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A model for the ignition probability of flammable gases
Phase 2

Prepared by
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Page 7, Equation (3.2). Second half of equation to be deleted, giving:

$$a = \frac{t_a}{t_a + t_i}, \quad \lambda = \frac{1}{t_a + t_i} \qquad (3.2)$$

Same correction applies to equation on Page A.2.

Page 7, Paragraph 1, final sentence to be changed to '.... continuous sources are a special case with $\underline{t_i = 0,\ t_a = \infty}$ $\underline{\text{and thus } a = 1 \text{ and } \lambda = 0}$.'

Pages 11 and 13, Tables 3.1 and 3.2. All values of λ_j equal to ∞ to be changed to 0.

Same correction applies to values in Table B.12 (Page B.14) and Table C.4 (Page C.32).

Page A.1, Paragraph 4, final sentence to be changed to '....λ can be set to $\underline{0}$.'

MISC 167

A model for the ignition probability of flammable gases

Phase 2

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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 (HSE) 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.

A study was undertaken with the purpose of improving the understanding of ignition probability modelling, involving two phases, the first phase of which comprised a review of current modelling and data. 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 statistical framework for calculating ignition probability was also outlined in which the approach used was to model the distribution of likely ignition sources 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 and includes effects such as gas ingress into buildings.

In the second phase of the study, described in this report, data was collated on the properties of ignition sources within three generic land-use types: industrial, urban and rural. This data is then incorporated into a working model for ignition probability in a form capable of being implemented within risk assessment models. The model is compared against current methods based on incident data and expert judgement. The sensitivity of the model results to assumptions made in deriving the ignition source properties is investigated and consideration is given to how risk calculations would be affected by use of the model compared with use of other available methods.

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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.

This study, which was undertaken with the purpose of improving the understanding of ignition probability modelling, involves two phases, the first phase of which (Spencer & Rew, 1997) comprised a review of current modelling and data. 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 statistical framework for calculating ignition probability was also outlined in Phase 1 of the study. The suggested approach was 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.

The second phase of the research is described in this report. It comprises the collation of ignition source data for a range of off-site land use types (industrial, urban and rural) which is used to produce a working model for ignition probability based on the framework developed in Phase 1 of the study. Note that this report does not consider, or collate data for, on-site ignition sources. The objectives and full scope of work for the project are described below.

1.2 Objectives and scope of work

1.2.1 Objectives

The overall objective for the research programme was to develop a model for the estimation of the probability of ignition of flammable gas clouds, providing a more rigorous approach than current, simple methods allow. Phase 1 provided a review of current methodologies and data and has defined a framework for improved ignition probability modelling.

The objective of Phase 2 of the study is the development of the framework defined in the first phase of the study, in order to produce a working model for ignition probability of flammable gases.

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1.2.2 Scope of work

Phase 1 - Review of Ignition Probability Modelling

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.

Phase 2 - Development of Ignition Probability Model

i. *Model development.* A model for ignition probability is developed, based on a detailed specification produced from the framework outlined in Phase 1.

ii. *Model comparison.* The model is compared against incident data and assessed with respect to its applicability to risk assessment of installations where flammables are stored. The model is also compared against current methodologies used for the prediction of ignition probability.

The approach used for Phase 2 is discussed below.

1.3 Methodology

Task 1 - Specification of model

A statistical framework for the prediction of ignition probability was outlined in Phase 1 of the study. Based on this framework, a working model is designed such that it covers the key modelling issues identified in the first phase of the project and is suitable for implementation in models such as the Flammables RISKAT program. The model will require the following input in order to predict ignition probability at a certain grid location:

- land use type at the point of ignition (industrial, urban, rural or special);
- flammable cloud duration at the grid location;
- time of release (day/night).

The model will use pre-defined ignition source characteristics and distributions for the four land use types given above. However, it is designed so that the user can modify default values based on knowledge of the site, for example, where more detailed definition of ignition sources is available at grid points close to the release location. In order to allow modification of default values, the model is designed to be transparent to the user (i.e. with model outputs clearly defined and with documentation which provides background information on ignition sources for particular industrial plant types). However, the model input will not require a site survey of possible ignition sources.

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Task 2 - Model development and collation of ignition source data

An ignition probability model is developed, based on the specification produced in Task 1. In order to use the statistical framework outlined in the first phase of the study to predict ignition probability, the density and characteristics of ignition sources within industrial, urban and rural land use types are defined. It should be noted that the activity of sources may vary from day to night, thus requiring six rather than three ignition source distributions to be defined.

Many useful data on ignition source characteristics were identified in Phase 1 and a recent review by HSL (Worsell, 1996) gives additional information on the types and proportions of sources involved in the ignition of flammable gas clouds. However, it is clear that a significant amount of further data is required in order to define the properties of every ignition source encountered for the different land use types listed above. The process of collating this data has been simplified as follows. Firstly, ignition sources are ranked and those which have a negligible effect on ignition probability eliminated. The ranking has been undertaken on a semi-quantitative basis, using information on current industrial practice and engineering judgement, as well as relevant experimental or incident data. Having completed the ranking, data on those items which are known to be certain, or strong, sources of ignition are collated. Then weaker sources are examined and, where possible, eliminated from consideration within the model if their effect on ignition probability is negligible compared with that of strong sources.

Task 3 - Model comparison

In order to validate an ignition model, comprehensive data on incidents involving the ignition of flammable gas clouds is required, including cloud area, ignition location and time, source type etc. This information is not readily available and, therefore, full validation of an ignition model is not possible. However, the model can be assessed against incident data, checking whether it accommodates all the various factors which are known to have a significant influence on ignition.

One of the studies identified in Phase 1, which summarised incidents involving the ignition of flammable vapour clouds, was that reported by Simmons (1974), and the model developed in Tasks 1 and 2 is compared against incident and ignition probability data given by in that study. The model is also compared with other existing methodologies, including that presently implemented in Flammables RISKAT, and the viability of using more recent UK data for the model comparison is investigated.

Task 4 - Model application and sensitivity

The sensitivity of ignition probability to the model inputs, and assumptions used in the methodology, are assessed with respect to its application to the risk assessment of installations where flammables are stored.

1.4 Report outline

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

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Section 2 outlines the model specification, providing background to the development of the model, the mathematical structure of the model and the required data. *Section 3* discusses the methods used in developing the model and summarises the ignition source data within industrial, urban and rural land-use areas.

Section 4 compares the model with current methods for estimating ignition probability and defines the modelling assumptions and data to which it is sensitive. Section 5 discusses the application of the model within risk assessments. Section 6 then presents the conclusions of the study.

Appendix A details the mathematical model for ignition probability. Appendices B and C list the assumptions and sources of data used in defining ignition source properties for urban and rural sites and industrial sites, respectively. Appendix D provides detailed results for sensitivity analyses of the effects of uncertainties in the model data on ignition probability.

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2. MODEL SPECIFICATION

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 (industrial, urban and rural).

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 ignition probability model described in this study is designed to be 'conservative best estimate'. The definition of generic ignition source data in Section 3 for various land use types allows its use for hazard assessments where detailed information is unavailable on ignition sources in the proximity of the site. However, the mathematical basis for the model and the derivation of the generic ignition source data are fully detailed in this report, in Sections 2.2 and 3, respectively. This should allow the effect of particular ignition source properties around a site to be incorporated where such detailed information is available.

In Phase 1 of this study (Spencer & Rew, 1997) a mathematical model for ignition probability was defined. In this model, ignition probability is calculated by considering the likelihood of a drifting and/or growing flammable gas cloud encountering ignition sources. The likelihood of ignition occurring will depend on the distribution of different types of ignition source within the area of the flammable cloud. Consideration is given to how the characteristics of ignition sources (area density, strength and whether they are intermittent or continuous) affect when and whether ignition occurs. In deriving the model the following effects were incorporated:

- flammable cloud size and concentration dependence;
- 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

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this is the approach followed in Flammables RISKAT (Clay et al, 1988). Also, data for on-site ignition sources has not been collated in this report and Section 3 considers only off-site ignition of large flammable releases. However, the mathematical model described below can be applied to both on-site and off-site ignition, provided that ignition source data is available.

The structure of the model is summarised in Section 2.2 below and further details of the model structure are provided in Appendix A. Section 2.3 defines the data required to characterise the ignition sources found within each generic land-use type.

2.2 Model structure

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. 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.

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 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) cause ignition and μ should be set to the area density of this type of traffic light, rather than that for all traffic lights, with p set to 1.

Parameter λ is the rate of activation of the source, as defined in Equation (3.2), 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 also defined in Equation (3.2). 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 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:

$$Q_1(t) = (1-ap)e^{-\lambda pt} \qquad (3.1)$$

$$\begin{aligned} a &= \frac{t_a}{t_a+t_i}, & \lambda &= \frac{1}{t_a+t_i} & &\text{for } t_i > 0 \\ a &= 1, & \lambda &= \infty & &\text{for } t_i = 0 \end{aligned} \qquad (3.2)$$

where $Q_1(t)$ is the probability of non-ignition, 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 $a = 1$ 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:

$$S_n = \frac{e^{-\mu A}(\mu A)^n}{n!} \qquad (3.3)$$

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:

$$\begin{aligned} Q_A(t) &= \sum_{n=0}^{\infty} S_n (1-ap)^n e^{-n\lambda pt} \\ \Rightarrow \ln\{Q_A(t)\} &= -\mu A\left[1-(1-ap)e^{-\lambda pt}\right] \end{aligned} \qquad (3.4)$$

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:

$$Q_A = Q_{A1}Q_{A2}\cdots Q_{AJ} = \prod_{j=1}^{J} Q_{Aj} = \prod_{j=1}^{J}\left\{\exp\left\{\mu_j A\left[(1-a_j p_j)e^{-\lambda_j p_j t} - 1\right]\right\}\right\} \qquad (3.5)$$

It should be noted that ignition sources are often not randomly distributed but may be clustered together, for example in a small industrial site. In this case, a number of ignition sources are assumed to be all in the same place in a site which has a random distribution throughout the land type use. Appendix A.3 shows how such a cluster of ignition sources can be defined as a single ignition source.

The assembly and discretisation of the model within a two-dimensional grid system, as used in risk assessment codes such as Flammables RISKAT, is discussed in Section 5.3 and details of modifications required to the maths are provided in Appendix A.2.

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Appendix A.4 also gives a number of simplified versions of the model derived for scenarios of fixed cloud size and for areas containing only continuous ignition sources.

2.3 Data requirements

As discussed in Section 2.1, ignition probability is calculated by considering the ignition sources found within a range of generic land-use types (industrial, urban and rural). Therefore, the ignition sources found within these land-use types need to be pre-defined within the model.

Section 2.2 gives the parameters required to define each type of 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.

Section 3 shows how the above data has been collated for the ignition probability model. It identifies the significant ignition sources to be found within each land-use type and summarises the parameters for each of these sources. The density and properties of ignition sources can vary diurnally and therefore separate values of source parameters are required for day and night.

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3. DERIVATION OF IGNITION SOURCE PROPERTIES

3.1 Data collation

In order for the model defined in Section 2 to be used within a risk assessment, information on the types and distribution of sources encountered within industrial, urban and rural areas must be collated. It is clear from the review of data conducted in the first phase of this study that defining the properties of every possible ignition source is not practicable.

Thus the first step in further developing the model is to define which ignition sources are significant and which ones can be ignored because they have a negligible effect on ignition probability in comparison to the significant sources. This is done by initially ranking possible ignition sources with respect to strength (for which there is a reasonable quantity of both quantitative and qualitative data). Then the properties of the perceived key ignition sources are defined. Having done this, the properties of weaker sources are investigated, and, where possible, eliminated from consideration within the model if their effect on ignition probability is negligible compared to the stronger sources.

In deriving the data for industrial land-use (and for some properties found in urban areas such as restaurants), a further simplification has been used. 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. Appendix A.2 discusses the method used to convert the properties of a cluster of sources into those of a single ignition source.

Sections 3.2 and 3.3 summarise the ignition source data for urban and rural areas and industrial areas, respectively, for both day and night. Appendices B and C provide details of the derivation of this data. Thus each of the J ignition sources (or groups of ignition sources) for each land-use type, during either day or night, are fully defined in Tables 3.1 and 3.2.

3.2 Urban and rural data

For the purpose of this study, 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). It should be noted that the cluster of ignition sources contained within a building has been considered as a single ignition source, as discussed in Section 3.1. 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

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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 (1982) and Simmons (1974). As discussed by Spencer & Rew (1997), the former provided a survey of the key ignition sources found in the Boston area.

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, including those from transport, population and housing. Sources of statistics include the Office for National Statistics and Department of Transport. A full discussion of the methods used to estimate the ignition source parameters from these statistics is given in Appendix B.

The ignition source parameters estimated for all ignition sources considered to be significant in urban and rural areas are given in Table 3.1.

The table 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 (see Appendix B.3.1). 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 3.1 that domestic housing is far more significant in terms 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. As discussed in Appendix B.4.1, parameters a and λ are based on judgement and are therefore uncertain.

The sensitivity of ignition probability to the assumptions made in deriving the data given in Table 3.1 is further discussed in Section 4.3.

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Source	Location	Λ_i [ach]	Land-use	Time	μ_i [per hectare]	p_j	λ_j [per min]	a_j
Road vehicles	Outdoor	∞	Urban	Day	0.51	0.1	∞	1
				Night	0.13	0.1	∞	1
			Rural	Day	0.027	0.1	∞	1
				Night	0.0068	0.1	∞	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	∞	1
				Night	7.4×10^{-5}	0.5	∞	1
			Rural	Day	2.6×10^{-5}	0.5	∞	1
				Night	9.2×10^{-6}	0.5	∞	1
Balanced flue gas appliances	Outdoor	∞	Urban	Day	2.33	1	∞	0.05
				Night	2.33	1	∞	0.125
			Rural	Day	1.7×10^{-3}	1	∞	0.05
				Night	1.7×10^{-3}	1	∞	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	∞	0.5
				Night	8.28	1	∞	0.5
			Rural	Day	0.20	1	∞	0.5
				Night	0.20	1	∞	0.5
Restaurants and public houses	Indoor	2	Urban	Day	0.034	1	∞	0.5
				Night	0.034	1	∞	0.3
			Rural	Day	9×10^{-4}	1	∞	0.5
				Night	9×10^{-4}	1	∞	0.3
Shops	Indoor	2	Urban	Day	0.27	1	∞	0.75
			Rural	Day	0.007	1	∞	0.75
Hospitals	Indoor	2	Urban	Both	9×10^{-4}	1	∞	1
Offices	Indoor	2	Urban	Day	0.16	1	∞	0.75

Table 3.1 Ignition Sources in urban and rural areas during the day and night

3.3 Industrial data

For the purpose of this study, an industrial area is assumed to comprise a mixture of manufacturing plants, wholesalers, retail outlets, vehicle repair workshops, storage facilities and offices.

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 3.1. A further external ignition source considered in industrial areas is smoking.

The analysis of the different types of industrial sites performed here, which is detailed in Appendix C, is based upon identifying groups of industries that can be represented by one set of ignition source parameters. Industries are classified using the Standard Industrial Classification (SIC) code as produced by ONS (1992). 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 non-manufacturing 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 3.2. This table also provides properties of general outdoor sources (road vehicles, rail and traffic lights).

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 (1997) 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 (and is detailed in Appendix C.2.3);
- *Smoking* - smoking is only a source of ignition when lighting up and occurs for 5 minutes every two hours (see Appendix C.2.4);
- *Ventilation* - a standard ventilation rate of 15 ach is applied to all sites where ignition sources are indoors. The use of this value is discussed in Appendix C.2.6 and is based on guidance provided by CIBSE (1986);
- *Day and night variations* - sites with more than 50 employees are assumed to operate 24 hours per day, 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.

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It can been seen that there is some uncertainty in many of the above assumptions; the sensitivity of ignition probability to these is further discussed in Section 4.3. In particular, it should be noted that the outdoor component of each industry type includes the effect of external boilers or balanced flue boilers. As within urban areas, externally located gas fired heating tends to be the most significant source of ignition.

Source	Location	Λ_i	p_i	λ_i	a_i	μ_i [per hectare]	
				[per min]		(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 & 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		0.125	0.127	0.032
Chemicals	Indoor	15	0.6	0.023	0.99	0.117	0.020
	Outdoor	∞	1	∞	1	0.018	0.003
	Outdoor	∞	1	∞	0.25	0.062	0.011
Non-metal	Outdoor	∞	1	∞	1	0.062	0.021
Basic Metals	Outdoor	∞	1	∞	1	0.028	0.009
Metal Products	Indoor	15	1	0.039	0.692	0.271	0.068
	Outdoor	∞	1	∞	0.125	0.143	0.036
Machinery	Indoor	15	1	0.022	0.584	0.140	0.035
	Outdoor	∞	1	∞	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	0.2813	0.080	0.008
Transport	Indoor	15	1	0.022	0.584	0.051	0.013
	Outdoor	∞	1	∞	0.125	0.029	0.007
Other	Indoor	15	0.6	0.037	0.862	0.170	0.026
	Outdoor	∞	1	∞	0.25	0.077	0.012
Vehicle Repair	Outdoor	∞	0.4	0.042	0.861	0.115	0.000
Wholesalers	Indoor	15	0.3	0.0167	0.25	0.564	0.000
	Outdoor	∞	1	0.033	0.0033	0.564	0.000
Road Vehicles	Outdoor	∞	0.1	∞	1	0.510	0.130
Trains	Outdoor	∞	0.5	∞	1	0.000	0.000
Traffic Lights	Outdoor	∞	1	$0.1^d/0.05^n$	0	0.004	0.004

d = day, n = night

Table 3.2 Summary of industrial ignition source data

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4. MODEL COMPARISON AND SENSITIVITY

4.1 Availability of ignition probability data for model comparison

In the first phase of this study, Spencer & Rew (1997) identified three models for ignition probability, two based on cloud area (Clay et al, 1988, Simmons, 1974) and one on release rate (Cox et al, 1990). These existing models have been compared with the proposed model described in Sections 2 and 3. Appendix D describes the comparison exercise and provides details of the above models.

Of the three available models, only that produced by Simmons is wholly based on incident data (59 accidents involving spills of LNG or LPG). Unfortunately, the data relates to US transportation incidents alone and is unlikely to reflect the densities and types of ignition sources found around UK sites storing flammable gases. Furthermore, the Simmons model does not separately consider variations in ignition probability between day and night and for changes in land-use (e.g. industrial, urban or rural). Therefore this model cannot be used for validation of the model developed in this study, although the models are compared in Section 4.2.

The current method used by HSE (Clay et al, 1988) is based on expert judgement alone. It is also compared with the proposed new model in Section 4.2, in which it is shown how the methods vary from each other for different land-use types. The model produced by Cox et al (1990) is based upon a combination of incident data and expert judgement and is for continuous releases only. It also relates to releases over sites, rather than off-site, and gives the variation in ignition probability for cases with and without control of ignition sources. Section 4.2 compares ignition probability calculated for two continuous releases.

HSL (Worsell, 1996) have recently completed a review of the risk of ignition of explosive atmospheres. Within this review, 100 incidents were identified in which a release of flammable material built up to form a cloud which grew until it came into contact with a source of ignition. Thus, potentially this data could be analysed further to produce a model with a similar format to that of Simmons. However, many of the incidents occurred outside the UK and the remaining data is likely to be sparse, especially if divided into day and night and three different land-uses. Therefore, this data has not been considered further in the present study, except in providing a rough estimate of the proportion of total releases that were ignited (see Section 4.2).

4.2 Comparison with existing ignition probability models

The probability of ignition is compared for four releases of propane; two large instantaneous releases (200 tonnes) and two continuous releases (50 kg/s) are simulated for different atmospheric conditions, one typical of day time (5D) and the other of night time (2F) conditions. Tables D.1 and D.5 of Appendix D provide full details of the release parameters.

The probability of ignition is calculated using the proposed model for industrial, urban and rural areas, using different model parameters for day and night time conditions, as defined in Sections 3.2 and 3.3. The results of these calculations are compared with the results from the current HSE model (Clay et al, 1988) and the Simmons model (Simmons, 1974) and are shown in Appendix D in Figure D.2 (repeated as Figures 4.1 to 4.4 below) for the instantaneous releases and Figures D.18 to D.20 for the

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continuous releases. A detailed analysis of the results and the comparisons are given in Appendix D, which is summarised here.

As shown in Figure 4.1, for the large, instantaneous release, 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 model predicts that probability of ignition in urban areas during the night is higher than that during the day and that both are higher than the probability of ignition in industrial areas at night. This pattern varies from the current HSE model which predicts that the probability of ignition is higher in industrial areas at night than in urban areas at night and that the probability is higher during the day for both. 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 in urban areas than during the day. Houses in 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 lower than that predicted by the current HSE model, especially at night.

In general, as shown in Figures 4.2 to 4.4, the probability of ignition calculated using the current HSE model tends not to show as much difference between day and night time conditions as the proposed model; the day time probability is always slightly higher than the night time probability. The probabilities using the proposed and current HSE models are about the same in industrial areas, slightly higher using the proposed model for urban areas and slightly lower using the proposed model for rural areas. 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 does not differentiate between different areas or times of day and 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.

Both the current HSE model and the Simmons model define the probability of ignition in terms of the cloud area only; time dependencies from the effects of intermittent ignition sources, or delay in flammable concentrations reaching internal ignition sources, are not considered. For the large instantaneous release, the cloud is above LFL only for a short time and, therefore, for the base case model parameters, there is little effect from intermittent and internal ignition sources since the concentration does not have enough time to reach LFL inside any buildings. However, two 30 minute duration releases are also simulated and intermittent and internal ignition sources affect the probability of ignition much more for these releases, for which a much smaller, more long lasting cloud is produced. For the day time conditions, the cloud reaches its maximum size quite quickly, whereas for the 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. The concentration field varies throughout the calculation domain and therefore the internal concentration reaches LFL at different times in different locations, depending on the external concentration history.

