0.003	0.564	0
Road vehicles	Outdoor	∞	0.1	0	1	0.510	0.130
Trains	Outdoor	∞	0.5	0	1	2×10^{-4}	7×10^{-5}
Traffic Lights	Outdoor	∞	1	$0.1^{d}/0.05^{n}$	0	0.004	0.004

Each line within the table corresponds to a single ignition source type j, and the data for all sources must be input to the model for either day or night time conditions. In producing the industrial ignition source data, a number of assumptions have been made in order to provide a picture of a general industrial area. These assumptions are described briefly below:

- *Composition*: the types of businesses and/or buildings that form an industrial area are based on the SIC code, as discussed above;
- *Density*: typical numbers of the different sites that are found in industrial areas is taken directly from the ONS Annual Abstract of Statistics [7] or else is based on employee numbers, also taken from this publication;
- *Machinery factor*: a method of simplifying the range of weaker ignition sources contained in the 'background' equipment of industrial sites has been used, as detailed in [3];
- *Smoking*: smoking is only a source of ignition when lighting up and occurs for 5 min every 2 h;
- *Ventilation*: a standard ventilation rate of 15 ach is applied to all sites where ignition sources are indoors. The use of this value is based on guidance provided by the UK CIBSE [13];
- *Day and night variations*: sites with more than 50 employees are assumed to operate 24 h day^{-1}, whereas smaller sites are assumed to operate only during the normal working hours;
- *Traffic*: ignition source properties are based on urban data;
- *Heating of buildings*: sites with more than 10 employees are assumed to use boilers in external housings, which present a continuous ignition source. One third of sites with less than 10 employees are assumed to use balanced flue boilers.

4. Model results and comparison with current methods

In the first phase of this study [1], two models for ignition probability were identified, one based on cloud area, Simmons [6], and one on release rate, Cox et al. [14]. Of these two models, only that produced by Simmons is wholly based on incident data. Fig. 1 compares the results of the proposed model described in Section 4 with the Simmons model for a large instantaneous releases (200 tonnes) of propane, noting that the Simmons model does not separately consider variations in ignition probability between day and night, nor changes in land-use (e.g. industrial, urban or rural) and is therefore plotted as a single curve.

It can be seen that the proposed model predicts that probability of ignition is highest in an industrial area during the day. The model predicts that probability of ignition is significantly lower at night, since many industrial sites are assumed to shut down at night. The strongest and most prevalent external ignition sources in urban areas are balanced flue boilers, used in residential housing for water and central heating. Since it is assumed that these are used more during darkness hours than during daylight, the probability of ignition at night is higher than during the day in urban areas. Houses in

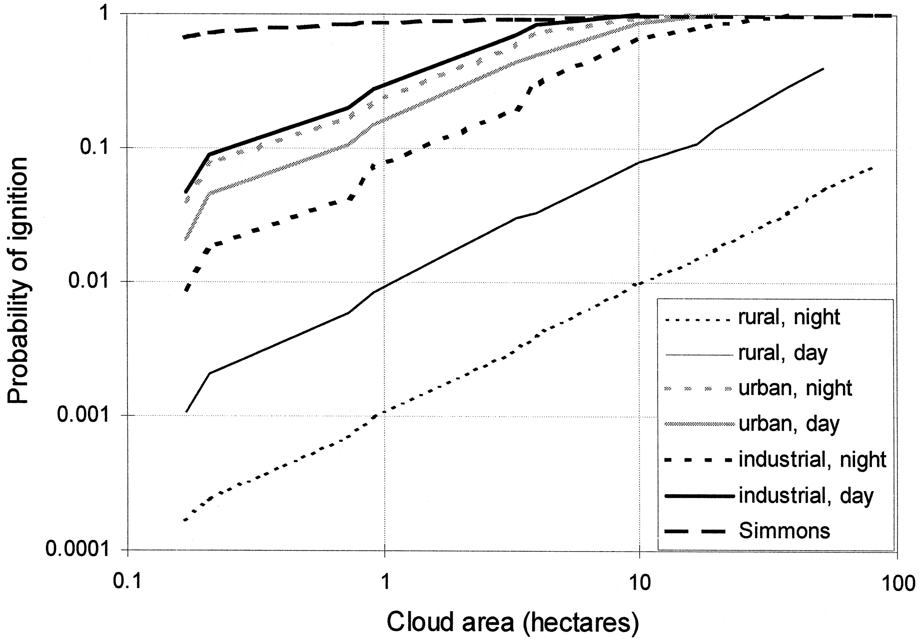

Fig. 1. Model results for 200 tonnes instantaneous release of propane.

rural areas contain a lower proportion of balanced flue appliances than in urban areas. This, amongst other effects, means that the probability of ignition predicted by the proposed model in rural areas is low.