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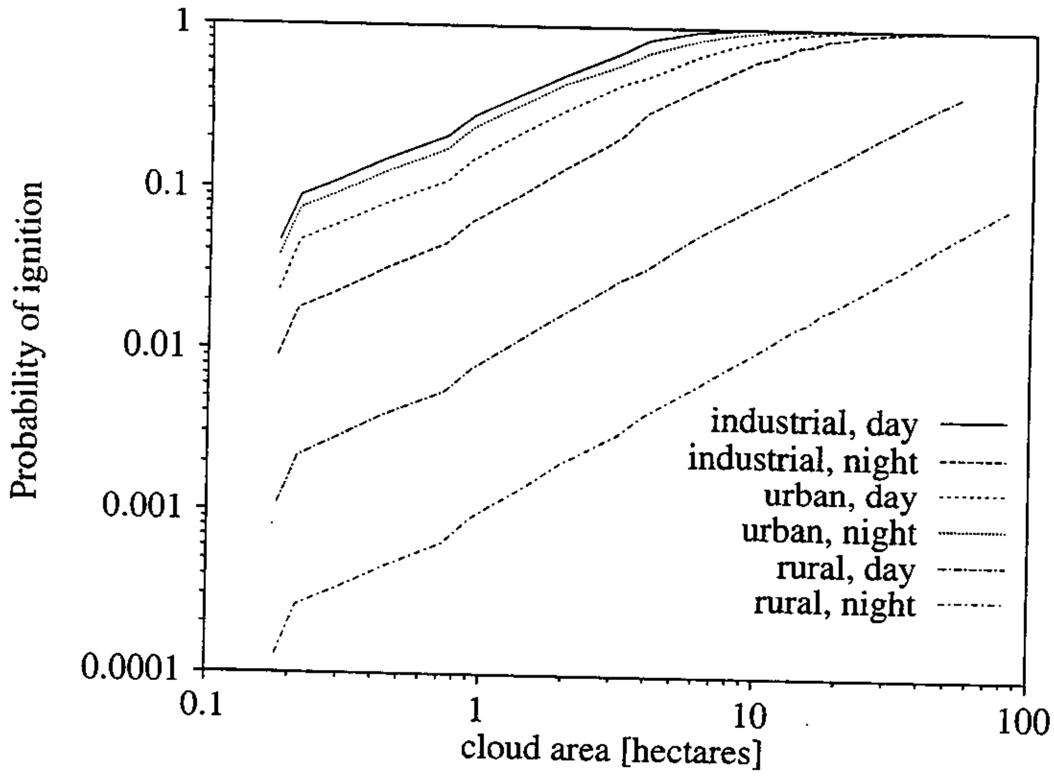

Figure 4.1 Results of proposed model for large instantaneous release of LPG

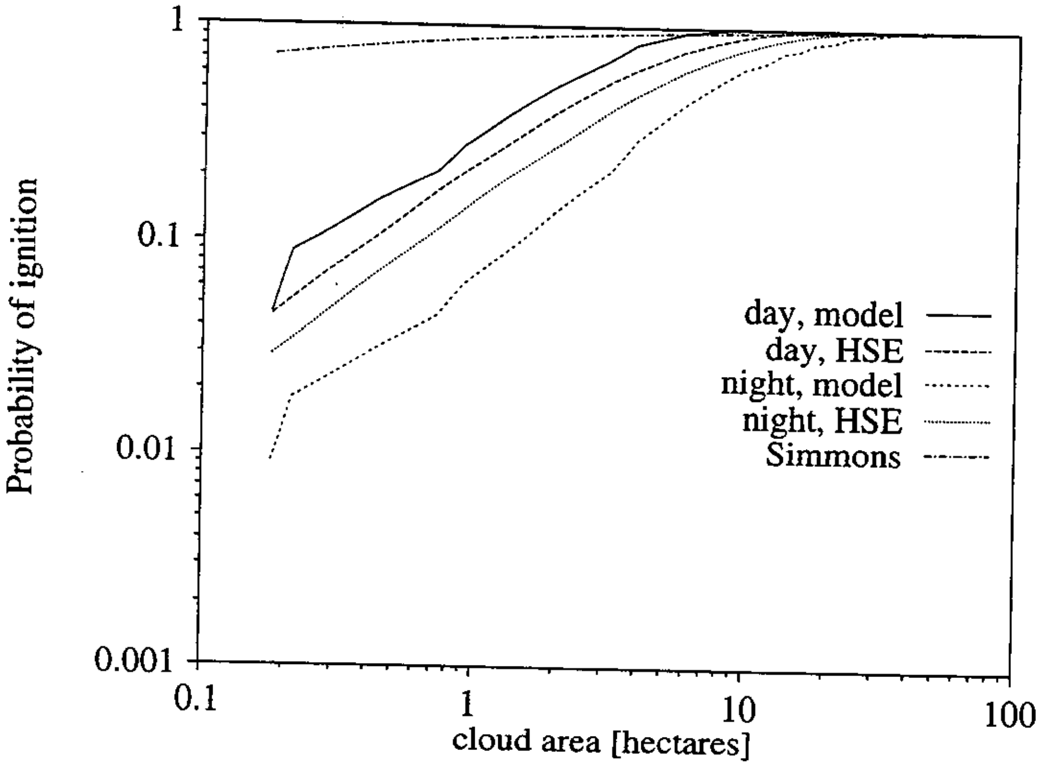

Figure 4.2 Comparison of proposed model with current HSE and Simmons models for industrial areas

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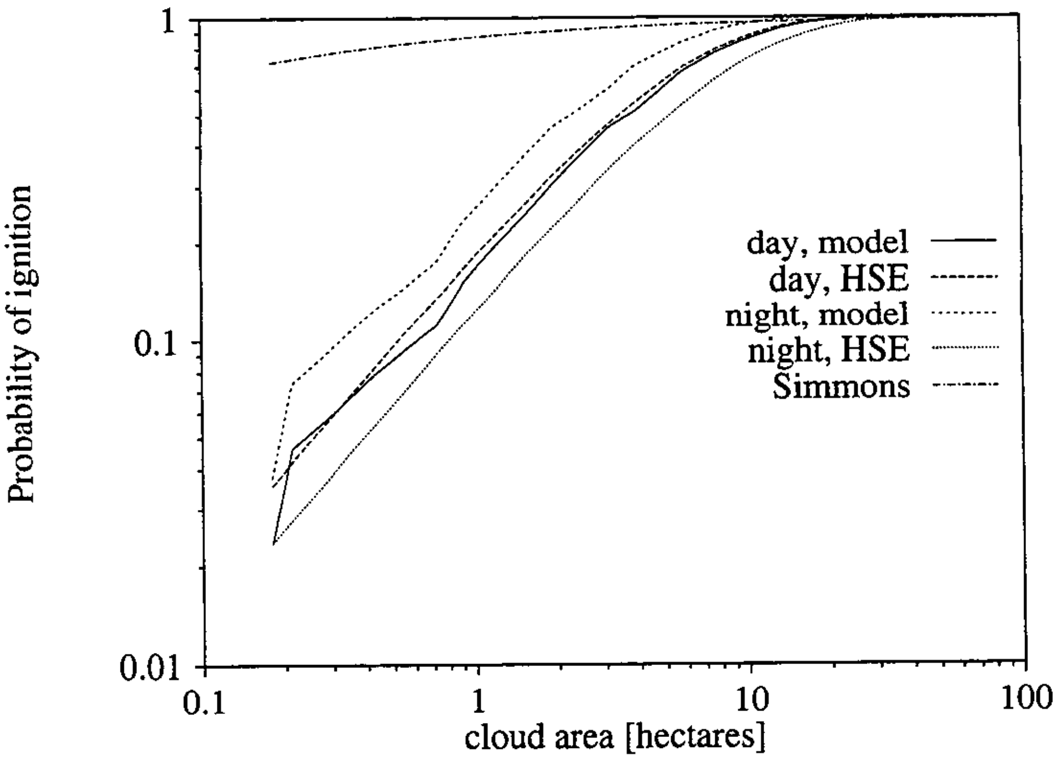

Figure 4.3 Comparison of proposed model with current HSE and Simmons models for an urban area

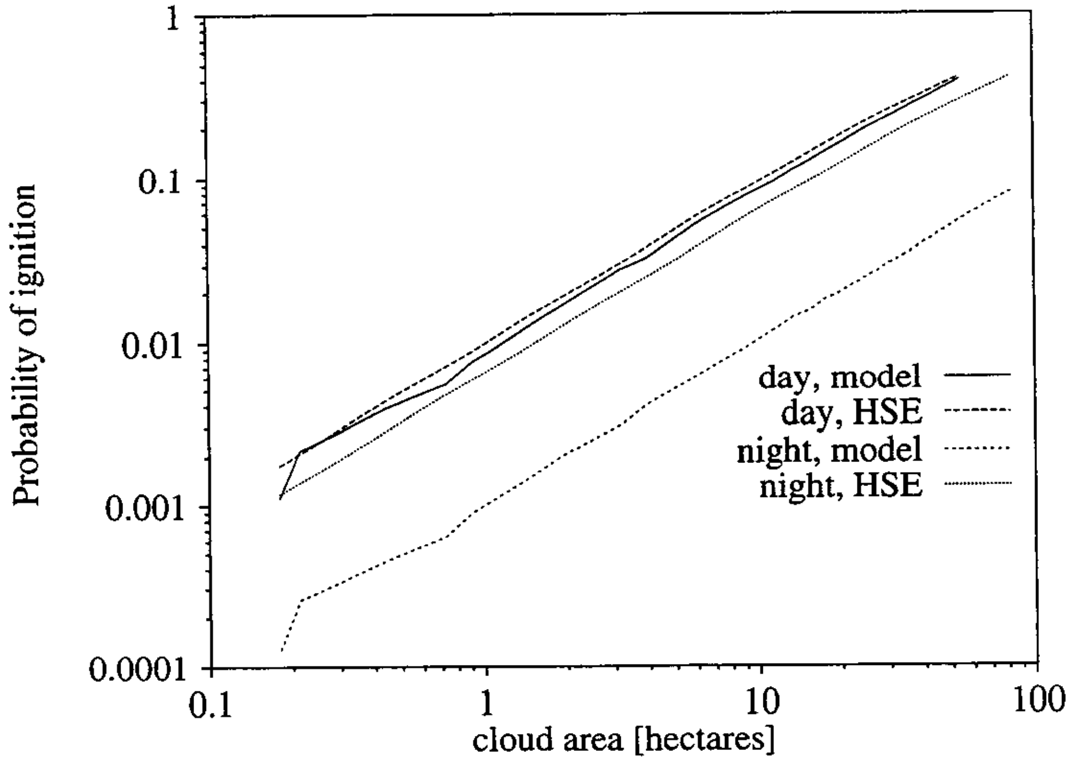

Figure 4.4 Comparison of proposed model with current HSE and Simmons models for a rural area

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Since intermittent and internal ignition sources are so much more significant for continuous than for short-duration releases, the difference in prediction between the proposed model and the current HSE model is far greater than when results for instantaneous releases were compared. The proposed model predicts significantly higher probabilities than the current HSE model for continuous releases. Furthermore, the proposed model predicts higher probabilities of ignition for urban than for industrial areas for the particular releases investigated. It should also be noted that the cloud tends to be closer to its maximum size when ignition occurs, which is especially evident for releases during the day. In Figure D.18, there is a jump in the probability of ignition at an area of 1 hectare, the maximum cloud size.

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. However the Simmons model still gives much higher probabilities in the early stages of the release and at all stages for rural areas.

For 50 kg/s releases of propane, the Cox et al (1990) model suggests that, based on observed incidents, the probability of ignition for a site is 0.3. 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.

HSL (Worsell, 1996) suggest 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 non ignited releases tend to be reported, especially for small releases). This data at least appears consistent with the proposed model for the four release scenarios over industrial and urban areas. However, as discussed in Section 4.1, further analysis of the data would be required in order to relate ignition probability to area of flammable cloud when ignition occurs.

4.3 Sensitivity of ignition probability to model uncertainties

In order to study the sensitivity of the probability of ignition to the choice of model parameters, a large number of variations on the base case model parameters are considered and the probability of ignition determined for all these variations. The base case model parameters for industrial, urban and rural areas during the day and night are defined in Sections 3.2 and 3.3. All the variations considered are defined in Appendix D, which also contains a detailed discussion of the results of the sensitivity analysis. A summary of the results is given here.

It should be noted that, when considering the following sensitivity studies, only the large short duration releases described in Section 4.2 and defined in Table D.2 of Appendix D are considered. For these releases, the probability of ignition is most sensitive to the density of strong external continuous releases. Internal ignition sources are less important due to the relatively long time it takes for the internal concentration to reach LFL, in comparison to the transient nature of the dispersing cloud. Similarly, intermittent ignition sources are not very significant since they are unlikely to be activated within such a short dispersion time.

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4.3.1 Industrial Areas

As discussed in Appendix C, many assumptions have been made in defining the ignition source properties for an industrial area and these may impact on the calculation of ignition probability. The key assumptions made, for which there is some uncertainty, are listed below, together with identification of the figures in Appendix D which illustrate the effect of uncertainties in each of these assumptions:

- density and use of boilers (Figure D.3);
- building ventilation rates (Figure D.4);
- density of industrial sites (Figure D.5);
- night time activity (Figure D.6);
- ignition from background sources (Figure D.7);
- frequency of smoking (Figure D.8);
- composition of an industrial area (Figure D.9);
- density of flares (Figure D.10);
- effect of transportation (Figure D.11).

Boilers are the most prevalent and strongest external source of ignition in industrial areas. It is assumed that a certain percentage of industrial sites have boilers that take air directly from outside, as described in Appendix C. The probability of ignition is therefore highly sensitive to this percentage and the proportion of time for which boilers are used. Figure D.3 illustrates the difference in ignition probability for maximum credible variations on boiler density and usage. During the growth of the flammable cloud, the cumulative ignition probability varies by up to a factor of 2 from the base case for the release scenario considered.

The probability of ignition is also sensitive to assumptions made regarding ventilation rates. Some industrial sites are considered to be so open and well ventilated that ignition sources inside these sites are effectively external ignition sources. The probability of ignition is therefore sensitive to this assumption and the density of this type of site. Figure D.4 shows a variation in cumulative ignition probability of up a factor of 1.5 from the base case for the maximum credible differences in ventilation rate.

There is a wide variation in density of ignition sources between sites (see Table 3.2 of Section 3.3). Figure D.5 shows that ignition probability is highly sensitive to halving or doubling site density, with predicted ignition probabilities varying by up to a factor of 2 from the base case. Therefore, ignition probability for certain areas containing a predominance of certain industrial types may vary significantly from that calculated using ignition source parameters based on the combination of sites defined in Appendix C. The effect of varying the composition of the industrial area is also illustrated in Figure D.9.

Figure D.6 shows that probability of ignition is also sensitive to assumptions made regarding the proportion of sites taken to be active at night. For realistic upper and lower limits on night time operation, the cumulative ignition probability varies by up to a factor of 1.5 from the base case.

Ignition probability does not appear to be sensitive to either background ignition sources or cigarette smoking, both being sparse sources compared to other industrial

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sources. Chemical sites are also so sparse that the probability of ignition is only slightly sensitive to the proportion of chemical sites with flares. Similarly, external ignition sources associated with transportation, such as road vehicles, are weaker and sparser ignition sources than others found in an industrial area. Therefore the probability of ignition is not very sensitive to the density of these sources.

In summary, for the release scenarios considered, the probability of ignition is sensitive to the density and use of boilers which take air directly from outside. It should be noted that little data was found to confirm assumptions regarding the use of boilers on industrial sites and, therefore, use of these assumptions introduces significant uncertainty into the model. Ignition probability is also sensitive to assumptions regarding the ventilation rates of buildings (and hence the access internal ignition sources have to the outside air), the industrial site composition and the density of sites operational at night.

Appendix C.5 discusses the sensitivity analyses more fully. It outlines the choice of parameter variations used in the analysis and provides notes on adjustments that may be required when considering particular industrial sites.

4.3.2 Urban and Rural Areas

As discussed in Appendix B, certain assumptions have been made in defining the ignition source properties for urban and rural areas which may impact on the calculation of ignition probability. The key assumptions made for which there is some uncertainty are listed below, together with the figures in Appendix D which illustrate the effect of uncertainties in these assumptions:

- building ventilation rates (Figure D.12);
- density of balanced flue boilers (Figure D.13);
- density of road vehicles (Figure D.14);
- density of housing (Figure D.15);

The relative effect of different ignition sources on the total probability of ignition is illustrated in Figure D.16.

Buildings in urban and rural areas are all assumed to have a low ventilation rate (approximately 2 ach). Therefore, for a short duration release, such as that considered, the concentration tends not reach LFL inside the buildings. The modelling is sensitive to this assumption, since, for higher ventilation rates, the concentration reaches LFL within the dispersion time, with a coincident rapid rise in the probability of ignition. However, it should be noted that the ventilation rate needs to be increased to over 10 ach before the ignition probability is changed significantly.

In urban areas, balanced flue boilers, which take air directly from the outside, are the most prevalent ignition source. Therefore, at night, the probability of ignition is highly sensitive to the proportion of households which have this type of boiler, the housing density and the proportion of time for which these boilers are in use (with ignition probability increasing by a factor of 1.5 if it is assumed that 50% rather than 33% of households have them). Note that if balanced flue boilers were not considered to be an external ignition source then urban ignition probabilities would drop by a factor of 10. The proportion of housing using balanced flue boilers in rural areas was found to be significantly lower than for urban areas. The probability of ignition in rural areas is sensitive to this reduction in use, with cumulative probabilities varying by a factor of 10 from the base case if the proportion of housing using balanced flue boilers was as for urban areas.

Road vehicles are the second most prevalent external ignition source in urban areas and rural areas during the day and the most prevalent external ignition source in rural areas during the night. Therefore the probability of ignition is sensitive to assumptions regarding their density, although not as sensitive to assumptions regarding use of balanced flue boilers.

Occasional fires such as bonfires and barbecues are strong and quite frequent external ignition sources in rural areas. They are the most prevalent external ignition source during the day and the second most prevalent source during the night. Therefore, ignition probability in rural areas is sensitive to assumptions made in defining the frequency of occasional fires.

In summary, for urban and rural areas, for the releases considered, the probability of ignition is most sensitive to assumptions regarding the density and use of boilers which take air directly from outside. To a lesser extent, it is also sensitive to the ventilation rates of buildings, the density of housing, the density of road vehicles and, for rural areas, the frequency of occasional fires.

It should be noted that the conclusions presented in this section are valid for short duration releases and low ventilation buildings. When a release is long enough for the concentration to reach the lower flammability limit indoors, indoor ignition sources become the most prevalent in all areas during the day and night.

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5. MODEL APPLICATION

5.1 Application within risk assessment studies

The proposed model has been developed with the objective of estimating the probability of delayed ignition of flammable gas clouds. This phase of the study has focused on the derivation of ignition source properties for three generic land-use types (industrial, urban and rural) which are used within a mathematical framework for ignition probability modelling developed in the first phase of the project. Although the model has been developed with risk assessment models, such as HSE's Flammables RISKAT, in mind, the model can be applied more generally within risk assessment studies. However, in doing so, it should be noted that:

- The model is applicable only to delayed ignition and does not include immediate or 'event-initiated' ignition. Thus it does not include ignition sources associated with the release event, for example lightning or transportation accidents.

- The model has been developed for the purpose of determining off-site ignition probability. Although the mathematics of the model are as applicable to on-site releases as they are to off-site releases, the ignition source data used within the model has been collated for typical off-site areas. Therefore, the off-site industrial data will not be relevant to on-site gas processing or storage areas where there tends to be better control of ignition sources, for example through the use of hazardous area classification, and where different ignition sources are more significant.

- In some instances, 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.

A large number of assumptions have been made in deriving the ignition source data used within the model and the sensitivity of ignition probability modelling to these has been investigated in Section 4.3. Section 5.2 discusses the likely impact of these uncertainties on risk calculations. Section 5.3 outlines the requirements for implementing the model within a risk assessment program.

5.2 Sensitivity of risk calculations to model uncertainties

Figure 5.1 illustrates the effect of changing the area density of continuous ignition sources on risk calculated for flash fire type events. It is based on calculations conducted in Phase 1 of this study by Spencer & Rew (1997). These calculations suggest that, for a certain release size, there is an ignition source density, μ_{max}, which gives a maximum value of risk. As the source density is increased beyond this value, the flammable cloud is more likely to ignite before it reaches its maximum size and the calculated risk is reduced. As the source density is reduced below this value, the flammable cloud is more likely to disperse to its maximum size, but less likely to ignite.

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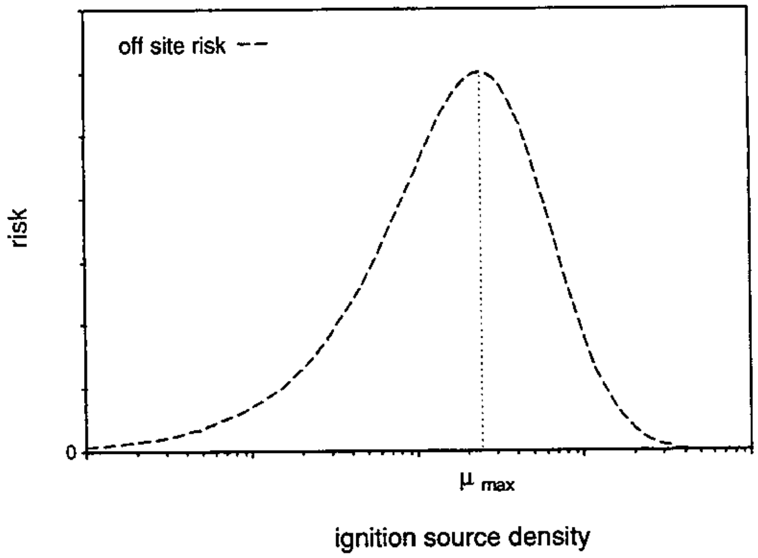

Figure 5.1 Effect of ignition source density on calculated risk

<u>Large instantaneous releases</u>

As discussed in Section 4.2, the model proposed in this study uses a higher density of continuous sources than the current HSE model, giving higher values of probability. The continuous ignition source densities for industrial and urban areas in the current HSE model are significantly greater than μ_{max} for the instantaneous release of 200 tonnes of propane considered in Section 4.2. Therefore, noting that the short cloud duration of an instantaneous release means that ignition occurs almost totally due to continuous sources rather than intermittent sources, Figure 5.1 suggests that use of the proposed ignition probability model rather than the current HSE model will tend to reduce calculated offsite risk for large instantaneous releases.

However, it should be noted that the above discussion does not necessarily mean that total offsite risk for all events is reduced. Figure 5.1 is for flash fire events only and total risk will also depend on escalation of the event (resulting, for example, in BLEVEs and other secondary fires and explosions) or early ignition leading to fireball effects. It will also depend on the relative frequency of large catastrophic releases compared to smaller releases on a site (use of higher ignition source densities tends to increase the calculated risk for small continuous releases, as discussed below). Note also that the above analysis does not suggest that large releases will never reach their maximum cloud area as there is always a small probability that ignition sources are not encountered until the final stages of cloud development. Also many releases occur over rural land, for which ignition probability is low, before reaching urban or industrial areas.

<u>Small continuous releases</u>

For small releases, the optimum source density, μ_{max}, is likely to be greater than the industrial and urban source densities used in the current HSE model. Thus the use of higher source densities in the proposed model will tend to give higher calculated risk values (unless μ_{max} is exceeded). Note also that, for continuous releases, there is

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sufficient time for flammable gas concentrations to be produced within buildings, where it is assumed that there are large densities of ignition sources. This not only increases the probability of ignition of the cloud but, due to the time taken for gas ingress to occur, results in the cloud having grown to a greater size before ignition occurs, resulting in an increased cloud area at ignition and thus a higher calculated risk.

5.3 Implementation within risk assessment programs

Appendix A.2 provides details of the calculation steps required to determine ignition probability within a risk assessment program such as Flammables RISKAT, assuming that the area over which the release is occurring is divided up into a two-dimensional grid and that ignition probabilities are required at discrete time steps during the growth of the cloud.

The implementation of this calculation method within a risk assessment program requires that it is used in conjunction with a gas dispersion code capable of modelling the transient effects of releases and thus providing the change in concentration at a point within a gas cloud with respect to time. As discussed in Appendix A.2, a method must be incorporated within the model for calculating gas ingress into buildings and, thus, the length of time that internal ignition source types have been exposed to flammable concentrations. A further requirement is that ignition source data must be pre-defined for generic land-use types. Tables 3.1 and 3.2 in Section 3 provide full parameters for ignition source types found in industrial, urban and rural land-use areas. Having calculated ignition probability of the cloud over a time step, consequence and vulnerability models can then be used to calculate the risk of fatality or injury to people located within or around the flammable cloud.

It should be noted that the model defined in this report is for calculating delayed ignition probability only and does not consider immediate or 'event-initiated' ignition which must be modelled separately (see Section 2.1). It should also be noted that calculated risk is likely to be sensitive to the size of grids into which a site is divided. Assuming that risk is related to the size of the cloud upon ignition, use of large grid sizes will tend to give higher risk values than for small grid sizes, as the model will not consider ignition of the cloud while it is smaller than the grid size.

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6. CONCLUSIONS

In the first phase of this study a mathematical model for delayed ignition probability of flammable gas clouds was defined and is summarised in Section 2. In the second phase of the study, described in this report, data has been collated on properties of ignition sources within three generic land-use types (industrial, urban and rural) in the UK. 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). This data has then been used to derive ignition source parameters, for each of the generic land-use types suitable for input to the mathematical model. Section 5.3 discusses the implementation of the model within risk assessment programs.

Data collation and uncertainties

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.

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, all of which have been noted in Appendices B and C. The sensitivity analyses described in Section 4.3 shows that the calculation of ignition probability is sensitive to many of these assumptions. 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, 1982). 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 project 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.

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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.

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.

Model comparison

As noted in Section 4.1, insufficient incident data of relevance to UK sites is available for validation of an ignition probability model. However, the model has been compared against US data provided by Simmons (1974) and against other available models.

The model was found to underpredict consistently the Simmons model, which does not differentiate between different areas or times of day and is based on a survey of 59 incidents of ignition of clouds resulting from accidents in storage or transportation of LNG or LPG. Therefore, it was considered that the Simmons model may give higher probabilities because it is based on reported incidents in places where ignition sources may be clustered.

Generally, the proposed model gives higher ignition probabilities for large short duration releases than those predicted using the current HSE model (Clay et al, 1988), with the exception of rural night time conditions. The model suggested that ignition probability was higher for urban night time conditions than urban day time conditions (due to the use of central heating systems), whereas in the HSE model day time ignition sources are always considered to be more prevalent than night time sources. Also the model suggests that industrial night time conditions provide a lower probability of ignition than urban conditions, which again varies from that assumed in the current HSE model.

For continuous releases, the predictions of ignition probability using the proposed model are significantly higher than for the current model. This is due to the prevalence of internal ignition sources, illustrating the importance of considering gas ingress to buildings.

Application of model within risk assessment studies

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. As discussed in Section 2.1, the

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ignition probability model described in this study is designed to be 'conservative best estimate'. The definition of generic ignition source data in Section 3 for various land use types allows its use for hazard assessments where detailed information is unavailable on ignition sources in the proximity of the site. The mathematical basis for the model and the derivation of the generic ignition source data should allow the effect of particular ignition source properties around a site to be incorporated where such detailed information is available.

However, when applying the model, care needs to be exercised when defining ignition source data. As discussed in Section 5.2, 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. 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 such as BLEVEs.

Model development

As discussed above, 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.

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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APPENDIX A

MATHEMATICAL MODEL FOR IGNITION PROBABILITY

The mathematical model of ignition probability is presented in this appendix. It describes how to calculate the probability of ignition as a function of time due to a flammable cloud spreading or drifting over an area of land which may contain different regions with different land uses. The different land uses contain different ignition sources which are assumed to be randomly distributed within that region. The strength and density of the ignition sources in different regions are defined by a number of parameters which are described in Section A.1. The mathematical model is defined in Section A.2 and a description of how to apply the model on a two dimensional grid is given. The basic model assumes ignition sources are randomly distributed. However some ignition sources may always occur close together. In this case they are grouped into one ignition source for the sake of the mathematical model. The description of how this is done is given in Section A.3. The full model requires numerical solution on a two dimensional grid, which can be quite time consuming. However with a couple of simplifications, the model becomes much simpler and analytical solutions are available. These simplifications are investigated in Section A.4.

A.1 Ignition source definition

Each ignition source in the solution domain is characterised by four parameters, p, λ, a and μ which are described below:

Parameter **p** is the probability of ignition from a source given that it is active and enclosed in the cloud. 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 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.

Parameter λ is the rate of activation of the source, and is equal to the inverse of the average time between source activations, i.e. it is equivalent to the frequency with which the source becomes active. For continuous sources, λ can be set to ∞.

Parameter **a** is the proportion of time for which the source is active. Thus, for continuous sources, a is equal to one and for intermittent sources, a tends to zero.

Parameters a and λ can be determined as follows, where t_a is the average time for which the source is active and t_i is the average time between activations:

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$$a = \frac{t_a}{t_a + t_i}\ , \quad \lambda = \frac{1}{t_a + t_i} \quad \text{for } t_i > 0$$
$$a = 1, \quad \lambda = \infty \quad \text{for } t_i = 0 \tag{3.2}$$

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.

A.2 Definition of model for a two-dimensional grid

It is assumed that there are K land use types, $L_1,...L_K$, and that each type contains J_k ignition sources, which may be indoors or outdoors, labelled $j = 1,...,J_k$. For each land use type, each ignition source has parameters p_j, λ_j, a_j and μ_j. Ignition source type j is either outside or inside building type j, with ventilation rate Λ_j.

The ground containing the release is divided up into 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. In this project, three land-use types have been considered: industrial, urban and rural. The properties of the ignition source types found in these land-use types have been fully defined in Tables 3.1 and 3.2 of Section 3.

At each time-step during the cloud development, the following calculations must be undertaken in order to calculate the probability of ignition of the cloud:

1. It is first necessary to calculate the indoor and outdoor concentrations of flammable gas as a function of time in every cell. There may be different building types with different ventilation rates and so the concentration in each building type in each cell must be found. Thus the concentration associated with each ignition source type in each cell, $C_{ji}(t)$, must be calculated, noting that each ignition source type is associated with a building type. Values for $C_{ji}(t)$ can be found from the outside concentration in that cell, $C_{io}(t)$, the previous inside concentration, $C_{ji}(t-\Delta t)$, and the ventilation rate of the building in which the ignition source is located, Λ_j. A first order accurate method for such a calculation, based on that given by Davies & Purdy (1986), is as follows:

   $$C_{ji}(t) = C_{ji}(t-\Delta t) + \frac{\Lambda_j}{3600}\left[C_{io}(t) - C_{ji}(t-\Delta t)\right]\Delta t$$

   where Λ_j is in air changes per hour and t is in seconds. For external ignition source types, $C_{ji}(t)$ should be set to $C_{io}(t)$.

2. Next, it is necessary to calculate the duration of time, at time t, that each building type within the cell has contained a flammable atmosphere. These durations are denoted by d_{ij}, i.e. for ignition type j, in a building with ventilation rate Λ_j, in cell i, the concentration has been within the flammability limits for d_{ij} seconds.

3. Now the probability of no ignition in cell i, due to ignition source j, can be calculated. This is denoted by $Q_{ji}(t)$ and is given by:

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$$\ln\{Q_{ji}(t)\} = \begin{cases} 0 & \text{if } C_{ji}(t') < \text{LFL for all } t' < t \\ \mu_j A_i\left[\left(1 - a_j p_j\right)e^{-\lambda_j p_j d_{ij}} - 1\right] & \text{otherwise} \end{cases}$$

4. If the probability of no ignition over a particular time step, Δt, is required, the difference in probability of no ignition for two consecutive times must be taken. Thus, the probability of no ignition in cell i due to ignition source j during the time interval $(t, t+\Delta t)$ is:

$$\Delta Q_{ji}(t) = Q_{ji}(t) - Q_{ji}(t+\Delta t)$$

5. Then the total probability of no ignition of the cloud at time t is given by:

$$\begin{aligned} Q(t) &= \prod_{i=1}^{I}\prod_{j=1}^{J} Q_{ji}(t) \\ \Rightarrow \ln\{Q(t)\} &= \sum_{i=1}^{I}\sum_{j=1}^{J} \ln\{Q_{ji}(t)\} \end{aligned}$$

and the probability of no ignition over the interval $(t, t+\Delta t)$ is:

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

6. Thus the total probability of ignition of the cloud at time t is given by:

$$P(t) = 1 - Q(t)$$

and the probability of ignition over the interval $(t, t+\Delta t)$ is given by:

$$\Delta P(t) = 1 - \Delta Q(t)$$

The risk can also be calculated on a cell by cell basis for each time step using relevant consequence and vulnerability models and the probability of ignition for each cell:

$$\Delta P_i(t) = 1 - \prod_{j=1}^{J} \Delta Q_{ji}(t)$$

A.3 Grouping of Ignition Sources

Frequently, particular sites contain a number of ignition sources close together, for example workshops in industrial areas. In this case, the ignition sources are not randomly distributed; if one of them is surrounded by flammable gas from a release, it is likely that they all will be. In this case, the site can be defined as one ignition source by combining the parameters of all the ignition sources contained in the site.

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A particular site type may have density, μ_S, i e there are on average μ_S sites of type S per hectare of land. This site may contain J different ignition source types, j = 1,...,J. There are on average n_j ignition sources of type j on site S and type j has ignition source parameters a_j, p_j and λ_j. If the site has been completely covered by a flammable gas cloud for a time d, then the probability of no ignition due to source type j is given by:

$$Q_j = \left(1 - a_j p_j\right)^{n_j} e^{-n_j \lambda_j p_j d} \qquad \text{(A.1)}$$

Therefore the probability of no ignition for the whole site is given by:

$$\begin{aligned} Q_S &= \prod_{j=1}^{J} Q_j = \prod_{j=1}^{J}\left\{\left(1 - a_j p_j\right)^{n_j} e^{-n_j \lambda_j p_j d}\right\} \\ &= \prod_{j=1}^{J}\left(1 - a_j p_j\right)^{n_j} \prod_{j=1}^{J} e^{-n_j \lambda_j p_j d} \\ &= e^{-d\sum_{j=1}^{J} n_j \lambda_j p_j} \prod_{j=1}^{J}\left(1 - a_j p_j\right)^{n_j} \end{aligned} \qquad \text{(A.2)}$$

However, it is required to find ignition source parameters for the site as a whole. These are denoted by a_S, p_S and λ_S (the site density, μ_S, is already known). Then the probability of ignition due to the site if it has been enclosed by flammable gas for a time d is:

$$Q_S = \left(1 - a_S p_S\right) e^{-\lambda_S p_S d} \qquad \text{(A.3)}$$

Equating Q(t) from Section A.2 with Q_S from Equation (A.3) and setting p_S to 1 (or a smaller, arbitrary value) gives the following expressions for a_S and λ_S:

$$\begin{aligned} a_S &= \frac{1}{p_S}\left\{1 - \prod_{j=1}^{J}\left(1 - a_j p_j\right)^{n_j}\right\} \\ \lambda_S &= \frac{1}{p_S}\sum_{j=1}^{J} n_j \lambda_j p_j \end{aligned} \qquad \text{(A.4)}$$

Thus, such a site, containing a number of ignition sources close together, can be treated as one ignition source type with parameters as described above.

A.4 Simplifications for Special Cases

The mathematical model for ignition probability described is quite complicated and requires numerical solution on a two-dimensional grid, which can become quite time consuming to solve. However, with two simplifications, the model becomes much simpler and analytical solutions are available. The two simplifications are, firstly,

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assuming that the cloud size and concentration does not change with time and secondly assuming all ignition sources are continuous.

A.4.1 Fixed Cloud Size and Concentration

If a flammable cloud is approximated by a fixed size, fixed concentration, stationary cloud, then the solution domain does not need to be divided into a two dimensional grid; instead the different land types areas within the flammable cloud are used. The cloud has a total area A_C and within the cloud there is an area of industrial land, A_I, an area of urban land, A_U, and an area of rural land, A_R. Outside, the duration for which an area has been surrounded by flammable gas, d, is equal to the simulation time, t. The concentration inside a building is quite simple to calculate since the outside concentration is constant. If the outside concentration is denoted by C_o, then the concentration inside building type j with ventilation rate Λ_j air changes per second, $C_j(t)$, is given by:

$$C_j(t) = C_0\left(1 - e^{-\Lambda_j t}\right) \tag{A.5}$$

Therefore, the time at which the concentration inside building type j reaches the lower flammability limit, LFL, is given by:

$$t_{LFL} = -\frac{1}{\Lambda_j}\ln\left(1 - \frac{LFL}{C_0}\right) \tag{A.6}$$

and the duration for which the gas concentration has been above LFL for source type j is given by:

$$d_j = \begin{cases} \max\left\{t - \frac{1}{\Lambda_j}\ln\left(1 - \frac{LFL}{C_0}\right), 0\right\} & \text{if j inside} \\ t & \text{otherwise} \end{cases} \tag{A.7}$$

Therefore, the probability of no ignition at time t due to ignition source j in land type L (= I, U or R), Q_{jL}, is given by:

$$\ln\{Q_{jL}(t)\} = \begin{cases} 0 & \text{if } C_j(t) < LFL \\ \mu_j A_L\left[\left(1 - a_j p_j\right)e^{-\lambda_j p_j d_j} - 1\right] & \text{otherwise} \end{cases} \tag{A.8}$$

and the probability of no ignition due to all ignition sources in all land types, Q, is given by:

$$\ln\{Q(t)\} = \sum_{L=I,U,R}\sum_{j=1}^{J}\ln\{Q_{jL}(t)\} \tag{A.9}$$

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This is a similar equation to that given in Section A.2 but the summation is only over the three land use types instead of over all grid cells. Also, the indoor concentrations are simpler to calculate since the outdoor concentration is constant.

A.4.2 All Continuous Sources

If all ignition sources are continuous, then the model is no longer time dependent, only cloud area dependent (where the area denotes the total area swept by the cloud, rather than the instantaneous area above LFL). It is no longer necessary to keep track of the durations for which grid cells have been in the cloud. Instead, the probability of ignition is calculated using the areas, A_{jL}, which are the total areas in land types L (= I, U, R) for which, at some point in time, the concentration $C_j(t)$ has been above LFL. $C_j(t)$ is the outside concentration if the ignition source is outside and it is the concentration inside a building with ventilation rate Λ_j if ignition source j is inside such a building. Then the probability of no ignition, Q, is given by:

$$\ln\{Q(t)\} = \sum_{L=I,U,R} \sum_{j=1}^{J} \ln\left(-\mu_j A_{jL} p_j\right) \qquad \text{(A.10)}$$

This model is equivalent to the model currently in use by HSE with $p_j = 1$ and with only one ignition source type which is outside.

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APPENDIX B

URBAN AND RURAL IGNITION SOURCE DATA

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B.1 Introduction

In this appendix, the values of the parameters for significant ignition sources in urban and rural areas are estimated. Separate sets of parameters are defined for night and day since there may be significant diurnal variation of the densities and activation rates of ignition sources. The parameters required for each ignition source are the average density, μ, (i.e. average number of sources per unit area of land), the probability that the source ignites the cloud given that it is active and surrounded by flammable gas, p, the average activation rate of the source, λ, and the proportion of time for which the source is active, a. In order to estimate values for these parameters, some preliminary information, relevant to a number of ignition sources, is defined in Section B.2. The methods of estimating the ignition source parameters are given in Sections B.3 and B.4 and all the results are summarised in Section B.6.

B.2 Preliminary Information.

B.2.1 Hours of Night and Day

Hours of night and day vary throughout the year and so, for simplicity, it is assumed that night is between 7:30pm and 7:30am.

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B 2 2 Units

Ignition source densities are calculated in 'number per hectare' and ignition source activation rates are calculated in 'activations per hour'. 1 hectare is equal to 10^4 m^2 or 2.471 acres and 1 acre is 4046.9 m^2.

B.2.3 Land Cover in the UK

The density of an ignition source is 'the number of sources per unit area'. Since total numbers of sources for all urban and rural areas in the UK are estimated, the total urban and rural areas in the UK are needed in order to find the average density. In 1991, 10.5 % of England's land cover was urban (Office for National Statistics, 1997). The area of the UK is 24,088,000 hectares, excluding inland water (Central Statistics Office, 1996). Therefore, assuming that the proportion of urban land cover in the UK is similar to that in England, then urban land cover is approximately 2,529,000 hectares and rural land cover is 21,559,000 hectares. A summary of this information is given in Table B.1.

Region	Area (hectares)	Proportion (%)
UK	24,088,000	100
Urban	2,529,000	10.5
Rural	21,559,000	89.5

Table B.1 Areas of land in the UK

B.2.4 Population in the UK

For some ignition sources, it has only been possible to find the average density of ignition sources for the whole country, rather than separately for urban and rural areas. The densities of some of these ignition sources, such as houses, flats and public houses, are assumed to be proportional to the population densities in urban and rural regions.

In 1995, 10.4 million people out of 57 million in Great Britain, lived in rural areas (Office for National Statistics, 1997). Assuming this proportion is similar for the whole of the UK, approximately 18 % of the population live in rural areas, leaving 82 % in urban areas. The population of the UK was 58,395,000 in 1994 (Central Statistics Office, 1996). From these statistics, estimates of the urban and rural populations for the whole of the UK are given in Table B.2. Population densities, based on the areas given in Table B.1, are also estimated and given in Table B.2.

Region	Population (no of people)	Proportion (%)	Density [people per hectare]
UK	58,395,000	100	2.42
Urban	47,884,000	82	18.93
Rural	10,511,000	18	0.49

Table B.2 Population and population densities in the UK

B.2.5 Households

There were an average of 2.4 people per household in Great Britain in 1996 (Office for National Statistics, 1997). Assuming this figure also holds for Northern Ireland and is the same for urban and rural areas, there are approximately 19,952,000 households in urban areas and 4,333,000 households in rural areas. These numbers, and the densities of households, are given in Table B.3.

Region	Number of households	Proportion (%)	Density [per hectare]
UK	24,331,250	100	1.01
Urban	19,952,000	82	8.28
Rural	4,333,000	18	0.20

Table B.3 Households numbers and densities in the UK

B.3 Outdoor Ignition Sources

The outdoor ignition sources for urban and rural areas considered are road vehicles, traffic lights, railways, lightning and open flames. Different values for some of the model parameters, such as density, are found for urban and rural and night and day time conditions.

B.3.1 Road Vehicles

Based on observations made by Simmons (1974) and Jeffreys (1982), vehicles are capable of igniting flammable clouds predominantly when they are started. However, driving into a flammable gas cloud makes the fuel/air mixture entering an internal combustion engine rich, which therefore makes it stall. Drivers frequently attempt to restart their vehicle in such a situation, which may ignite the flammable cloud. Alternatively, people may try to escape a flammable gas cloud by driving away. Jeffreys gives starter motors as a medium strength ignition source. Many of the incidents recorded by Simmons were ignited by drivers attempting to start or restart vehicles. Therefore an initial value of 0.1 for p is used for all vehicles. Vehicles are assumed to be continuous ignition sources, giving $a = 1$ and $\lambda = 0$. The densities of vehicles in urban and rural areas during the night and day are found from transport statistics as described below.

The number of vehicles per hectare in urban or rural areas, during the day, μ_{vd}, or night, μ_{vn}, is found from the number of vehicle kilometres driven by all vehicles in a year in each area, d, the average speed in km/hr in each area, u, the proportion of distance driven during the day, c_d, and night, c_n, and the area of the region, A, in m^2 as follows.

$$\mu_{vx} = \frac{c_x d}{1\ \text{year}} \frac{1}{uA} \qquad \text{(B.1)}$$

where $1\ \text{year} = 365 \times 12$ hours

$x =$ d (day) or n (night)

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One year is taken to be 365 × 12 hours since the distance driven during only the day or night is of interest. The average speed in each area includes contributions from when engines are switched on but vehicles are stationary. The areas of the different regions were found in Section 2.3.

Between 1986 and 1990, the average speed of vehicles with their engines running in London during daytime, off-peak periods was about 20 mph ≈ 32 km/hr (Department of Transport, 1993). This value is used for all urban areas and includes time spent stationary. Observed speed of vehicles on motorways, dual carriageways and single carriageway 'A' roads are also reported. They are about 50 mph ≈ 80 km/hr, varying with vehicle and road type. This value is used for all rural areas.

Therefore it remains to find the number of vehicle kilometres driven in urban and rural regions during the night and day. The number of vehicle kilometres driven on different road types in built-up and non built-up areas is reported by the Department of Transport (1997) and are given in Table B.4. Built-up and non built-up areas loosely translate to urban and rural areas (Department of Transport, 1992). Statistics are not given for motorways separately in built-up and non-built up areas. Instead, the length of motorways in urban areas is estimated to be 200 km from an atlas (Ordnance Survey, 1996). There are 3146.7 km of motorway in Great Britain in all areas (Department of Transport, 1992). If it is assumed that motorways have roughly the same amount of traffic on them in urban and rural areas, then the vehicle kilometres driven on motorways in urban and rural areas can be estimated. In reality, motorways in urban areas may carry more traffic, but the difference is probably not as marked as on other road types. In the absence of further information, it is assumed motorways in urban and rural areas carry the same amount of traffic.