The probability of ignition calculated using the Simmons model is consistently higher than that calculated from either of the other two models. The Simmons model is based on a survey of 59 incidents of ignition of clouds resulting from accidents in storage or transportation of LNG or LPG. Therefore this model may give higher probabilities because it is based on reported incidents in places where ignition sources could be clustered and is unlikely to reflect the densities and types of ignition sources found around UK sites storing flammable gases.

For continuous releases, the probability of ignition calculated using the Simmons model is more similar to that predicted using the proposed model for industrial and urban areas than when the instantaneous release was considered, as illustrated in Fig. 2 for a 50 kg s^{-1} release of propane. However the Simmons model still gives much higher probabilities in the early stages of the release and at all stages for rural areas. Fig. 2 also illustrates the effect of intermittent and internal ignition sources on ignition probability for a long-lasting cloud (rather than the instantaneous, short duration cloud in Fig. 1). For day time conditions, the cloud reaches its maximum size (1 ha) quite quickly, whereas for night time conditions, the cloud continues to grow throughout the dispersion time. Even after the cloud has stopped growing, the probability of ignition continues to increase due to the intermittent and internal ignition sources, which accounts for the jump in the probability of ignition for day time conditions at an area of 1 ha.

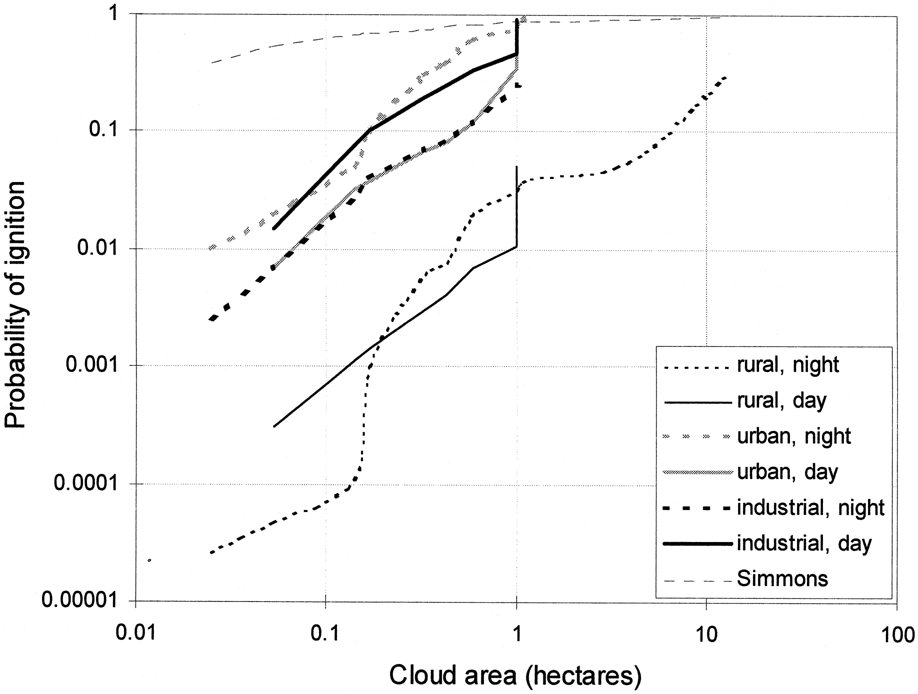

Fig. 2. Model results for 50 kg/s continuous release of propane.

The Cox et al. [14] model suggests that based on observed incidents, the probability of ignition for a 50 kg s^{-1} release is 0.3, noting that this is for ignition of releases on-site rather than off-site. For a site with no control of ignition sources this probability increases to 0.7. In comparison, the proposed model suggests that ignition probabilities will be higher than 0.7 for both day and night time releases. This seems reasonable as most sites storing or using flammable gases are likely to contain fewer gas fired heating systems and vehicle movements than urban or industrial areas.