All motor vehicles [billion vehicle kilometres]	Built-up	Non built-up	All
Motorways	4.7*	69.0*	73.7
Major roads	81.1	125.8	206.9
Minor Roads	115.7	46.3	162
All roads	201.5*	241.1*	442.6

* estimated

Table B.4 Traffic by road class in 1996 (Department of Transport, 1997)

The Department of Transport (1997) report traffic distributions throughout the day for various roads and various vehicle types and on different days of the week. It is found that, on average, 80 % of traffic occurs during the day and 20% at night. Using these figures, the vehicle kilometres in Table B.4, the average speeds assumed in urban and rural areas and the areas of urban and rural regions, given in Table B.1, the density of motor vehicles during the night and day in urban and rural areas is estimated and the results are given in Table B.5.

All motor vehicles [vehicles per hectare]	Urban	Rural
Day	0.51	0.027
Night	0.13	0.0068

Table B.5 Densities of all motor vehicles

Note that, in defining the above parameters, it is assumed that motor vehicles are purely continuous ignition sources and there is no time dependency in the probability of ignition. However, in reality there may be some time dependency associated with the rate at which vehicles pass into the flammable region of the gas cloud for continuous releases.

B.3.2 Traffic Lights

Jeffreys (1982) performed experiments on traffic lights and found that only flashing electromechanical (as opposed to solid state) traffic lights caused ignition of a 7% methane/air mixture. Department of Transport data suggests that there are approximately 10,000 flashing electromechanical traffic lights in the UK. These are all assumed to be in urban areas, giving a density of 0.004 traffic lights per hectare.

There is a minimum pedestrian × (volume of traffic)^2 criterion for installing pelican crossings (Institute of Highways & Transportation, 1997). The requirement measurement is the average number of people crossing per hour over the busiest four hours of the day. During peak time, the minimum requirement of people crossing for any volume of traffic is 50 people. However, people will not necessarily cross individually, but may cross in groups. During other periods of the day crossings will be much less frequent. Since this is the minimum requirement there will be many crossings with more than 50 people crossing per hour in the peak pedestrian flow. For the purpose of this report, it will be assumed that there are between 1 and 50 group crossings an hour during the day, i.e. the pelican crossing will be activated between 1 and 50 times per hour during the day and between 0 and 5 activations an hour at night.

B.3.3 Rail

The strongest ignition sources on railways are expected to be trains, including electrical systems and arcing to the third rail for electric trains and diesel engines and exhausts for diesel trains. Jeffreys (1982) estimates these to be strong ignition sources, stronger than most road vehicle sources. However, trains are unlikely to stall and restart in a flammable cloud. Simmons (1974) noted that a train drove through part of a flammable cloud and did not ignite it in one of the incidents he studied. Due to the competing effects of trains being stronger ignition sources in normal operation than road vehicles but not stalling and restarting in a flammable cloud, they are given the probability of ignition, p, of 0.5. Trains are assumed to be continuous ignition sources therefore $\lambda = 0$ and $a = 1$.

The number of trains per hectare in urban or rural areas, during the day or night, μ_t, is found from the number of kilometres driven by all trains in a year, d, the proportion of journey distance in urban or rural regions, p_u or p_r, the proportion of day or night time

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journeys, p_d or p_n, the average speed in km/hr in each area, u_u or u_r, and the area of the region, A_u or A_r, in m^2 as follows.

$$\mu_{t\,u/r\,d/n} = \frac{d}{1\text{ year}} p_{u/r} p_{d/n} \frac{1}{u_{u/r} A_{u/r}} \qquad \text{(B.2)}$$

where 1 year = 365 × 12 hours

The areas of the different regions were found in Section 2.3.

In 1993/4, all British Rail trains travelled a total of 390.7×10^6 km in a year (Department of Transport, 1996). British Rail gave the average train speed to be about 55 mph = 88 km/hr (it is not known whether this includes time waiting at stations). This value is used as the average train speed in rural areas. To find the average speed in urban areas, a train timetable between Epsom and Horsham (Connex South Central, 1997) is studied. This length of track is studied here because it is also used to find the average length of track in urban and rural areas. The proportion of track along this route in urban and rural areas is found from an atlas (Ordnance Survey, 1996). From these the average speed in urban areas is found as follows:

$$\text{urban speed} = \frac{\text{distance in urban areas}}{\text{journey time} - (\text{distance in rural areas / average rural speed})} \qquad \text{(B.3)}$$

Using this method, the average urban speed was found to be 41 km/hr. The data used from the timetable (Connex South Central, 1997) and the atlas (Ordnance Survey, 1996) is given in Table B.6.

Station 1	Station 2	Length of track in urban areas [km]	Length of track in rural areas [km]	Time between stops [mins]	Average urban speed [km/hr]
Epsom	Ashtead	3.0	0.4	4	48
Ashtead	Leatherhead	2.3	0.0	3	46
Epsom	Leatherhead	5.3	0.4	6	56
Leatherhead	Boxhill & Westhumble	0.7	4.6	4	49
Boxhill & Westhumble	Dorking	0.0	1.3	5	
Leatherhead	Dorking	0.7	5.9	6	21
Dorking	Holmwood	0.6	7.6	7	20
Holmwood	Ockley	0.0	3.6		
Ockley	Warnham	0.0	6.9		
Warnham	Horsham	2.9	0.8	4	50
Dorking	Horsham	3.5	18.9	18	41
Average					41

Table B.6 Distances (Ordnance Survey, 1996) and times between stations without stops between them. (Route 19, Connex South Central, 1997).

To find the proportion of journeys travelled at night and in urban and rural areas, timetables and an atlas (Ordnance Survey, 1996) are again studied. It is assumed that the proportion of train kilometres in urban or rural areas is proportional to the length of track in each area. The proportion of train kilometres driven at night is found from timetables, assuming night time is between 7:30pm and 7:30am. It is found that

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approximately 30% of track is in urban areas, leaving 70% in rural areas and 26% of journeys are at night, leaving 74% during the day. The data used to arrive at these figures is given in Table B.7. From this data the train densities can now be calculated, using Equation (B.2) and are given in Table B.8.

Station 1	Station 2	Length of urban track [km]	Length of rural track [km]	Number of trains each way per week	
				night	day
Sanderstead	Upper Warlingham	0.95	2.1	56	168
Upper Warlingham	Woldingham	0.95	1.9	56	73
Woldingham	Oxtead	0.19	4.6	56	73
Oxtead	Hurst Green	1.5	0	91	158
Hurst Green	Lingfield	0.76	7	56	73
Lingfield	Dormans	0	1.9	56	73
Dormans	East Grinstead	1.9	1.9	56	73
Hurst Green	Edenbridge Town	1.7	5.5	29	87
Edenbridge Town	Hever	0.57	2.1	14	91
Hever	Cowden	0.57	2.9	14	91
Cowden	Ashurst	0.57	3.8	14	91
Ashurst	Eridge	0	5.7	24	86
Eridge	Crowborough	0.38	4.8	30	101
Crowborough	Buxted	0.18	7.4	30	101
Buxted	Uckfield	0.95	2.5	30	101
Doncaster	Grimsby	14	67	21	189
Doncaster	Hull	14	51	17	95
Doncaster	York	4.2	51	43	225
York	Newcastle	24	106	56	114
Darlington	Middlesborough	6.5	9.9	36	92
Durham	Newcastle	11	12	66	90
Newcastle	Sunderland	11	5.5	42	95
Kings Cross	Hitchin (via Welwyn)	36	11	119	400
Kings Cross	Hitchin (via Hertford)	38	16	103	79
Hitchin	Cambridge	12	29	83	378
Hitchin	Peterborough	16	58	81	159
Epsom	Ashtead	3	0.4	146	473
Ashtead	Leatherhead	2.3	0	146	473
Epsom	Leatherhead	5.3	0.4	5	2
Leatherhead	Boxhill & Westhumble	0.7	4.6	80	142
Boxhill & Westhumble	Dorking	0	1.3	80	142
Leatherhead	Dorking	0.7	5.9	20	145
Dorking	Holmwood	0.6	7.6	10	77
Holmwood	Ockley	0	3.6	10	77
Ockley	Warnham	0	6.9	10	77
Warnham	Horsham	2.9	0.8	10	77
Dorking	Horsham	3.5	18.9	5	7
Total		216.87	520.9	1801	5048

Table B.7 Urban and rural track lengths and trains during the day and night (Connex South Central, 1997, GNER, 1997 and WAGAN, 1997)

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Trains per hectare	Day	Night
urban	2.1×10^{-4}	7.4×10^{-5}
rural	2.6×10^{-5}	9.2×10^{-6}

Table B.8 Train Densities

B.3.4 Lightning

Lightning is most likely to cause ignition of a flammable cloud if the lightning has also caused the spill of the flammable cloud. These may occur simultaneously (immediate ignition) or, in a thunderstorm, two separate lightning strikes may cause the flammable spill and ignition. However, for delayed ignition, lightning is not considered significant in comparison to the other ignition sources studied. Therefore lightning densities and frequencies have not been found.

B.3.5 Open Flames

It is assumed that the probability of ignition if a flammable cloud encounters an open flame is unity, giving $p = 1$. It therefore remains to calculate the density of open flames, μ, the activation rate, λ, and the proportion of time for which they are active, a.

The most prevalent outdoor open flame sources in the city of Boston were listed by Jeffreys (1982). These were found to be gas-fired vented wall furnaces, roof top unit heaters, residential gas-fired heating equipment using outside air and decorative gas lights. Each of these give a probability of igniting a flammable cloud of one. Jeffreys scales the source density by the seasonal use ratio and the probability of the source being active. This gave a corrected density of 0.74 per hectare. However, Jeffreys noted that the density of such flames was highly area specific and varied greatly throughout Boston, and would also vary greatly for different cities. Therefore this density is not used in the current work. Instead, UK data was used to define the densities of such sources.

Balanced flue gas boilers take air directly from outside, as opposed to more traditional boilers, which take air from inside a building. It is estimated that about 30%, out of the 18 million households nation-wide with mains gas, have balanced flue appliances. Although these appliances are likely to have pilot lights, they are only considered to be a significant ignition source when they are drawing air in from the outside, i.e. when the heating system is operating. The pilot lights are effectively indoor ignition sources when the heating system is not operating since the concentration of flammable gas surrounding the pilot light will not immediately equalise with the external concentration.

In order to find the density of balanced flue gas boilers, the number of houses and blocks of flats must be estimated. A block of flats is assumed to be just one ignition source since, if one of the flats in a block is surrounded by a flammable cloud, they all will be, i.e. the individual flats are not randomly distributed. Information on the number and size of houses and flats in England has been found (Green et. al., 1997). This is used to estimate the number of houses and blocks of flats, i.e. accommodation

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units, in England. It is then assumed that the proportion of accommodation units to households is the same in the whole of the UK as in England.

There were 16,009 thousand houses and 3,414 thousand flats in England in 1995/96. (Green et. al., 1997) also gives the number of floors in all buildings. Using this data and assuming houses have 1 and 2 floors and blocks of flats have greater than 2 floors, it is estimated that there are on average 3.26 floors to every block of flats. Assuming every flat occupies on average one floor, it is estimated that there are 997 thousand blocks of flats in England. Therefore the number of accommodation units in England is 88% of the number of households in England. This percentage is assumed to also be applicable to the UK.

The 18 million households with mains gas correspond to practically all households in the UK in urban areas. Of those, it is estimated that 30% have balanced flue gas boilers. This gives an urban density of 2.646 such appliances per hectare. To eliminate the boilers very close together in blocks of flats, this density is scaled by 88%. This gives and urban density of 2.33 per hectare. If flammable gas from outside is ingested into these appliances, ignition of the flammable cloud is certain to occur immediately assuming no flame arresters are present. Jeffreys et al (1982) also assumes that these appliances are certain sources of ignition although there may be differences between current UK appliances and those in the US IN 1982. It is assumed that these appliances are active during the winter months between 7am and 9am and between 4pm and midnight for approximately half of the time. During the winter it is assumed that daylight hours are between 8am and 5.30pm. Therefore these appliances are active for approximately a tenth of all daylight hours and quarter of all night time hours during half of the year, i.e. ignition source parameter a has a value of 0.05 for day time and 0.125 for night time. Within rural regions, LPG is used rather than mains gas. In 1998, CALOR supplied approximately 40,000 domestic users in the UK with bulk tanks of LPG and 20,000 users with racked cylinders. CALOR have approximately 50% of the market share, giving a total of 120,000 domestic LPG users in the UK. It is ssumed that, as for urban areas, approximately 30% of these users have balanced flue appliances. This gives an area density for these appliances of 0.0017 per hectare.

Bonfires, campfires and barbecues are also considered as these may be significant ignition sources in rural areas. In order to estimate the activation rate of these ignition sources, a limited survey of the Science and Technology department of WS Atkins was carried out. 24 people were asked how many bonfires, campfires, fireworks and barbecues they have a year, and whether they lived in an urban or rural area. 20 of these people lived in urban areas and 4 in rural areas. A summary of the results is given in Table B.9. A typical bonfire, campfire or barbecue is assumed to last for 2 hours. These flames are termed occasional fires.

		Average number per household, per year				
		Bonfires	Campfires	Barbecues	Fireworks	Total
Urban	Day	0.15	0	5.5	0	5.65
	Night	0.15	0	0.7	0.05	0.9
Rural	Day	22.25	0	42.5	0	64.75
	Night	0	1.5	0	0	1.5

Table B.9 Results of a survey of 20 people living in urban areas and 4 people living in rural areas

It is assumed that the density of these open flames is equal to the density of households in the areas. The survey is therefore used to find the activation rate and proportion of time active. The results are given in Table B.10.

		Density [no. per hectare]	Proportion of time active	Activation rate [no per min]
Urban	Day	8.28	2.6×10^{-3}	2.2×10^{-5}
	Night	8.28	4.1×10^{-4}	3.4×10^{-6}
Rural	Day	0.20	3.0×10^{-2}	2.5×10^{-4}
	Night	0.20	6.8×10^{-4}	5.7×10^{-6}

Table B.10 Ignition parameters for occasional fires in urban and rural areas

B.4 Indoor Ignition Sources

Ignition sources indoors are assumed only to ignite a flammable cloud once the average gas concentration inside the building has reached the lower flammability limit. Values of the ignition source parameters are found for the insides of a number of buildings but individual ignition sources inside buildings are not considered in detail.

B.4.1 Households

Jeffreys (1982) lists many strong ignition sources inside residential houses, including pilot lights, open fires, stoves, doorbells, cloths dryers, light switches, electric tools, hair dryers, toasters, central and water heating and electrical appliances. It is therefore assumed that the probability of ignition inside a house is one, once the average concentration inside the house has reached the lower flammability limit and if any of these ignition sources are active. This assumption is also used for other buildings containing kitchens. The time of ignition is therefore dependent on the ventilation rate of the building and the probability of an ignition source being active. The densities of households was given in Section B.2.5.

It is assumed that, on average, houses contain ignition sources capable of igniting a flammable mixture only when they are occupied by people who are awake, although some houses contain continuous pilot lights and some do not contain ignition sources even when they are occupied. It is assumed that, on average, houses are occupied between 7am and 9am and between 4pm and midnight, i.e. for approximately half of all night time hours and half of all daylight hours, although, again, some houses will be occupied more and some less. Additionally, it is assumed that household

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appliances that may cause ignition are in use for on average half of the time the household is occupied. Therefore the inside of houses are active ignition sources for, on average, a quarter of the time during the day and night.

B.4.2 Restaurants and Public Houses

Restaurants always have kitchens that are in use continuously when open and public houses frequently have kitchens. Both sometimes also contain candles, smokers, juke boxes and arcade games. Therefore it is assumed that, if a restaurant or public house is open, once the concentration inside has reached the lower flammability limit, the cloud will ignite.

It is assumed that, on average, both restaurants and public houses are open during traditional opening hours, i.e., 11am - 3pm and 5pm - 11pm. Assuming daylight hours between 7.30am and 7.30pm, restaurants and public houses are open for approximately half all daylight hours and one third of all night time hours. Therefore the inside of restaurants and public houses are active ignition sources for, on average, a half of the time during the day and a third of the time at night.

2670 restaurants and 768 public houses advertised in the SW London Yellow Pages 1997. The area covered was 100,000 hectares and this was urban. This corresponds to a density of 0.034 restaurants and public houses per hectare. This is taken to be the density of each establishment for any urban area in the UK and therefore there is a total of approximately 85,000 restaurants and public houses in urban areas in the UK. It is assumed that restaurants and public houses are distributed with the population, i.e. 18 % are in rural areas and 82 % are in urban areas. Therefore it is estimated that there are approximately 103,600 restaurants and public houses in the UK with a density of about 9×10^{-4} restaurants and public houses per hectare in rural areas.

B.4.3 Shops

Shops frequently have kitchens for staff use, central and water heating and cash registers. It is assumed that an ignition source is active for half of the time the shop is open. Therefore , if a shop is open, once the concentration inside has reached the lower flammability limit, then the shop has a probability of one half of igniting the cloud.

It is assumed that, on average, shops are open between 9am and 6pm. Assuming daylight hours between 7.30am and 7.30pm, shops are open for approximately three quarters of all daylight hours and no night time hours. Therefore the insides of shops are assumed to be active ignition sources for 0.375 of daylight hours.

There were 470,800 shops and restaurants and 98,600 shops with accommodation in England and Wales in 1994 (Department of the Environment, 1995). Subtracting the number of restaurants in England and Wales and, again, assuming the shops are distributed with the population (18 % in rural areas and 82 % in urban areas), there are approximately 0.27 shops per hectare in urban areas and 0.007 shops per hectare in rural areas.

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B 4 4 Hospitals

Hospitals always have kitchens and heating plants and often have cafes and shops on the ground floor. They also contain a large quantity of heavy electrical equipment. Therefore it is assumed that, once the concentration inside has reached the lower flammability limit, the cloud will ignite.

Hospitals are always open, therefore the proportion of time for which they are active ignition sources is one.

There were 2086 hospitals in the UK in 1996/97 (NHS Year Book 1996/97). It is assumed that these are all in urban areas. Therefore the density of hospitals in urban areas is 9×10^{-4} hospitals per hectare.

B.4.5 Offices

Offices have heating plants, lifts, kitchens and electrical equipment such as photocopiers and slide projectors. Therefore it is assumed that, if an office is in use, once the concentration inside has reached the lower flammability limit, the cloud will ignite.

It is assumed that, on average, offices are in use between 9am and 6pm. Assuming daylight hours between 7.30am and 7.30pm, offices are in use for approximately three quarters of all daylight hours and no night time hours. Therefore the inside of offices are active ignition sources for, on average, a three quarters of the time during the day and no time at night.

There were 252,600 commercial offices in England and Wales in December 1994 (Department of the Environment, 1995). It is assumed that these are all in urban areas. Therefore there are approximately 0.16 offices per hectare in urban areas.

B.5 Sheltering of ignition sources by buildings

Some outdoor ignition sources, such as balanced flue boilers (see Section A.3.5), are attached to the side of buildings. If such an ignition source is attached to the downwind side of the building and a flammable gas is released from upwind of the building, the ignition source may be sheltered for a short time from the flammable gas due to the wake of the building.

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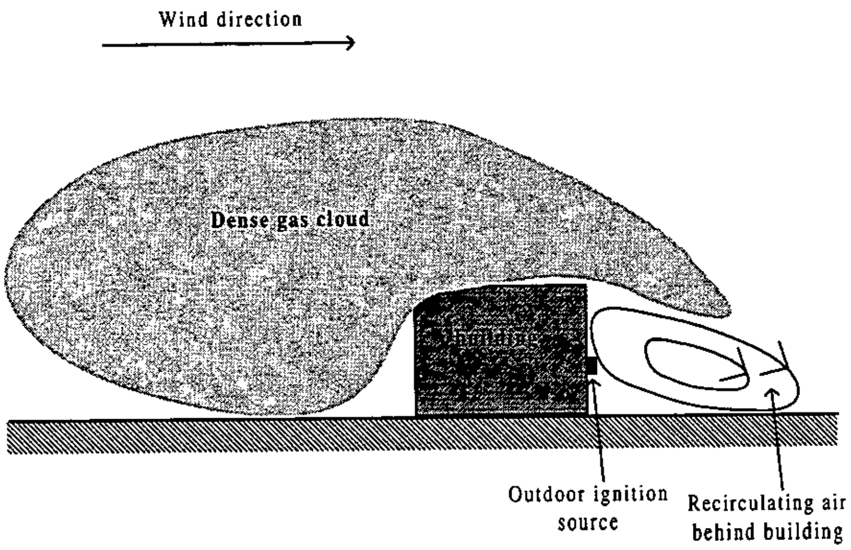

Figure B.1 Effect of buildings sheltering outdoor ignition sources

Simple models have been developed to estimate the effect of the building on the gas dispersion and the residence time of a pocket of gas in the wake (Lines et. al., 1997). For slightly dense or neutral gases, the residence time within the wake is given by:

$$\text{residence time} = \frac{h}{U}\frac{11\left(b/h\right)^{1.5}}{1+0.6\left(b/h\right)^{1.5}} \qquad \text{(B.4)}$$

where h is the building height, U is the wind speed and b is the building width. A number of sample residence times for various building dimensions and wind speeds is given in Table B.11. Residence times are higher for larger buildings in low wind speeds. The wake region of a building can be thought of as another building with a high air change rate. Therefore, using the same method as is used to find the concentration inside a building, the concentration inside the wake can be found. The air change rate of the wake is simply the reciprocal of the residence time, and typical air change rates are also given in Table B.11. Except for very large buildings, wake residence times are small in comparison to the dispersion time of a flammable cloud and air change rates are therefore large in comparison to the buildings considered. The ignition sources considered that are on the side of buildings are balanced flue boilers. These boilers tend to be fitted to residential housing which are not very big. It is therefore considered reasonably accurate to assume these ignition sources are entirely outside and not sheltered in any way.

Variable	Notation	Units	Values					
Building height	h	m	5	20	100	100	20	100
Building width	b	m	5	20	100	20	100	100
Wind speed	U	m/s	2	2	2	2	2	5
Residence time	t_r	s	17	69	344	47	160	138
Air change rate	Λ	1/hour	209	52	10	77	23	26

Table B.11 Residence times in the wakes of various buildings

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B.6 Results

The ignition source parameters for the sources considered in urban and rural areas during the day and night are summarised in Table B.12.