A recent review [15] suggests that based on various sources of incident data, between 70 and 100% of all releases will be ignited (although they note that the percentage may be lower as not all nonignited releases tend to be reported, especially for small releases). This data at least appears consistent with the proposed model for releases over industrial and urban areas.

5. Sensitivity of model to uncertainties in defining ignition source data

The analysis of the data suggests that boilers used for industrial and domestic heating are the most prevalent off-site source of ignition. For urban and rural areas, road vehicles were the next most common external ignition source, although occasional fires were significant sources within rural areas. For releases of sufficient duration to cause build-up of flammable gas concentrations within buildings, the data suggests that internal ignition sources can be assumed to have a dominant effect on ignition probability. However, it should be noted that in deriving the ignition source properties, the effect of certain ignition sources has been found to be insignificant in comparison with others located in a particular generic land-use area and these sources have been ignored within the proposed model. However, this does not imply that these sources would not ignite a flammable cloud nor that they would not be important sources if the land-use areas were defined differently.

The derivation of the ignition source properties has required the use of a large number of assumptions. The effects of these assumptions are fully considered in Ref. [3], but, in particular, the following should be noted.

(a) The modelling is sensitive to the definition of properties for balanced flue boilers, which take air directly from the outside and are, therefore, considered to be external sources with a probability of ignition of unity (in agreement with data on US appliances provided by Jeffreys et al. [5]). Due to the large number of such boilers in both domestic and industrial buildings, the calculation of ignition probability for all three land-use types depends strongly on assumptions made regarding their use and density. It should also be noted that the use of such appliances is likely to increase in the future.

(b) The use of source properties averaged across generic land-use types may result in significant errors in the prediction of ignition probability for certain sites. Although the purpose of the study was to define average properties for generic sites, these properties may vary significantly from site to site, in particular for industrial areas which may consist predominantly of one type of industry rather than a mixture of industries, and for different times during the year. Ignition probability will be very sensitive to variations in these properties.

(c) The collation of data for industrial sites was found to be far more complex than for urban and rural areas and, therefore, it is likely that there is more uncertainty in the derived ignition source properties than for urban and rural sites. The sensitivity analyses suggest that for large instantaneous releases, predicted ignition properties can vary by up to a factor of two for upper and lower limits on key assumptions made in deriving the industrial ignition source parameters.

6. Conclusions

6.1. Model use within risk analyses

Despite the effect of the above uncertainties on the calculation of ignition probability, the analysis of data for different land-use types has allowed identification of the key off-site ignition sources. Also, the production of the mathematical model has provided a sounder basis for estimating ignition probability, allowing the effect of differences in properties of ignition sources (including intermittency and shelter within buildings) on cloud growth to be considered. The model framework can potentially be used to model the variation in ignition probability between different sites and to indicate the relative benefit of implementing control of ignition sources. Such a comparison is not possible using current models, which tend to be based on incident data and do not consider properties of individual ignition sources.

However, when applying the model, care needs to be exercised when defining ignition source data. Varying ignition source parameters may either increase or reduce predicted risk levels depending on the size of the release and whether it is continuous or of short duration [16]. Therefore, the overall effect on risk calculations for a particular site is difficult to predict and will depend on the relative frequency of different release scenarios. Calculated risk will also depend on how escalation to other fire events is modelled. In particular, the proposed model for delayed off-site ignition must be used in conjunction with consistent models for immediate (event-initiated) ignition, early (on-site) ignition and frequencies of escalation to other events.

6.2. Model development

There are two key areas where the model would benefit from further development.

(1) The ignition source parameters given in this study are derived for off-site releases only. However, the model framework is equally applicable to the estimation of on-site ignition and could potentially be used to provide information on the effect of control of ignition sources, such as permit-to-work procedures and hazardous area classification, on site risk.

(2) The results of the proposed model are highly sensitive to assumptions made regarding certain key ignition sources. Further investigation of the use and ignition potential of balanced flue boilers and starter motors may reduce these uncertainties. Also, the ignition probability of continuous releases is highly sensitive to indoor ignition sources and, therefore, further investigation of the mixing of gas clouds within buildings and its access to these sources may also be of benefit.

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