Source	Location	Λ_i [ach]	Land-use	Time	μ_i [per hectare]	p_j	λ_j [per min]	a_j
Road vehicles	Outdoor	∞	Urban	Day	0.51	0.1	∞	1
				Night	0.13	0.1	∞	1
			Rural	Day	0.027	0.1	∞	1
				Night	0.0068	0.1	∞	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	∞	1
				Night	7.4×10^{-5}	0.5	∞	1
			Rural	Day	2.6×10^{-5}	0.5	∞	1
				Night	9.2×10^{-6}	0.5	∞	1
Balanced flue gas appliances	Outdoor	∞	Urban	Day	2.33	1	∞	0.05
				Night	2.33	1	∞	0.125
				Day	1.67×10^{-3}	1	∞	0.05
				Night	1.67×10^{-3}	1	∞	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	∞	0.5
				Night	8.28	1	∞	0.5
			Rural	Day	0.20	1	∞	0.5
				Night	0.20	1	∞	0.5
Restaurants and public houses	Indoor	2	Urban	Day	0.034	1	∞	0.5
				Night	0.034	1	∞	0.3
			Rural	Day	9×10^{-4}	1	∞	0.5
				Night	9×10^{-4}	1	∞	0.3
Shops	Indoor	2	Urban	Day	0.27	1	∞	0.75
			Rural	Day	0.007	1	∞	0.75
Hospitals	Indoor	2	Urban	Both	9×10^{-4}	1	∞	1
Offices	Indoor	2	Urban	Day	0.16	1	∞	0.75

Table B.12 Ignition Sources in urban and rural areas during the day and night

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APPENDIX C

INDUSTRIAL IGNITION SOURCE DATA

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C.1 INTRODUCTION

It is clear from analysis of any area (urban, rural, industrial or otherwise), that there is a wide range of types of ignition source that can occur and that each of these can occur with varying strengths, rates, durations and densities. It is the range of possible sources that may occur *within an individual building* which creates the main difference between industrial and other areas.

Although the exact patterns of occurrence will vary, it is reasonable to assume that all buildings within urban and rural areas will have similar characteristics. That is, houses, flats, shops and offices (etc.) will have broadly the same types of ignition source, with approximately similar distributions and densities within them. This assumption cannot be made for industrial areas, where the different types of building that can occur can have very different ignition sources. For example, some sites of the base metal manufacturing industry are dominated by furnaces and other high temperature processes, whereas a typical warehouse or wholesale outlet is unlikely to contain any strong ignition sources at all. Thus, the emphasis in evaluating ignition probability within an industrial area must be placed on distinguishing between the ignition potential of different building types, while in other areas it is the density of the ignition sources (which may be buildings or external sources) that is most important.

It should be noted that for many ignition sources, particularly those found in industrial environments, it is often conservatively assumed that the probability of ignition, p, is one, i.e. that these sources would always ignite a flammable gas cloud. However, the objective of this study is to identify the realistic probability of ignition from various sources since, for growing clouds, the maximum off-site risk is not always obtained with the maximum strength, or density, of ignition sources. Thus, the main aim of the industrial model data is to allow distinction between the risks posed by different industrial sites.

The approach used here is to identify groups of different industries which are judged to have similar ignition sources (e.g. manufacturers of electrical products, or vehicle repair workshops). For each group, or industry type, a profile of a typical plant is assumed and the ignition sources that will occur, within this typical site, are identified. Once the typical ignition sources have been established, they are combined to produce a set of parameters, for each type of site, so that each industry type may be represented by a single ignition source.

As well as creating these different groups of industry types, a number of additional assumptions have been made in order to provide a picture of a 'general' industrial area. These assumptions are described briefly below and discussed in more detail in Section C.2 of this appendix.

- *Composition* - types of business that are contained in an industrial area,
- *Density* - typical numbers of the different sites that are found in industrial areas,

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- *"Machinery factor"* - a proposed method of simplifying the huge range of weaker ignition sources contained in the 'background' equipment of industrial sites,
- *Smoking* - standard assumptions to be applied to all sites,
- *Ventilation* - standard assumptions to be applied to all sites,
- *Day and night variations* - changes in ignition sources, and/or their densities, from daytime to night time, in an industrial area,
- *Heating* - standard assumptions to represent the ignition potential provided by heating equipment.

The ignition source profiles assigned to each industry type are detailed individually in Section C.3, which describes the assumptions made, the calculations, and the final values of ignition source parameters which are derived. These parameters are summarised in the table given in Section C.4.

Basic alterations to the data which may be made to improve the overall accuracy of the model, when a particular area is being analysed (i.e. when more detailed, less generic, information is available) are discussed in Section C.5. The sensitivity of the model results to changes in the assumptions is also discussed briefly in Section C.5, while a full, overall sensitivity analysis is given in Appendix D and summarised in Chapter 5.2.

C.2 GENERAL ASSUMPTIONS

C.2.1 Industrial Area Composition

It could be assumed that a purely "Industrial" area would contain solely manufacturing plants. In practice, however, a typical industrial area will contain a mixture of manufacturing plants, wholesalers, retail outlets, storage facilities, and offices. Thus, both manufacturing and non-manufacturing sites are considered here.

The different industries are considered according to the Standard Industrial Classification code (SIC), which is defined by the Office of National Statistics (ONS, 1992). This code system exists in order to collate the vast range of different industries into manageable groups of businesses with similar characteristics.

C.2.1.1 Manufacturing Groups

All of the areas classified as manufacturing by the SIC have been considered to occur in industrial areas, with the exception of "Coke, refined petroleum products and nuclear fuel manufacturing". (This classification is considered to be a special case, as such sites either occur outside normal industrial areas, or have controlled ignition sources because of the higher than usual risk of a gas release.)

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The one addition to the sites defined as manufacturing by the SIC is "maintenance and repair of motor vehicles". Vehicle repair workshops are commonly found in industrial areas, and have relatively strong ignition sources, so are grouped here as 'manufacturing' sites. It is assumed that 75% of all vehicle repair workshops occur in industrial areas, while the remainder will be found in urban areas (e.g. high street garages).

C.2.1.2 Non-manufacturing Groups

These non-manufacturing types of sites are assumed all to have the same low level of ignition source probability (discussed in more detail in Section C.3.14).

The number of non-manufacturing sites within an industrial area can vary greatly, particularly in the number of retail and office sites that occur. The assumption made to allow for these factors is that all wholesale outlets will occur in industrial areas, and all offices and retail outlets can be considered as urban sources only. In practice, some wholesale outlets will occur in urban areas and some retail outlets and offices will occur in industrial areas but, since they will tend to have the same (low) ignition source potential, the overall ignition source density should not be significantly affected.

Warehouses and storage facilities are often a part of a larger manufacturing plant, but also occur as individual buildings or sites. When part of a plant, the ignition sources presented by storage facilities are assumed to be negligible compared with those on other sections of the plant. Stand alone storage facilities are assumed to be represented by the high percentage of wholesalers occurring in industrial areas.

C.2.1.3 Business Groups Contained In Industrial Areas

The composition of each of the groups, which are listed below, is detailed by the ONS (1992).

- Manufacture of ...
  - ... food products; beverages and tobacco
  - ... textiles and textile products
  - ... wearing apparel; dressing and dyeing of fur
  - ... leather and leather products
  - ... wood and wood products
  - ... pulp, paper and paper products
  - ... publishing, printing and reproduction of recorded media
  - ... chemicals, chemical products and man-made fibres
  - ... rubber and plastic products
  - ... other non-metallic products
  - ... basic metals
  - ... fabricated metal products (excluding machinery and equipment)
  - ... machinery and equipment, not elsewhere classified
  - ... office machinery and computers

  - ... electrical machinery and apparatus not elsewhere classified
  - ... radio, television and communication equipment and apparatus
  - ... medical, precision and optical equipment; watches and clocks
  - ... motor vehicles, trailers and semi-trailers
  - ... other transport equipment
  - ... furniture and manufacturing not elsewhere classified
- Maintenance and repair of motor vehicles (75% - see assumption in C.2.1.1)
- Wholesale trade and commission trade, except motor vehicles

C.2.1.4 Business Groups Not Contained In Industrial Areas

All other businesses are assumed to occur either in urban areas (offices and retail) or rural areas (agricultural and special cases). Broad titles of the business types which are not included as industrial, again defined in more detail by ONS (1992), are listed below.

- Manufacture of coke, refined petrol products and nuclear fuel
- Agriculture, hunting, forestry and fishing
- Mining and quarrying
- Energy and water supply industries
- Construction
- Retail trade
- Hotels and restaurants
- Transport, storage and communication
- Financial
- Real estate, etc.
- Public administration, etc.
- Education
- Health
- Others

C.2.2 Area Density of Sites

Since, for the purposes of this analysis, each site within an industrial area is classified as an individual ignition source, the number of sites per unit area is an important factor. The model input requires that the density, μ, of each ignition source is known. Here, μ_j is the average number of "ignition sources" (i.e. sites of type j) per unit industrial area. There are two factors determining μ_j - the density of all industrial sites within an industrial area, μ_t, and the percentage of industrial sites which are of type j, P_j.

Thus, μ_j is determined from these parameters as follows.

$$\mu_j = \mu_t \times P_j / 100$$

The assumptions made in determining P_j and μ_t are discussed below.

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C.2.2.1 Percentage of Sites of Industry Type j - P_j

The calculated and estimated values of P_j are listed in Table C.1.

The first 12 groups of industry types are manufacturing type plants and for these the number of sites for each type is taken directly from the ONS Annual Abstract of Statistics (1997). For the remaining two groups, vehicle repairs and wholesale, only data giving the total number of employees is given by this publication, so the number of employees per site is estimated in order to calculate approximate values of the number of sites. Table C.1 shows the average number of employees per site for the manufacturing groups, which were used as a basis for these estimates.

C.2.2.2 The Average Number of Industrial Sites per Unit Industrial Area - μ_i

Using the data, from the ONS Annual Abstract of Statistics (1997), presented in Table C.1, the total number of industrial sites in the UK is taken as being 255,188. The total area that these sites cover is determined from the total industrial floorspace together with an estimate of the amount of non-productive space in industrial areas (i.e. the ratio of the area of the buildings to the total area).

DOE statistics (1995) give the floorspace covered by "factories and mills" in England and Wales in 1994 as being 14,000 hectares, and the floorspace of "warehouses and workshops" as being 16,000 hectares. Adding these two groups to get the total "industrial" floorspace, extrapolating to cover the rest of the UK, and assuming that the total floorspace remained approximately constant up to 1996, the total industrial floorspace in the UK (at the end of 1996) is assumed to be 35,000 hectares.

To extrapolate from the floorspace area to the actual area of land designated as industrial, an estimate of the proportion of industrial area that is not covered by buildings is required.

From analysis of several Ordnance Survey maps of industrial areas, it is found that the ratio of building area to total area ranges from around 0.2 to 0.32. Most of the areas selected are found to contain some non-industrial sites, such as hospitals and parks, which will decrease the ratio (since only buildings considered to be industrial are used in the building area estimates). The small grid-size employed by the model should ensure that there are few of these non-industrial sites in any area designated as industrial. Thus, it is assumed that the maximum value of 0.32 is the most appropriate for use in the model (i.e. 32% of an industrial area is covered by industrial buildings). Adjustments to this figure which can be made, based on knowledge of the particular area being assessed, are discussed in Section C.5.

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Group	Employees		No. of Employees per Site	Sites		
	Number	%		Number	%	% of Ind. Total
Food Products	414,000	10.65	39	10,580	5.88	4.15
Textiles	343,000	8.82	19	18,220	10.12	7.14
Wood & Paper	191,000	4.91	15	12,545	6.97	4.92
Printing	329,000	8.46	11	29,215	16.23	11.45
Chemicals	492,000	12.66	38	13,005	7.23	5.10
Non-metals	140,000	3.60	20	6,945	3.86	2.72
Basic Metals	139,000	3.58	45	3,110	1.73	1.22
Metal Products	415,000	10.68	14	30,045	16.69	11.77
Machinery	411,000	10.57	26	15,600	8.67	6.11
Electrical	484,000	12.45	30	16,130	8.96	6.32
Transport	359,000	9.24	64	5,645	3.14	2.21
Others	170,000	4.37	9	18,940	10.52	7.42
Manufacturing Total:	3,887,000	100	22	179,980	100	70.53

Group	Employees		No. of Employees per Site	Sites		
	Number	%		Number	%	% of Ind. Total
Vehicle Repair	126,750		*10	12,675		4.97
Wholesale	938,000		*15	62,533		24.50
Non-manufacturing Total:				75,208		29.47
"Industrial" Total:				255,188		100

NB All data is either taken directly from the ONS Annual Abstract of Statistics (1997), except points marked by a *, which are estimated.

Table C.1 Numbers and proportions of different types of industrial site

So the total industrial area in Britain is assumed to be:

$$(35{,}000 \text{ ha} / 0.32) = 109{,}375 \text{ ha}$$

The average number of sites per unit industrial area is thus:

$$(255{,}188 / 109{,}375 \text{ ha}) = 2.3 \text{ ha}^{-1}$$

So $\mu_t = 2.3$ (ha^{-1}).

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C.2.3 Ignition Due to Background Equipment

Almost all industries contain a large amount of both automated and manual equipment, which will include various machines and components, which may be mechanical, electrical, or both. This equipment is classed here as "general equipment". The type and quantity of the general equipment varies enormously between each type of industry and between each and every plant, or site, within that industry type. Almost every item of such equipment will contain a different number and combination of individual ignition sources. Examples of such sources are motors, pumps, switches and contacts. The analysis of the ignition potential is further complicated because each individual source can be enclosed or shielded from the air flow within the site by a number of layers.

Detailed analysis of the ignition sources contained within the general equipment will yield wide ranging values of ignition source parameters for each section of equipment and each site. Thus a method is required which can be used to simplify the collection of general ignition source data, for each industry type. The method adopted here is to use a "machinery factor", which is intended to provide an indication of the background level of ignition sources, i.e. the level of ignition probability from the general equipment, before the more significant (and easier to quantify) sources are considered.

C.2.3.1 The "Machinery Factor"

Because of the high variability of ignition sources in normal industrial equipment (as discussed above) the assumed machinery factor will be very uncertain for a specific site. The primary aim of the machinery factor is to provide a simple means of approximating the base level of ignition sources, enabling comparison to be made with other sites. The level of general equipment (which does not include significant sources such as furnaces, welding processes, etc.) in each industry type is identified as being either 'heavy', 'medium' or 'light', and the concentration of such machinery is also considered, so that approximate ignition source parameters can be attached using Table C.2, which is given below.

The assumptions and calculations used in establishing the given values are detailed in the following sections.

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Equipment Level		Ignition Probability			Other parameters
		High Density	Medium Density	Low Density	
Heavy	Large motors, pumps, etc.	p=0.5	0.4	0.3	a=0.992, λ=0.0277, n=1
Medium	Smaller motors and pumps, etc.	0.4	0.3	0.2	a=0.98, λ=0.0347, n=1
Light	Low voltage switches and contacts only	0.25	0.2	0.15	a=0.99, λ=0.0556, n=1

Table C.2 Ignition source parameters for each level of 'general equipment'

C.2.3.2 General Assumptions

The different levels of machinery are classed as either heavy, medium or light, which relate approximately to 'mainly mechanical', 'some mechanical' and 'mainly electrical', respectively.

Initially, because of the assumption that each site is a single ignition source, as well as the wide range of possible numbers and types of equipment, calculation of the ignition source due to equipment is simplified by assuming it to be equivalent to a single ignition source. Calculations of the ignition source parameters then use the strongest ignition source machine, continuously in contact with any gas entering the plant, as being representative of a high density of sources of that equipment level.

One of the biggest risks of ignition due to machinery (particularly electrical) is that caused by faults, which is assumed to be the same for all levels of equipment. Whatever the probability of faults resulting in ignition may be, the density of such potential faults, and thus the overall probability of ignition from such faults, will reduce as the density of equipment is reduced. This is the primary justification for the reduction in p for lower densities of equipment levels. Thus, the value of p calculated for 'high' densities of equipment (as described above) is reduced for two further cases, 'medium' and 'low' density.

Sensitivity analysis of the final model, including the initial, approximate 'machinery factor' assumptions, is presented in Appendix D. It is found that the source provided by background equipment is not significant compared with other sources affecting the model. Since the initial assumptions produce results midway between the maximum and minimum 'machinery factor' sensitivity cases, and achieve the main aim of distinguishing between the

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different levels of equipment that occur at different sites, they are considered to be acceptable.

The proportion of sources which are covered or shielded is a highly variable factor, as is the strength of such shielding. Therefore, the rate of gas ingress to such sources is impossible to quantify accurately. In order to represent the lower risk created by the delay in gas ingress, the ignition probability of a covered source is taken to be half of that assumed when the source is uncovered.

For each of the equipment levels considered, the ignition source content of a typical machine or section of equipment was derived by considering individual cases in detail and then attempting to generalise the contents for all such cases. For example, printing machinery was taken as representative of heavy machinery but a stronger element of 'additional components' (pumps, compressors, etc.) has been included to represent the make up of a more general site containing 'heavy' equipment.

Sections C.2.3.4 to C.2.3.5 list the assumed composition of a typical individual machine within each of the assumed equipment levels. Having established the ignition sources involved, the overall ignition source parameters attached to each equipment level are calculated using the method described in Section C.2.3.3.

C.2.3.3 Calculation Method

The equations used in the following analysis are derived in Phase I of this study (Spencer & Rew, 1997)).

Consider a site (or, in this case, a machine) containing j different types of ignition source (j=1, ... J). There are n_j sources of type j, which will have ignition source parameters p_j, a_j and λ_j. If the site is covered by flammable gas then the probability of no ignition due to source type j is given by:

$$Q_j(t) = (1 - a_j p_j)^{n_j} e^{-n_j \lambda_j p_j t} \qquad \text{(C.2.1)}$$

Therefore the probability of no ignition over the whole site (or group of equipment) is given by:

$$Q_s(t) = \prod_{j=1}^{J} \left\{ (1 - a_j p_j)^{n_j} e^{-n_j \lambda_j p_j t} \right\} \qquad \text{(C.2.2)}$$

The parameters representing an equivalent single ignition source, p_s, a_s and λ_s, are such that:

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$$Q_s(t) = (1 - a_s p_s)e^{-\lambda_s p_s t} \tag{C.2.3}$$

Equating (C.2.2) and (C.2.3):

$$\begin{aligned} t = 0 \quad &\Rightarrow \quad 1 - a_s p_s &&= \prod_{j=1}^{J} (1 - a_j p_j)^{n_j} \\ t \neq 0 \quad &\Rightarrow \quad +\lambda_s p_s &&= \sum_{j=1}^{J} n_j \lambda_j p_j \end{aligned} \tag{C.2.4}$$

In order to solve equations (C.2.4) for j sources, one of the three unknowns (a_s, p_s or λ_s) must have a specified value. In the 'heavy equipment' case, for example, the combination of the three continuous sources would result in a continuous source with p equal to 0.496. So p_s is set at 0.5 and the equation solved (where, in this case, J=4) to find a_s and λ_s.

C.2.3.4 'Heavy' Equipment Level Assumptions

This is dominated by mechanical equipment where a certain level of hot surfaces (and/or friction) will occur. Most of the machinery will be enclosed, but the hot surfaces will be exposed to the air within the site. Each mechanical machine will have a large motor as well as several additional ignition source components such as compressors, pumps and additional motors. All machinery will have a number of electrical components, some of which may be high voltage.

- *Hot surface source - uncovered*

Significant sources due to friction or hot surfaces are considered individually (see Section C.3), so a continuous low risk of p=0.1 is assumed (uncovered).
(p=0.1, a=1, $\lambda=\infty$, n=1)

- *Large motor - covered*

Assume a continuous risk of p=0.6 for an uncovered motor (giving p=0.3 for the covered case). This is a very conservative value which is assumed to also account for the risk of ignition due to faults occurring, as well as the variable number of components. (p=0.3, a=1, $\lambda=\infty$, n=1)

- *Additional components - covered*

Each individual component will be of low risk, but a continuous uncovered value of p=0.4 (giving p=0.2 for the covered case) is assumed to account for the variable number of such components. (p=0.2, a=1, $\lambda=\infty$, n=1)

- *Electrical components - covered*

The majority of electrical components (switches, contacts, etc.) will be low voltage and will have more than one level of shielding from the atmosphere presenting a negligible risk of ignition. To account for faults and high voltage

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components, an approximate value of 20 sources per machine is assumed where each may produce a strong spark (giving $p=0.5$ for the covered case) twice per, working, day ($t_i=360$ minutes). ($p=0.5$, $a=0$, $\lambda=0.00277$, $n=10$)

Given these assumed ignition sources, the various parameters (p, a, λ, n) may be combined using the method detailed above (i.e. equations 3.4), to produce one set of parameters which defines the heavy equipment machinery factor. Thus, the ignition source parameters for sites with high concentrations of heavy machinery are:

$$p=0.5, \ \lambda=0.0277, \ a=0.992$$

For heavy machinery levels with medium and low concentrations of equipment (with less chance of faults occurring) the value of p is reduced to 0.4 and 0.3 respectively.

C.2.3.5 'Medium' Equipment Level Assumptions

In this case, there are lower amounts of mechanical equipment than that assumed for "heavy equipment", and there will also be a lower level of risk. Any ignition source due to friction or hot surfaces will be of a low level and will be enclosed within the machinery. Any motors that occur will be relatively small and have a lower risk of ignition than those considered above. Additional ignition source components will occur as specified for heavy machinery. All machinery will have a number of electrical components which are all assumed to be low voltage (i.e. 24V or lower).

- *Hot surface source - covered*

The probability of ignition is reduced by being enclosed.

($p=0.05$, $a=1$, $\lambda=\infty$, $n=1$)

- *Small motor - covered*

Assume a continuous risk of $p=0.4$ for an uncovered motor. This is a very conservative value which is assumed also to account for the risk of ignition due to electrical faults occurring, as well as the variable number of components.

($p=0.2$, $a=1$, $\lambda=\infty$, $n=1$)

- *Additional components - covered*

Each individual component will be of low risk, but a continuous uncovered value of $p=0.4$ is assumed, to account for the variable number of such components.

($p=0.2$, $a=1$, $\lambda=\infty$, $n=1$)

- *Electrical components - covered*

The majority of electrical components (switches, contacts, etc.) will be low voltage and will have more than one level of shielding from the atmosphere, and will therefore present a negligible risk of ignition. To account for faults,

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an approximate value of 20 sources per machine is assumed where each may produce a strong spark (p=1, when uncovered) once per, working, day (t_i=720 minutes). (p=0.5, a=0, λ=0.00139, n=20)

Given these assumed ignition sources, the various parameters (p, a, λ, n) may be combined using the method detailed above, which gives the ignition source parameters for sites with high concentrations of medium machinery as:

p=0.4, λ=0.0347, a=0.98

For medium machinery levels with medium and low concentrations of equipment (with less chance of faults occurring) the value of p is reduced to 0.3 and 0.2 respectively.

C.2.3.6 'Light' Equipment Level Assumptions

These are dominated by electrical equipment and the only mechanical equipment that may occur is assumed to be of a relatively low ignition probability and will be covered. All components are assumed to be low voltage.

- *Additional components - covered*

Each individual component will be of low risk, but a continuous uncovered value of p=0.5 is assumed to account for the risk of ignition due to electrical faults occurring, as well as any motors that may be employed.
(p=0.25, a=1, $\lambda=\infty$, n=1)

- *Electrical components - uncovered*

To account for faults, an approximate value of 20 sources per machine is assumed where each may produce a strong spark once per, working, day (t_i=720 minutes). (p=0.5, a=0, λ=0.00139, n=20)

Given these assumed ignition sources, the various parameters (p, a, λ, n) may be combined using the method detailed above, which gives the ignition source parameters for sites with high concentrations of light machinery as:

p=0.25, λ=0.0556, a=1

For low machinery levels with medium and low concentrations of equipment (with less chance of faults occurring) the value of p is reduced to 0.2 and 0.15 respectively.

C.2.4 Ignition Due to Smoking

Because of the wide range of the possible number of smokers at each site, the risk of ignition caused by the lighting of cigarettes is taken as being continuous over the start of each break period. Breaks are assumed to occur every 2 hours, and for the first 5 minutes of each break there will be a continuous source, of p=1, due to cigarettes being lit.

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Based on the conclusions of Jeffreys et al (1982), it is assumed that the ignition source related to smoking is from lighters only and burning cigarettes produce a negligible risk of ignition.

Patterns of smoking vary considerably across industry and from site to site. Here, the most likely arrangement for smoking in each group is considered and taken to be representative of all sites in that industry group. For example, in base metal processing plants employees may be allowed to smoke while working, so smoking will be an intermittent on-site source, whereas in food processing plants smoking will only be allowed outside, so will occur externally during specified periods.

These assumptions are conservative, since:

- it is extremely unlikely that, in the event of a vapour cloud being present, anyone would attempt to smoke,
- during the assumed 5 minute initial period of each break period the source due to lighting cigarettes would be intermittent rather than continuous.

C.2.5 Day and Night Variations

In all other sections of this appendix the assumptions, and resulting data, are based on the sites being in continuous operation throughout the day. It is assumed that sites either remain in continuous operation throughout the night or are completely shut down at the end of the day. In the latter case, any risk of ignition caused by activity taking place out of working hours is assumed to be negligible, unless otherwise specified in Section C.3. Thus, the ignition source parameters remain the same at night, but the densities of the different sources (i.e. the sites that are in use) reduce significantly.

Data indicating the proportion of plants which operate through the night is not readily available. However, the size, by number of employees, of plants is given by the ONS statistics (1997), and these figures are used to define plants as either 'large' or 'small' scale. Large plants are defined here as those with more than 50 employees per site. These large plants are assumed to operate continuously for 24 hours, whereas small plants will only work during normal working hours (i.e. daytime).

In some cases this general assumption is considered to be inappropriate, for example in the 'Printing' group where almost all sites would be classed as 'small'. Where alternative assumptions about night time operation are used they are specified in the relevant part of Section C.3.
The ratio of large to small plants is specified in Table C.3, as r_{24}, and the overall density of ignition sources which exist at night (for each industry type), μ_{j24}, is $\mu_j.r_{24}$. Where the assumption that only sites with greater than 50 employees are continuously run is considered to be unsuitable, an alternative ratio, r'_{24}, is used, and the assumption stated. The final values of μ_{j24} are given in Table C.4.

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Group	No. of Sites	Density of Sites (μ)	No. of Large Sites	% (r24)	Alternative Assumption (r'24)	Density of Sites (μ24)	Assumption
Food Products	10,580	0.10	1,645	16	-	0.015	large plants
Textiles	18,220	0.16	1,790	10	-	0.016	large plants
Wood	12,545	0.11	880	7	-	0.008	large plants
Printing	29,215	0.26	1,135	4	25	0.066	1/4 of total
Chemicals	13,005	0.12	1,840	14	-	0.017	large plants
Non-metals	6,945	0.06	620	9	33.3	0.021	1/3 of total
Basic Metals	3,110	0.03	500	16	33.3	0.009	1/3 of total
Metal Products	30,045	0.27	1,490	5	25	0.068	1/4 of total
Machinery	15,600	0.14	1,490	10	25	0.035	1/4 of total
Electrical	16,130	0.14	1,800	11	-	0.016	large plants
Transport	5,645	0.05	875	16	25	0.013	1/4 of total
NEC	18,940	0.17	715	4	15	0.026	15% of total
Vehicle Repair	12,675	0.12	-	-	0	0	daytime only
Wholesalers	62,533	0.56	-	-	0	0	daytime only

Table C.3 Data used in estimating the number of sites operating at night

C.2.6 Effect of Ventilation

The ventilation rate is used to determine the time taken for gas to enter a building which is covered by a flammable gas cloud. Thus, for drifting clouds (etc.), the ventilation rate determines whether the internal ignition sources become significant during the period over which the cloud is present.

The exact ventilation rate of buildings can vary as widely from one site to another, within a particular industry type, as it can from one industry type to another. For this reason, the method adopted here simply aims to distinguish the industrial sites with very high rates of ventilation from those with more typical ventilation rates.

A standard ventilation rate of 15 air changes per hour (ach) is assumed to represent most industrial sites. The industry types which have very high ventilation rates are considered here to be equivalent to external sources. That is, there is little or no resistance to air entering the site, so the delay in gas entering the site is assumed to be negligible (relative to other industrial sites). These assumptions are discussed in the following sections (C.2.6.1 and C.2.6.2).

The assumptions made in determining whether an industry type has a 'typical' or 'high' ventilation rate are given in the relevant part of Section C.3.

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Also given in Section C 3, for each industry type, are more detailed estimates of the ventilation rate. Modification of the model would be required to allow different ventilation rates to be assigned within a land use type. Although the overall probability of ignition will eventually reach the same value, irrespective of the various ventilation rates used, more accurate ventilation rates would improve the accuracy of the model over the initial time period that a cloud is present (which would be of particular benefit when drifting clouds are being considered).

C.2.6.1 Assumptions

In selecting 15 ach as a typical industrial ventilation rate, consideration was given to the full range of possible ventilation rates within industry, based on ventilation requirements defined by CIBSE (1986).

A typical ventilation rate for a well sealed house is 2 ach or less. Industries are assumed always to have greater natural ventilation than houses (having more openings, etc., that will introduce air) and will normally have some mechanical ventilation to meet employees comfort needs. Therefore the minimum industrial ventilation rate is assumed to be 5 ach, as is typical for office accomodation. The maximum ventilation rate for industrial buildings is assumed to be around 30 ach, which is the upper limit of the rate given by CIBSE (1986) for boiler houses and engine rooms (15-30 ach).

Any substantial increase in natural ventilation caused by large openings is assumed to represent a special 'high ventilation' case, as discussed below. So, for typical industrial sites, the range of possible ventilation rates is 5 to 30 ach. The occurrence of such ventilation rates is assumed to vary uniformly around the median value. Thus, 15 ach is selected to represent a typical industrial ventilation rate.

C.2.6.2 Calculations

The following calculations are used as a guide to the upper values of the natural ventilation that can occur in different site types, and use equations taken from WSA reports by Lines et al (1997). A number of calculations were performed to explore the full range of site sizes and types and two examples are given below.

$$n = \frac{Q}{V} * 3600 \tag{C.2.5}$$

$$Q = \frac{A_1 w}{\sqrt{1 + A_1^2 / A_2^2}} \tag{C.2.6}$$

Where:

n - number of air changes per hour (ach);
w - wind speed (m/s) = 5 m/s here;
V - volume of ventilated area (m^3);
Q - volume flow rate (m^3/s).

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Typical Ventilation Rates - Example Calculation

The maximum natural ventilation for a typical industrial building is assumed to occur when several doors and windows are continuously open. Consider a medium sized building ($V = 60x40x4 = 9600m^3$) with several windows ($A_1 = 2m^2$) and one door left open ($A_2 = 1m^2$), to be the worst case for typical sites. Putting these figures into equations C.2.5 and C.2.6 gives a value of n of 1.67 ach. However, it should be noted that thermal effects may produce a similar contribution to ventilation.

Thus, the highest rate of ventilation that will occur in normal cases is likely to be less than 4 ach and can be neglected.

High Ventilation Rates - Example Calculation

In buildings which may have open sections or permanently open large doors, the maximum rate of ventilation will occur if there are two large openings, which can be treated as an inlet and an outlet. Consider a medium sized plant ($V = 60x40x4 = 9600m^3$) with large main doors left open (for deliveries, cooling, etc.)($A_1 = 5x4 = 20m^2$) and various other openings (windows, doors, delivery inlets, etc.) which may be treated as one large opening ($A_2 = 20m^2$), to be the worst case for high ventilation rate buildings. Putting these figures into equations C.2.5 and C.2.6 gives a value of n of 26.51 ach.

This indicates that, in these open-building cases, natural ventilation may be as high as the maximum mechanical ventilation rate. Thus, if higher ventilation rate buildings are defined as those with both high mechanical and natural ventilation they can be assumed to have a combined ventilation rate of greater than 30 ach (although ventilation rates may not necessarily be superimposed). In order to distinguish these examples from the typical ventilation rate cases they are assumed to be represented as external sources.

Note that, to confirm that this assumption is reasonable, sample ignition source parameters were entered into the model as (i.) internal sources with 15 ach ventilation rate, (ii.) internal with 30 ach, and (iii.) external sources. The resulting probability of ignition profile for the 30 ach case was much closer to that of the external sources than it was to the 15 ach results. Since the ventilation rate for the 'higher' cases will always be greater than 30 ach, the external source assumption appears to be valid.

C.2.7 Ignition Due to Boilers/Heating Systems

C.2.7.1 Types of Boiler Ignition Source

The type of heating, and cooling, equipment used in industrial areas is usually independent of the type of site. It is assumed here that, in terms of ignition source potential, industrial heating equipment will vary with the size rather than the type of the site. The main assumptions are listed below.

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- The risk of ignition from cooling and ventilation equipment is negligible.
- Smaller sites will employ a variety of heating methods, such as simple radiant air heaters or domestic-style gas boilers. It is assumed that, as in domestic heating, one third of these sites will use balanced flue boilers. As discussed in Appendix B, these types of boiler draw in air directly from outside and so are treated as external ignition sources, with probability of ignition of one. The source is active continuously while the boilers are in operation. Other than for balanced flue boilers, it is assumed that the probability of ignition from smaller scale heating equipment is negligible.
- Larger sites are assumed to use industrial type boilers. The most common types of such boiler (whether oil, gas or coal fired) are 'forced air draft' and 'atmospheric' boilers, which use the air surrounding them. Typically, such boilers are situated in designated rooms or buildings which have louvered doors or windows to allow a supply of fresh, external air to the boilers. Any delay in gas from a vapour cloud entering such a site will be minimal, so these boilers are assumed to be external sources. The probability of ignition will be unity, continuously, while the boiler is in operation.
- In terms of boiler sizes, sites are defined as being 'small' if they have less than 10 employees. All other sites are considered to be 'large'.

C.2.7.2 Operation of Boilers

The operation of boilers will vary widely throughout the year, and also between different sites. In order to produce an estimate of the average usage of boilers in industry, the calendar is split into 2 sections. It is assumed that for 6 months of the year ('summer') there is no requirement for boilers to be used (neglecting hot water requirements). For the remaining, 'winter', months the base assumption is that heating will be required for half the time that a site is in operation. This base case would give ignition source parameters for boilers as: $p=1$; $\lambda=\infty$; $a=0.25$ (where $a=1/2 \times 1/2$).

This estimate is refined slightly to allow for heavy industries that have high temperature processes. Such sites will heat themselves to some extent and have a reduced heating requirement even in winter, which is assumed to be half of that of the base case. So: $p=1$; $\lambda=\infty$; $a=0.125$ (where $a=1/2 \times 1/2 \times 1/2$).

C.2.8 Effect of early detection of gas

The possibility of detection of gas in supervised processes was considered in selecting model parameters, but the general assumption made was that detection would occur too late to be of benefit. For example, a welder would not detect gas until it had reached him. The possibility that gas may be detected in a 'safe' area of the site, giving time to allow shut down of supervised processes, was also considered. However, it was decided that modelling of this feature would be subjective and that it would have negligible

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effect in comparison to sources which could not easily be shut down, such as boilers.

C.3 INDUSTRY-SPECIFIC ASSUMPTIONS

Each building within an industrial area is being considered as a single ignition source. Density data is available for the broad SIC groups listed in Section C.2.1, and so it greatly simplifies the analysis if a single set of ignition source parameters can be assigned to each of these SIC groups. The groups are based on businesses which manufacture similar products, and so the manufacturers within each group generally have similar processes, and thus similar ignition sources. (This assumption is based on investigation of the composition of each of the SIC groups.)

Further sub-dividing the groups in order to have more types of ignition source (so decreasing the uncertainty of the ignition sources covered by each group) has been considered as a means of improving the accuracy. However, every single industrial site will have different sources, whatever product is being made, and so the model can never be expected to produce an exact estimate of ignition probability. It is assumed that, if the individual ignition sources are made more representative by sub-dividing the groups, the improvement in the accuracy of the model would be more than off-set by the accompanying decrease in accuracy of the available density data.

Analysis of the SIC groups shows that some of the groups share similar processes, though making different products, and so will have similar ignition sources. These SIC groups have been combined to form larger groups which are assumed to be represented by the same single ignition source. These groups, or industry types, are discussed individually in the following sections (C.3.1 to C.3.14).

For each industry type, the assumed characteristics are listed, together with the significant ignition sources that will occur within a typical site of that industry. The model parameters (p, a, λ, n) attached to each of these ignition sources are stated, and the overall (combined) ignition source parameters are given. In each section the resultant ignition source parameters, for a site containing the given sources, are calculated with equations C.2.1 and C.2.2, using the same method as described in Section C.2.3.

Other assumptions, and parameters required for the model, such as density, ventilation rate and night time operation densities, are discussed for each industry type. (The model input requires ventilation rates to be defined as either internal - 'typical' - or external - 'high'. More detailed estimates of ventilation rates are given for each industry type, for completeness, although they are not used with the present model.)

C.3.1 Food Products

Includes SIC groups:

- ...food products
- ...beverages and tobacco

Examples:

- meat and poultry processing; brewing; manufacture of bread; grain milling; water bottling; manufacture of confectionery; manufacture of cereals; etc.

Assumed characteristics:

- high degree of automation,
- some use of ovens and drying furnaces but generally no significant sources (ovens will be relatively low temp and well sealed),
- heaviest equipment will be packaging and canning equipment,
- clean environment - smoking will be outside only,

Internal sources:

- high concentration of light machinery ($p=0.25$; $a=0.99$; $\lambda=0.0556$)
- no other major sources

External sources:

- smokers ($p=1$; $a=0.0417$; $\lambda=0.00833$)
- heating boilers ($p=1$; $a=0.25$; $\lambda=\infty$)
- combined ($p=1$; $a=0.2813$; $\lambda=0.00833$)

No. of sites:

- 10,580 (4.2% of total)
- (0-50 employees) 8,935
- (50+ employees) 1,645 (16%)(24 hour operation)

Ventilation:

- 'typical' - 15 ach
- (low - base ventilation rate only - 5 to 10 ach)

C.3.2 Textiles

Includes SIC groups:

- ...textiles and textile products
- ...wearing apparel
- ...dressing and dyeing of fur
- ...leather and leather products

Examples:

- preparation and spinning of fibres; jeans cloth weaving; finishing of textiles; manufacture of women's underwear; tanning and dressing of fur; leather handbag manufacture; manufacture of footwear; etc.

Contents

Assumed characteristics:

- relatively low concentration of light machinery,
- some drying equipment and occasional heating/burning machinery but generally no significant sources
- clean environment (often with flammable products) - smoking will be outside only,

Internal sources:

- low concentration of light machinery ($p=0.15$; $a=0.99$; $\lambda=0.0556$)
- no other major sources

External sources:

- smokers ($p=1$; $a=0.0417$; $\lambda=0.00833$)
- heating boilers ($p=1$; $a=0.25$; $\lambda=\infty$)
- combined ($p=1$; $a=0.2813$; $\lambda=0.00833$)

No. of sites:

- 18,220 (7.1% of total)
- (0-50 employees) 16,430
- (50+ employees) 1,790 (10%)(24 hour operation)

Ventilation:

- 'typical' - 15 ach
- (low - base ventilation rate only - 5 to 10 ach)

C.3.3 Wood and Paper

Includes SIC groups:

- ...wood and wood products
- ...pulp and pulp paper products

Examples:

- saw milling and planing of wood; wooden spoon manufacture; manufacture of plywood; manufacture of paper; manufacture of paper stationary; etc.

Assumed characteristics:

- medium concentration of medium level machinery,
- some drying processes but generally no significant sources
- smokers typically outside (fire risk from sawdust, etc.)

Internal sources:

- medium concentration of medium machinery ($p=0.3$; $a=0.98$; $\lambda=0.0347$)
- no other major sources

External sources:

- smokers ($p=1$; $a=0.0417$; $\lambda=0.00833$)
- heating boilers ($p=1$; $a=0.25$; $\lambda=\infty$)
- combined ($p=1$; $a=0.2813$; $\lambda=0.00833$)

Contents

No. of sites:
- 12,545 (4.9% of total)
- (0-50 employees) 11,670
- (50+ employees) 880 (7%)(24 hour operation)

Ventilation:
- 'typical' - 15 ach
- (quite low - increased ventilation due to sawdust/fumes - 10 to 15 ach)

C.3.4 Printing

Includes SIC group:
- ...publishing, printing and reproduction of recorded media

Examples:
- publishing of books; bookbinding; publishing of newspapers; postage stamp printing; art publishing; etc.

Assumed characteristics:
- high degree of automation
- high concentration of relatively heavy machinery
- generally no other significant sources
- mixture of mechanical and electrical equipment
- smoking inside plant in designated area (at set times)
- lower heating requirement - small sites, high machinery level ($a=1/8$)

Internal sources:
- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- smokers ($p=1$; $a=0.0417$; $\lambda=0.00833$)
- combined ($p=0.8$; $a=0.883$; $\lambda=0.0277$)

External sources:
- heating boilers ($p=1$; $a=0.125$; $\lambda=\infty$)

No. of sites:
- 29,215 (11.5% of total)
- (0-50 employees) 28,080
- (50+ employees) 1,135 (4.0%)
- mostly smaller sites, assume 25% will have 24 hour operation

Ventilation:
- 'typical' - 15 ach
- (quite low - increased ventilation due to high level of machinery - 10 to 15 ach)

C.3.5 Chemicals

Includes SIC groups:
- ...chemicals, chemical products and man-made fibres

Contents

- ...rubber and plastic products

Examples:

- manufacture of ... industrial gases; fertilisers; soap and detergents; perfumes; man-made fibres; rubber tyres and tubes; rubberised textiles; plastic packing goods; plastic goods; etc. N.B. oil refineries not included

Assumed characteristics:

- high concentration of relatively heavy machinery
- some degree of boilers, furnaces, etc. - leakage and hot surfaces will be minimal because of flammable nature of products and reactants
- mixture of mechanical and electrical equipment
- no smoking on or around site
- small amount of use of external flares - 15% of plants

Internal sources:

- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- furnaces, hot surfaces, etc. ($p=0.2$; continuous)
- combined ($p=0.6$; $a=0.99$; $\lambda=0.023$)

External sources:

- (flare)=$0.15\mu_j$: flares ($p=1$; cont.)
- (boilers)=$0.85\mu_j$: heating boilers ($p=1$; $a=0.25$; $\lambda=\infty$)

No. of sites:

- 13,005 (5.1% of total)
- (0-50 employees) 11,165
- (50+ employees) 1,840 (14%)(24 hour operation)

Ventilation:

- 'typical' - 15 ach
- (quite low - increased ventilation - toxic products, etc. - 10 to 15 ach)

C.3.6 Non-Metal Products

Includes SIC group:

- ...other non-metallic (mineral) products

Examples:

- manufacture of ... glass; glass fibres; ceramics; bricks, tiles and construction products; concrete products; stone cutting; abrasive products; etc.

Assumed characteristics:

- almost all sites will contain large furnaces, kilns, etc., with high ignition probability
- some will have very high temperature products and hot surfaces
- generally low concentration of 'background' equipment

Contents

- smoking permitted on site, but negligible risk compared with other on site sources
- low heating requirement because of high temperature processes - neglected because of other high sources on-site

Internal sources:

- continuous risk of ignition (p=1) from combination of furnaces, kilns, hot products, etc. ($p=1$; $a=1$; $\lambda=\infty$)

External sources:

- none

No. of sites:

- 6,945 (2.7% of total)
- (0-50 employees) 6,325
- (50+ employees) 620 (9.0%)
- assume 1/3 of plants operate 24 hours (so that furnaces, etc. can operate continuously)

Ventilation:

- 'high' - treat as external source (high temperature processes and relatively high levels of smoke and fumes will result in a high level of mechanical ventilation - open layout and nature of processes will also increase natural ventilation through open doors, etc. - > 30 ach)

C.3.7 Basic Metals

Includes SIC group:

- ...basic metals

Examples:

- manufacture of basic steel and ferro-alloys; first processing of iron and steel (forging, etc.); aluminium smelting; precious metals production; casting of non-ferrous metals; etc.

Assumed characteristics:

- all processing will involve molten or very high temperature metals
- large furnaces and very high temperature products exposed to air within site
- low concentration of heavy machinery
- smoking permitted on site, but negligible risk compared with other on-site sources
- low heating requirement because of high temperature processes - neglected because of other high sources on-site

Internal sources:

- continuous risk of ignition (p=1) from combination of furnaces, kilns, hot products, etc. ($p=1$; $a=1$; $\lambda=\infty$)

Contents

External sources:

- none

No. of sites:

- 3,110 (1.2% of total)
- (0-50 employees) 2,610
- (50+ employees) 500 (16.0%)
- assume 1/3 of plants operate 24 hours (so that furnaces, etc. can operate continuously)

Ventilation:

- 'high' - treat as external source (high temperature processes and relatively high levels of smoke and fumes will result in a high level of mechanical ventilation - open layout and nature of processes will also increase natural ventilation through open doors, etc. - > 30 ach)

C.3.8 Metal Products

Includes SIC group:

- ...fabricated metal products, excluding machinery and equipment

Examples:

- manufacture of ... metal structures; builders materials; steam generators and boilers; treatment and coating of metal; general metal working; light metal packaging; paper-clips; fasteners, screws and springs; etc.

Assumed characteristics:

- high concentration of basic (heavy) machinery
- some hot products
- no open flames, furnaces, etc., but some welding, cutting and grinding (some of these processes will be covered)
- smoking permitted on site, but negligible risk compared with other on-site sources
- lower heating requirement - relatively high machinery level ($a=1/8$)

Internal sources:

- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- hot surfaces or products ($p=0.2$, $a=1$; $\lambda=\infty$)
- welding - average 10 minutes, every hour ($t_a=10$, $t_i=50$)
  ($p=1$; $a=0.1667$; $\lambda=0.0167$)
- grinding - average 10 minutes, every hour ($t_a=10$, $t_i=50$)
  ($p=0.5$; $a=0.1667$; $\lambda=0.0167$)
- combined ($p=1$; $a=0.692$; $\lambda=0.0389$)

External sources:

- heating boilers ($p=1$; $a=0.125$; $\lambda=\infty$)

No. of sites:

- 30,045 (11.8% of total)

Contents

- (0 50 employees) 28,555
- (50+ employees) 1,490 (5.0%)
- mostly smaller sites, assume 25% will have 24 hour operation

Ventilation:

- 'typical' - 15 ach
- (quite high - increased ventilation due to high levels of machinery, heat, fumes, etc. - 15 to 20 ach)

C.3.9 Machinery

Includes SIC group:

- ...machinery and equipment, not elsewhere classified

Examples:

- manufacture of ... engines and turbines; lifting and handling equipment; machine tools; textile industry equipment; pumps and compressors; etc.

Assumed characteristics:

- high concentration of basic (heavy) machinery
- high degree of automation
- some hot products
- no open flames, furnaces, etc., but some welding, cutting and grinding (these processes will be covered)
- smoking permitted on site, but negligible risk compared with other on-site sources
- lower heating requirement - relatively high machinery level ($a=1/8$)

Internal sources:

- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- hot surfaces or products, covered ($p=0.1$, $a=1$; $\lambda=\infty$)
- welding etc. (i.e. a strong source) covered - average 10 minutes every hour ($t_a=10$, $t_i=50$) ($p=0.5$; $a=0.1667$; $\lambda=0.0167$)
- combined ($p=1$; $a=0.584$; $\lambda=0.0222$)

External sources:

- heating boilers ($p=1$; $a=0.125$; $\lambda=\infty$)

No. of sites:

- 15,600 (6.1% of total)
- (0-50 employees) 14,110
- (50+ employees) 1,490 (9.6%)
- mostly smaller sites, assume 25% will have 24 hour operation

Ventilation:

- 'typical' - 15 ach
- (quite high - increased ventilation due to high levels of machinery, heat, fumes, etc. - 15 to 20 ach)

Contents

C.3.10 Electrical, etc.

Includes SIC groups:
- ... office machinery and computers
- ... electrical machinery and apparatus not elsewhere classified
- ... radio, television and communication equipment and apparatus
- ... medical, precision and optical equipment; watches and clocks

Assumed characteristics:
- relatively high concentration of medium machinery,
- generally no other significant sources
- clean environment - smoking will be outside only,

Internal sources:
- high concentration of medium machinery (p=0.4; a=0.98; λ=0.0347)
- no other major sources

External sources:
- smokers (p=1; a=0.0417; λ=0.00833)
- heating boilers (p=1; a=0.25; $\lambda=\infty$)
- combined (p=1; a=0.2813; λ=0.00833)

No. of sites:
- 16,130 (6.3% of total)
- (0-50 employees) 14,330
- (50+ employees) 1,800 (11%)(24 hour operation)

Ventilation:
- 'typical' - 15 ach
- (low - base ventilation rate only - 5 to 10 ach)

C.3.11 Transport

Includes SIC groups:
- ... motor vehicles, trailers and semi-trailers
- ... other transport equipment

Examples:
- manufacture of ... cars; vans; ambulances; golf carts; aircraft and spacecraft (including engines); ships; caravans; motor vehicle parts; etc.

Assumed characteristics:
- high concentration of basic (heavy) machinery
- high degree of automation
- some hot products
- no open flames, furnaces, etc., but some welding, cutting and grinding (these processes will be covered)

Contents

- smoking permitted on site, but negligible risk compared with other on site sources
- lower heating requirement - relatively high machinery level (a=1/8)

Internal sources:

- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- hot surfaces or products, covered ($p=0.1$, $a=1$; $\lambda=\infty$)
- welding etc. (i.e. a strong source) covered - average 10 minutes, every hour ($t_a=10$, $t_i=50$) ($p=0.5$; $a=0.1667$; $\lambda=0.0167$)
- combined ($p=1$; $a=0.584$; $\lambda=0.0222$)

External sources:

- heating boilers ($p=1$; $a=0.125$; $\lambda=\infty$)

No. of sites:

- 5,645 (2.2% of total)
- (0-50 employees) 4,770
- (50+ employees) 875 (16.0%)
- mostly smaller sites, assume 25% will have 24 hour operation

Ventilation:

- 'typical' - 15 ach
- (quite high - increased ventilation due to high levels of machinery, heat, fumes, etc. - 15 to 20 ach)

C.3.12 Others

Includes SIC group:

- ... furniture and manufacturing not elsewhere classified

Examples:

- manufacture of ... chairs and seats; office and shop furniture; mattresses; jewellery; musical instruments; sports goods; arcade games; etc.

Assumed characteristics:

- range of processes but generally no major ignition sources
- high concentration of relatively heavy machinery
- smoking inside plant in designated area (at set times)

Internal sources:

- high concentration of heavy machinery ($p=0.5$; $a=0.992$; $\lambda=0.0277$)
- smokers ($p=1$; $a=0.0417$; $\lambda=0.00833$)
- combined ($p=0.5$; $a=0.862$; $\lambda=0.0369$)

External sources:

- heating boilers ($p=1$; $a=0.25$; $\lambda=\infty$)

No. of sites:

- 18,940 (7.4% of total)

Contents

- (0-50 employees) 18,225
- (50+ employees) 715 (3.8%)
- mostly smaller sites, assume 15% will have 24 hour operation

Ventilation:

- 'typical' - 15 ach
- (quite low - increased ventilation - high machinery level. - 10 to 15 ach)

C.3.13 Vehicle Repairs

Includes SIC group:

- maintenance and repair of motor vehicles

Examples:

- servicing of motor vehicles; exhaust fitting centre; car body repair; etc.

Assumed characteristics:

- some welding and grinding
- engines running frequently
- there will be other equipment and machines, but not to the extent found in manufacturing plants
- no other major ignition sources
- smoking permitted on site, but negligible risk compared with other on-site sources
- risk of ignition from heating equipment assumed to be negligible

Internal sources:

- welding - average 15 minutes, every 2 hours (t_a=15, t_i=105)
  (p=1; a=0.125; λ=0.0083)
- grinding - average 15 minutes, every 2 hours (t_a=15, t_i=105)
  (p=0.6; a=0.125; λ=0.0083)
- vehicle engines running (open bonnets) (t_a=30, t_i=30)
  (p=0.2; a=0.5; λ=0.01667)
- other background equipment (generators, lamps, etc.)
  (p=0.1; a=1; $\lambda=\infty$)
- combined (p=0.4; a=0.861; λ=0.0416)

External sources: none

No. of sites:

- estimated as 12,675 (5.0% of total)
- based on average of 10 employees per site, with 75% of total 169,000 employees based in industrial areas
- assume no 24 hour operation

Ventilation:

- 'high' - treat as external source (high levels of smoke and fumes will result in a high level of mechanical ventilation or, more commonly, increased natural ventilation through open doors, etc. - > 30 ach)

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C.3.14 Wholesalers

Includes SIC group:
- wholesale trade and commission trade, except motor vehicles
- (also used to represent any retail outlets and offices that may be found in industrial areas)

Examples:
- wholesale of ... tobacco products; textiles; waste and scrap; metals and metal ores; construction machinery; fruit and vegetables; etc.

Assumed characteristics:
- small risk of ignition due to material handling equipment
- there will be some other equipment and machinery, mostly electrical, but significantly less than that found in manufacturing plants
- no major ignition sources
- smoking will occur outside the site and is mainly due to customers
- risk of ignition from heating equipment assumed to be negligible

Internal sources:
- material handling equipment (t_a=15, t_i=45) (p=0.3; a=0.25; λ=0.0167)

External sources:
- one customer leaving site and lighting cigarette per 30 minutes (p=1; a=0.0332; λ=0.0033)

No. of sites:
- estimated as 62,533 (24.5% of total)
- based on average of 15 employees per site, with 938,000 employees working in industrial areas
- assume no 24 hour operation

Ventilation:
- 'typical' - 15 ach
- (low - base ventilation rate only - 5 to 10 ach)

C.3.15 'Urban' Sources

It is assumed that the traffic levels in and around an industrial area will be the same as for urban areas. Thus, in addition to the 14 'industry type' ignition sources which are discussed above, the following 'urban' ignition sources are present in industrial areas (as derived in Appendix B.)

Road Vehicles:
- p=0.1; a=1; $\lambda=\infty$;
- μ(day)=0.51; μ(night)=0.13;
- external source.

Traffic Lights:
- p=1; a=0; λ(day)=0.1; λ(night)=0.05;

- μ=0.004;
- external source.

Trains are also considered as an ignition source, although the density of their occurrence is low enough for their overall impact to be negligible.

C.4 INDUSTRIAL IGNITION SOURCE DATA

The data for each industrial ignition source, as calculated from the data presented in Section C.3, is summarised in Table C.4. Each industry type, or industrial group, is represented by a single internal ignition source (In), and in some cases by further external ignition sources (Ex). Each ignition source, j, is defined by:

- p - the probability of ignition from that source, given that it is active and enclosed within the gas cloud
- a - the proportion of time for which that source is active
- λ - the rate of activation of the source
- μ - the average number of sources, of type j, per unit industrial area (calculated from the proportion of industrial sites which are of type j (P_j) and the average density of industrial sites (μ_t), both of which are also given in the table)
- these values of μ and P are for daytime operation - night time figures are also given as $\mu(24)$ and P(24), respectively

The table also contains brief notes on the main assumptions that are made for each type of ignition source, and the main areas of uncertainty that are created by the assumptions.

C.5 SENSITIVITY OF DATA TO ASSUMPTIONS MADE

Appendix D compares the industrial source data discussed in this appendix, with the equivalent urban and rural data and existing models. The sensitivity of the derived model to changes in the parameters is also evaluated. For each of the main assumptions made (Sections C.2 and C.3), the sensitivity results from Appendix D are discussed below (Sections C.5.1 to C.5.9) and the most significant parameters identified.

When a specific site is being examined using the model, more detailed information may be available which can improve, or eliminate, the general assumptions which have been made. The main areas where this may be of benefit (i.e. the parameters identified as the most significant from the sensitivity analysis) are discussed briefly, where appropriate, in the following sections.

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μt= 2.30

No.	Industry Type	Notes on Assumptions	In/Out	p	λ	a	P	μ	P(24)	μ(24)	Main Uncertainty
1	Food Products	High conc. light eqpt., no major sources	In	0.25	0.056	0.99	4.2	0.097	16	0.015	machinery factor (m.f.)
		Smokers	Out	1	0.0083	0.042		0.037		0.006	night time density (n.d.
		Boilers	Out	1	0.0083	0.281		0.059		0.009	smoking assumptions
2	Textiles	Low conc. light eqpt., no major sources	In	0.15	0.056	0.99	7.1	0.163	10	0.016	m.f. & n.d.
		Smokers	Out	1	0.0083	0.042		0.072		0.007	
		Boilers	Out	1	0.0083	0.281		0.091		0.009	smoking assumptions
3	Wood & Paper	Med. conc. med. eqpt., no major sources	In	0.3	0.035	0.98	4.9	0.113	7	0.008	m.f. & n.d.
		Smokers	Out	1	0.0083	0.042		0.053		0.004	
		Boilers	Out	1	0.0083	0.281		0.059		0.004	smoking assumptions
4	Printing	High conc. heavy eqpt., smoking	In	0.8	0.0277	0.883	11.5	0.265	25	0.066	m.f. & n.d.
		Boilers	Out	1	∞	0.125		0.127		0.032	smoking assumptions
5	Chemicals, etc.	High conc. heavy eqpt., hot surfaces, etc.	In	0.6	0.023	0.99	5.1	0.117	17	0.020	machinery factor
		Flare (on 15% of sites)	Out	1	∞	1		0.018		0.003	night time density
		Boilers	Out	1	∞	0.25		0.062		0.011	density of sites with flares
6	Non-metal	Furnaces & high temp. processes	Out	1	∞	1	2.7	0.062	33.33	0.021	n.d. & ventilation rate
7	Basic Metals	Furnaces & high temp. processes	Out	1	∞	1	1.2	0.028	33.33	0.009	n.d. & ventilation rate
8	Metal Products	High conc. heavy eqpt., welding, etc.	In	1	0.039	0.692	11.8	0.271	25	0.068	machinery factor
		Boilers	Out	1	∞	0.125		0.143		0.036	night time density
9	Machinery	High conc. heavy eqpt., welding, etc.	In	1	0.022	0.584	6.1	0.140	25	0.035	machinery factor
		Boilers	Out	1	∞	0.125		0.081		0.020	night time density
10	Electrical	High conc. med. eqpt., no major sources	In	0.4	0.0347	0.98	6.3	0.145	10	0.014	machinery factor
		Smokers	Out	1	0.0083	0.042		0.065		0.006	night time density
		Boilers	Out	1	0.0083	0.2813		0.080		0.008	
11	Transport	High conc. heavy eqpt., welding, etc.	In	1	0.022	0.584	2.2	0.051	25	0.013	machinery factor
		Boilers	Out	1	∞	0.125		0.029		0.007	night time density
12	Other	High conc. heavy eqpt., smoking	In	0.6	0.037	0.862	7.4	0.170	15	0.026	m.f. & n.d.
		Boilers	Out	1	∞	0.25		0.077		0.012	variation within group
13	Vehicle Repair	Welding, engines running, etc.	Out	0.4	0.042	0.861	5	0.115	0	0.000	ventilation rate
14	Wholesalers	Materials handling eqpt.	In	0.3	0.0167	0.25	24.5	0.564	0	0.000	density/no. of sites
		Smokers	Out	1	0.033	0.0033		0.564			smoking assumptions
15	Urban Sources	Road vehicles	Out	0.1	∞	1		0.510		0.130	
		Trains	Out	0.5	∞	1		0.000		0.000	
		Traffic lights	Out	1	0.1 **0.05	0 (night)		0.004		0.004	

Table C.4 Summary of industrial ignition source data

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C.5.1 Density and Use of Boilers

Figure D.3 shows how the probability of ignition in industrial areas changes if the assumptions about boiler density and boiler usage are varied. The 'no boilers' and 'more boilers, more use' variations represent the minimum and maximum cases (respectively) of probability of ignition due to boilers. The relatively large differences between these plots and the base case indicate how sensitive the model is to changes in the boiler assumptions. This is because boilers are strong external ignition sources and occur in a high proportion of all plants (i.e. a strong, high density source).

The actual usage of boilers will vary greatly, both seasonally and between different plants. The assumptions used in the base case (see Section 2.7) represent a best estimate of the average usage across all plants. Because of the relative impact of this assumption, it is one of the main areas in which the model should be adjusted, or refined, if a particular, well-defined, area is being examined.

Adjustments
Certain industrial areas (for example, those served by municipal CHP plants) may have an unusually low incidence of boilers, which can be easily accounted for by changing the input data to the model, if the information is available.

C.5.2 Ventilation Rates of Buildings

Figure D.4 suggests that varying the ventilation rate does not substantially change the actual probability of ignition. The maximum variation between the higher ventilation rate, of 25 ach, and the base case rate, of 15 ach, shown in Figure D.4, is less than 0.2). However, it should be noted that this figure is for a drifting cloud and the same conclusions may not apply to continuous releases.

The probability of ignition is also shown for the base case value of 15 ach, but without the 3 'high' ventilation sources being considered as external. This shows that the assumption that the 'high' ventilation sources are external increases the probability of ignition for all cloud sizes. (The high ventilation rate sites have strong and continuous sources, so have a significant impact when taken as being external.)

Adjustments
This is the best assumption that can be made for a general industrial area, but if a small, known area is considered, the sites which are open (i.e. high ventilation rate) may be identified individually. In this situation all industrial sites may be classed as internal (15 ach) and additional external sources identified for sites, of any industry type, that are found to be very open.

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C.5.3 Density

The variation in possible densities of industrial sites is illustrated in Figure D.5. By taking twice and half the base case value of μ_t (the average number of industrial sites per unit industrial area) the figure shows the realistic upper and lower limits of density variation.

Adjustments
The density of an industrial area can vary significantly from one region to another, resulting in the wide range of probabilities of ignition shown in Figure D.5. When a particular area is being considered, it will be possible to determine from a map whether the value of μ_t is significantly higher or lower than the assumed value of 2.3 ha^{-1}.

C.5.4 Night Time Density

Very little information is available regarding the overall number of industrial sites that operate at night, so the assumed night time operation rates are quite approximate (Section 2.5). Figure D.6 illustrates how the night time probability of ignition will vary if the proportion of sites operating at night changes.

The base case is based upon all sites of greater than 50 employees operating at night as well as through the daytime, but with this proportion increased to 25% or 33% where appropriate (detailed in Section 3). The model has been used with these proportions doubled and halved, and also with the proportion fixed for all sites at 50% and 10% of sites operating at night. It is found that the two upper cases (double the base case and with 50%) produce very similar probability of ignition profiles. This is the same for the lower cases (half the base case and 10%). So, for clarity, only the 50% and 10% cases are shown in Figure D.6 (representing the realistic upper and lower limits of night time operation).

Adjustments
Generally, the assumed densities of sources at night can be considered to be reasonably accurate. However, certain industrial areas may consist predominantly of large plants, all of which operate continuously (day and night). Where such a site is being analysed by the model, adjusting the data accordingly can greatly improve the accuracy of the (night time) model.

C.5.5 Machinery Factor

Figure D.7 illustrates the sensitivity of the model to variations in the assumptions made about the background level of ignition sources due to equipment in plants. The limits of such variation are considered by setting the machinery factor to be zero in all cases and then to have a probability of one in all cases. The graph shows that the overall probability of ignition is not significantly effected by the level of ignition sources from background equipment, primarily because they are internal sources.

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The difference between the probabilities of ignition in the 'zero' and base case 'machinery factor' levels is negligible. The small increase that can be seen between the base case and 'maximum' case is due to the increase in machinery factor in vehicle repair workshops, which are external sources.

C.5.6 Smoking

The results shown in Figure D.8 show that the effect of smoking on the overall model is very minor. Even the difference between the probability of ignition with no smoking and that with double the amount of smoking assumed in the base case is negligible.

C.5.7 Composition

The variations in parameters shown in Figure D.9 aim to demonstrate the sensitivity of the model to variations in the densities of individual industry types. The proportion of wholesalers is varied because it is the most common site in industrial areas (approximately a quarter of the total). To represent the effect of having more, or fewer, sites with strong sources, the proportion of the three high ventilation sites (base metals, non-metals and vehicle repair workshops) is varied.

Since wholesale outlets represent a very low ignition source, doubling the proportion reduces the overall probability of ignition because there will be fewer of the other, higher strength, ignition sources. The resulting ignition probability profile is very similar to that produced if the proportion of high ventilation rate sites is halved. Similarly, the profiles produced with half the proportion of wholesalers and double the proportion of high ventilation rate sites increase by the same amount over the base case.

The cases considered here are the most extreme cases of possible variation in the relative proportions of particular industry types. Figure D.9 shows the sensitivity of the model to these changes to be significant, but relatively low. Varying other individual industry type densities is not shown, as the change in the overall probability of ignition is negligible.

Adjustments
If the proportions of the different sites in a known industrial area is easily determined, then the data input into the model can be adjusted to improve the accuracy. However, unless an area is dominated by a particular type of site, the overall effect will be small.

C.5.8 Flares on Chemical Sites

The base case assumes that there will be a continuous flare present at 15% of chemical plants. Figure D.10 shows that varying the proportion of sites with a flare from 0 to 50% results in minimal change in the overall probability of ignition.

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C.5.9 Urban Sources

To assess the impact of the 'urban sources' which are present in industrial areas (i.e. road vehicles and traffic lights), the density of vehicles and all urban sources has been varied, as shown in Figure D.11. The difference between the probability of ignition with no urban sources at all and the probability with double the number of vehicles is small. (It is at most 0.05, and decreases to almost 0 for larger cloud sizes - where the internal industrial sources become most significant.)

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APPENDIX D

MODEL RESULTS AND SENSITIVITY STUDY

A large, instantaneous release of propane is simulated using the HGSYSTEM model HEGABOX (Post 1994). This release is simulated during typical day and night time conditions. Using the results from these simulations, the probability of ignition over industrial, urban and rural areas is then calculated using the base case model parameters for these areas during the day and night. The results of these calculations are compared with the results from the current HSE model (Clay et al, 1988) and the Simmons model (Simmons, 1974). A large number of variations on the base cases are then considered in order to find the sensitivity of the probability of ignition to the model parameters.

In order to evaluate the effect of the release type on the probability of ignition, two continuous releases are simulated using the HGSYSTEM model HEGADAS-T (Post 1994). For a long, continuous release, there is a higher contribution from intermittent and internal ignition sources.

D.1 Dispersion modelling

Two instantaneous releases of 200 tonnes of propane are simulated using HEGABOX (Post 1994), one during the day time and one during the night time. The input conditions used and some key results are given in Table D.1. The total area swept by the cloud as a function of time is shown in Figure D.1.

Release parameter	Day time	Night time
Initial aspect ratio	1	1
Initial diameter	48 m	48 m
Wind speed	5 m/s	2 m/s
Stability	D	F
Air and ground temperature	20°C	20°C
Ground roughness	0.1 m	0.1 m
Initial gas concentration	100%	100%
Initial gas temperature	-42°C	-42°C
Release size	200 tonnes	200 tonnes
Results when concentration reaches LFL		
Cloud area	5.432×10^5 m^2	8.336×10^5 m^2
Time	140 s	215 s

Table D.1 Input conditions for instantaneous release of propane and key results

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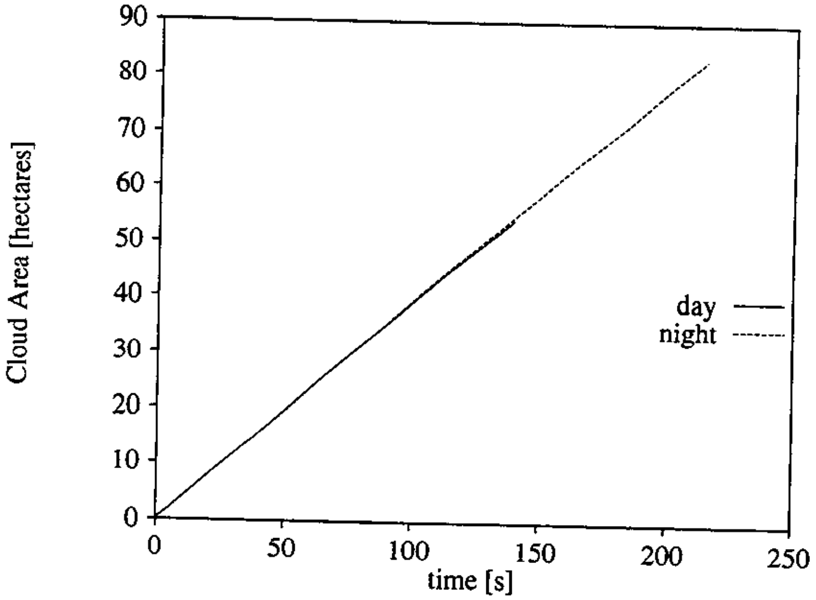

Figure D.1 Total area swept by cloud during day and night time conditions

D.2 Results and Comparisons with Other Models

D.2.1 Current HSE model (Clay et al, 1988)

The current HSE model can be interpreted as assuming that all ignition sources are certain, continuous and external and are randomly distributed with a particular density or equivalent density of certain ignition sources. The method of finding this equivalent certain ignition source density was described in the Phase I report (Spencer & Rew, 1996), along with the authors' interpretation of the current HSE model. The equivalent densities calculated for this model are given in Table D.2.

	Industrial	Urban	Rural
Day	0.25	0.20	9.9×10^{-3}
Night	0.17	0.13	6.5×10^{-3}

Table D.2 Equivalent certain ignition source densities per hectare for the current HSE model

D.2.2 Simmons' model (Simmons, 1974)

This model is based on a survey of 59 incidents of ignition of clouds resulting from accidents in storage or transportation of LNG or LPG. Simmons estimated the probability of ignition as a function of cloud area, A (in m^2), as:

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

This includes the probability of immediate ignition, which is not included in the proposed model. Simmons estimates the probability of immediate ignition at 50%. Excluding the probability of immediate ignition gives the following alternative to Simmons' model:

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$$P_L(A) = \mathrm{erf}\left(\frac{\log_{10} A - 1.38021}{2.45318}\right) \qquad (D.2)$$

where P_L is the probability of late ignition. This formulation is used to compare with the proposed model.

D.2.3 Base Case Model Parameters

The model parameters recommended for industrial areas during the day and night are given in Table 3.1 of Section 3 of main report and in Table 3.2 for urban/rural areas.

D.2.4 Results and Comparisons

The probability of ignition is calculated during the day and night in industrial, urban and rural areas. The results of all these calculations are shown in Figure D.2. This shows that the highest probability of ignition is found in industrial areas during the day. The probability of ignition in urban areas during the day and night is higher than the probability of ignition on an industrial site during the night. This is because many industrial sites shut down at night. However, central heating is used more during darkness hours in the winter in urban areas than in lightness hours. Hence the probability of ignition is higher during the night than during the day in urban areas. The probability of ignition in rural areas is much lower than in industrial and urban areas, and is much lower during the night than during the day since rural housing does not have as high a proportion of balanced flue boilers as in urban areas.

Comparisons between the proposed model, the current HSE model and Simmons' model ignoring immediate ignition are shown in Figure D.2 for industrial, urban and rural areas since the Simmons model does not differentiate between different areas, it is not compared with the model for rural areas, but it is quite clear that the probability of ignition based on Simmons' model is much higher than the probability of ignition calculated by either of the other models for all areas at all times of day. This could be because Simmons studied reported incidents due to transportation accidents, where ignition sources could be clustered.

The probability of ignition in industrial areas calculated using the proposed model is slightly higher during the day and slightly lower at night than the previous HSE model. This is due to the fairly high probability of ignition attached to industrial sites when they are active and to the assumption that most sites shut down at night. The probability of ignition calculated by the proposed model is very similar to the current HSE model for the day time in urban and rural areas. However the probability at night calculated by the proposed model for urban areas is higher than the probability during the day, whereas the probability during the night calculated by the HSE model' is lower at night for urban areas. This is due to the balanced flue boilers which are expected to be used predominantly during the winter in darkness hours in the early morning and evening for heating. The probability of ignition during the night in rural areas is much lower using the proposed model in comparison to the previous HSE model.

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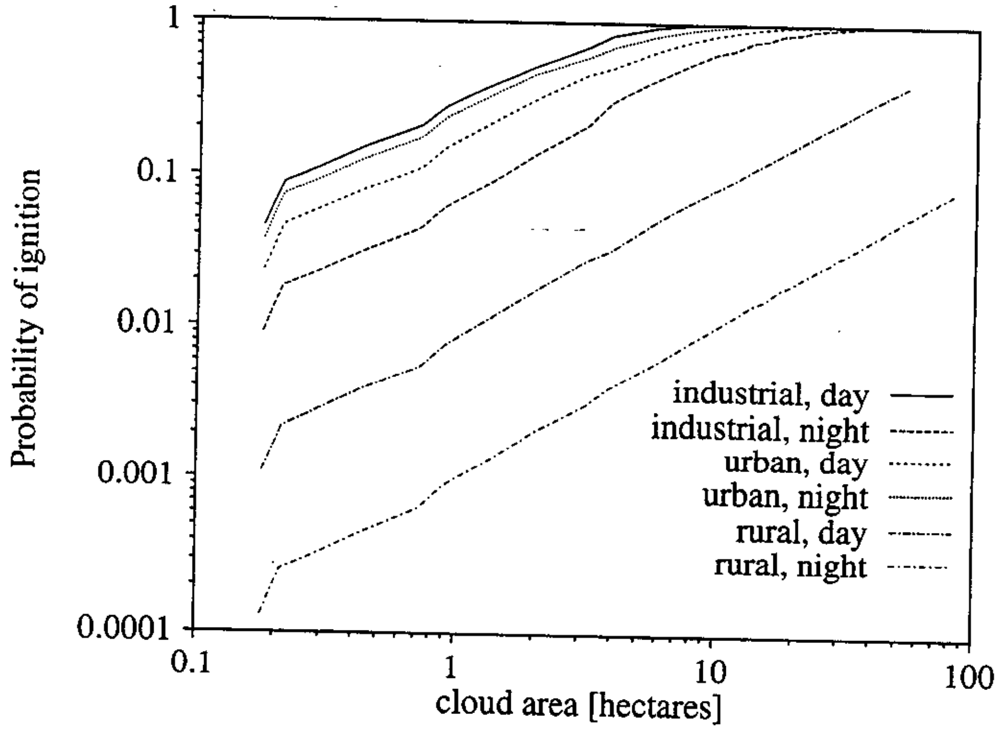
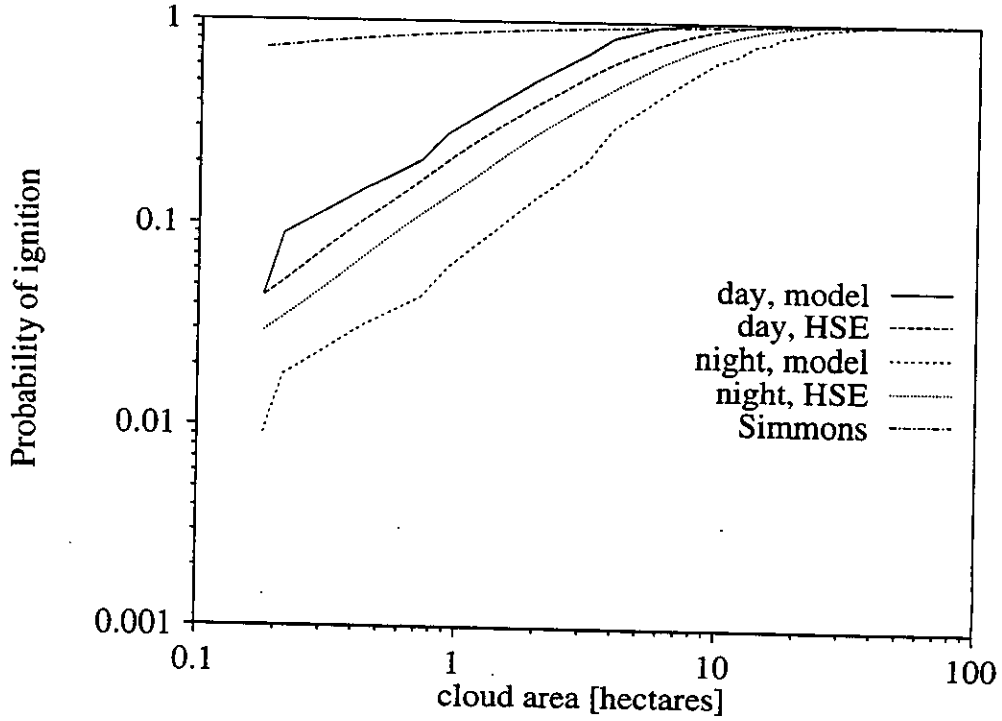
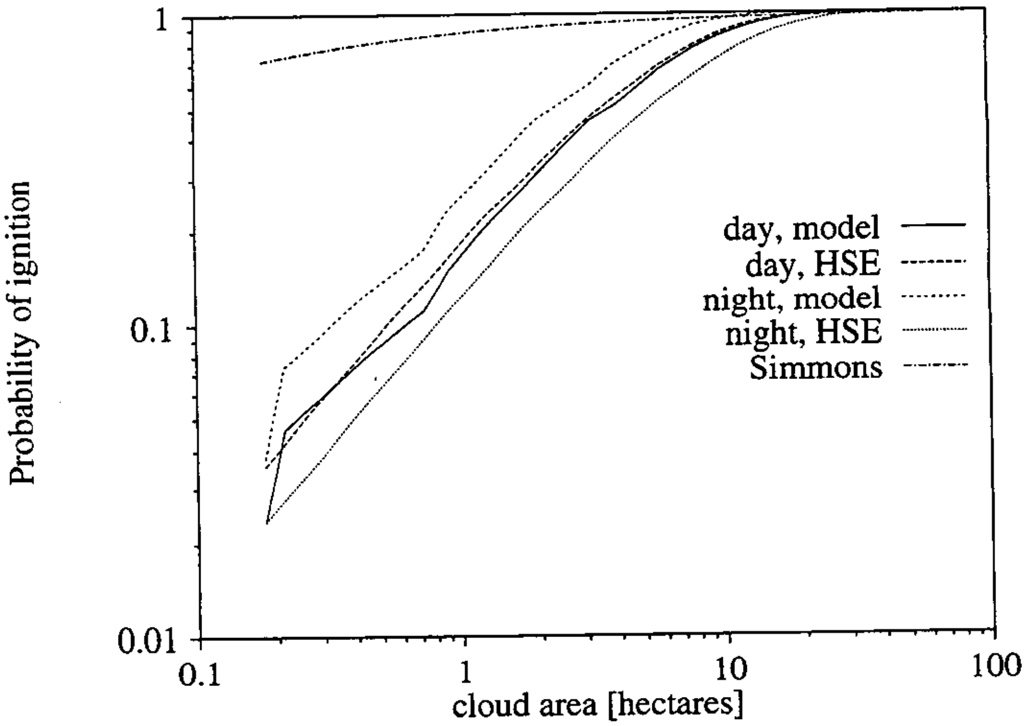


All areas, base cases

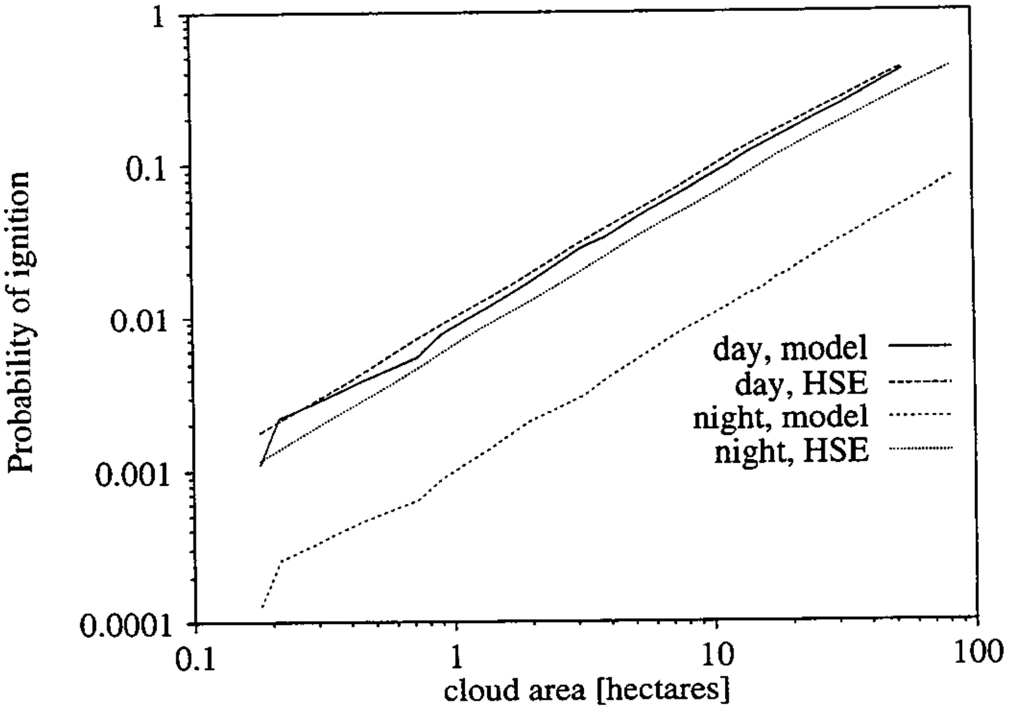


Industrial area

Figure D.2a Comparison of proposed base case for all areas during the day and night with current HSE and Simmons models



Urban area



Rural area

Figure D.2b Comparison of proposed base case for all areas during the day and night with current HSE and Simmons models (continued)

D.3 Sensitivity Study for an Industrial Area

A number of variations on the base case are considered in order to evaluate the sensitivity of the probability of ignition to various parameters.

D.3.1 Variation 1: Density and use of Boilers

The most prolific and strongest outdoor ignition sources in industrial areas are boilers for heating of sites. It is assumed that large sites have large boilers that take air directly from outside and therefore are an immediate ignition source. It is assumed that small sites are heated in a similar way to housing in urban areas. Therefore it is assumed that one third of small sites have balanced flue boilers, which take air directly from outside and therefore are an immediate ignition source. For the base case, the proportion of sites which are large is variable and dependent on the industry type. The proportion of time for which boilers are active is either a quarter or an eighth, depending on the heating requirements of the industry type. More details of the calculation of the parameters and the assumptions are given in Appendix C. Variations are made on these assumptions and compared with the base case and the current HSE model in Figure D.3. The "more use" of boilers variation assumes all boilers are active for half of the time, which represents the highest usage level, which will occur during the winter when more heating is required. The "more boilers" variation assumes that half of all sites have large boilers which are certain, immediate ignition sources. Both the "more use" and "more boilers, more use" variations significantly increase the probability of ignition and the "no boilers" variation, which might be typical of summer time conditions, significantly reduces the probability of ignition.

D.3.2 Variation 2: Ventilation Rates of Buildings

There is some uncertainty in, and variation of, the ventilation rate of the buildings. In the base case it is assumed that all buildings have a ventilation rate of 15 ach (air changes per hour), apart from three high ventilation rate industry types, identified in Appendix C, which are considered to be outside sources. The probability of ignition is also calculated assuming these industry types have the same ventilation rates as other building types, which is 15 ach. The base indoor ventilation rate is also varied and these comparisons are shown in Figure D.4. This shows that, for buildings with a ventilation rate of 15 ach, the concentration reaches LFL when the outside cloud has reached a size of about 4 hectares (after about 10 seconds). Therefore, at this time, the probability of ignition increases rapidly since there is now a contribution from indoor sources. For buildings with 5 ach, the concentration does not reach LFL within the dispersion time and for buildings with 25 ach the probability of ignition increases rapidly sooner, as the concentration reaches LFL inside sooner. If the three industry types with high ventilation rates (presently assumed to be external sources) are taken to be internal sources, like the other industry types (label "all sites 15 ach"), the probability of ignition is lower initially, before the concentration has reached LFL inside these buildings.

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D.3.3 Variation 3: Density of Industrial Sites

The density of sites varies significantly from one industrial area to another. The densities in the base case are average values over the whole of the UK. However, many industrial areas will have significantly different densities of ignition sources. Therefore the probability of ignition is calculated for twice and half the density (μ_t) of industrial sites. The results in Figure D.5, show that the probability of ignition varies significantly with the site density.

D.3.4 Variation 4: Night-time Activity

Parameters for the mathematical model at night in industrial areas are found using the proportion of sites which are active 24 hours a day, and scaling the day time site density by this proportion. The probability of ignition is calculated assuming 10% and 50% of sites are active 24 hours a day, whereas the base case value for activity is between 10% and 30% and is dependent on industry type. The results are shown in Figure D.6. With only 10% of sites active at night, the probability of ignition is significantly reduced whereas with 50% active at night it is increased and is similar to the current HSE model.

D.3.5 Variation 5: Probability of Ignition from Background Sources

The probability of ignition is calculated for the two cases assuming the probability of ignition from machinery is high (p=1) and zero. Comparisons of these cases with the base case and the current HSE model are shown in Figure D.7. All machinery is indoors in low ventilation buildings except for machinery in vehicle repair workshops. For the base case, the probability of ignition from a vehicle repair workshop is predominantly due to welding. Therefore, reducing the probability of ignition from machines in vehicle repair workshops does not affect the overall probability of ignition from such premises. Therefore reducing the probability of ignition from machines only affects the probability of ignition from indoor sources, and changing these parameters only affects the probability of ignition once the concentration has reached LFL inside the buildings. However, when the probability of ignition from machines is increased, it is dominant over welding in a vehicle repair workshop. Therefore the probability of ignition is increased outside as well as inside.

D.3.6 Variation 6: Frequency of Smoking

The probability of ignition is calculated both ignoring smoking and assuming smoking is twice as frequent as for the base case. Comparisons of these cases with the base case and the current HSE model are shown in Figure D.8.

D.3.7 Variation 7: Composition of an Industrial Area

The composition of industrial uses within the base case is varied, but the overall density of sites remains the same. Therefore, if the density of one type of site is increased or reduced, the remainder must be reduced or increased so that the total density remains the same. The probability of ignition is calculated assuming the density of wholesalers is both doubled and zero. The probability of ignition is also

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calculated assuming the density of the three high ventilation rate industry types is doubled and also zero. These are compared with the base case and the current HSE model in Figure D.9.

D.3.8 Variation 8: Density of Flares on Chemical Sites

Flares are one of the strongest ignition sources in industrial areas. In the base case it is assumed that 15% of chemical sites have flares. The probability of ignition is also calculated assuming that either 50% of or no chemical sites have flares. These are compared with the base case and the current HSE model in Figure D.10.

D.3.9 Variation 9: Urban Sources in Industrial Areas

For the base case it is assumed that the density of urban ignition sources, i.e. road vehicles and traffic lights, is the same in industrial as urban areas. The probability of ignition is also calculated without any urban sources and assuming the density of road vehicles is both doubled and halved. These are compared with the base case and the current HSE model in Figure D.11.

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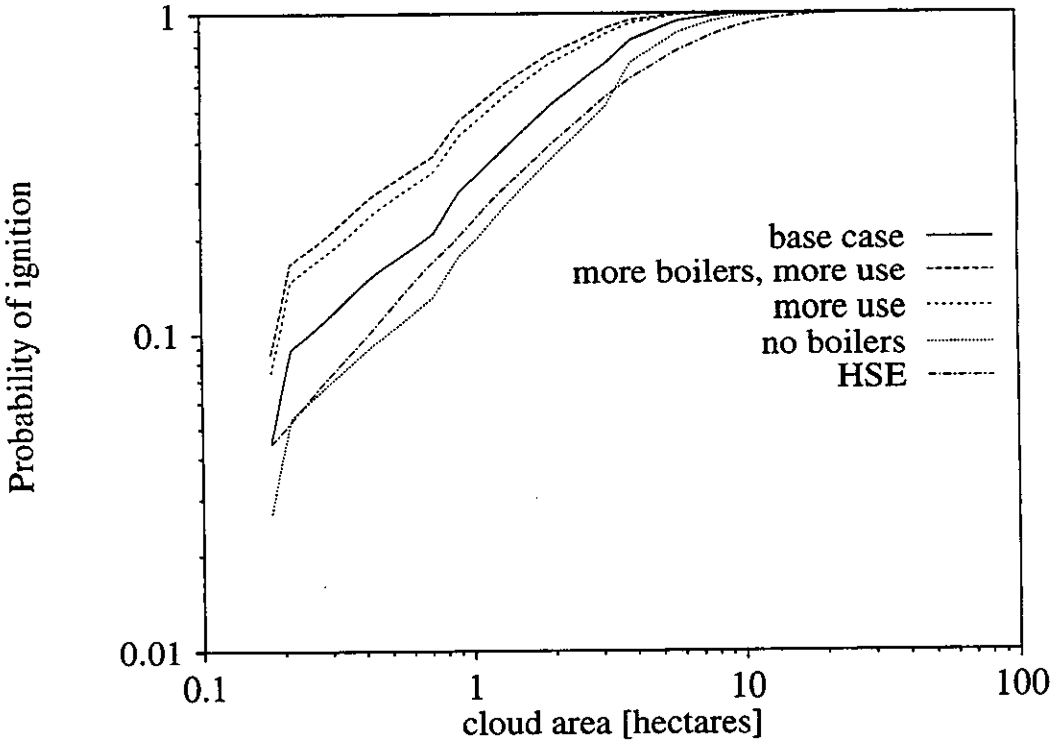

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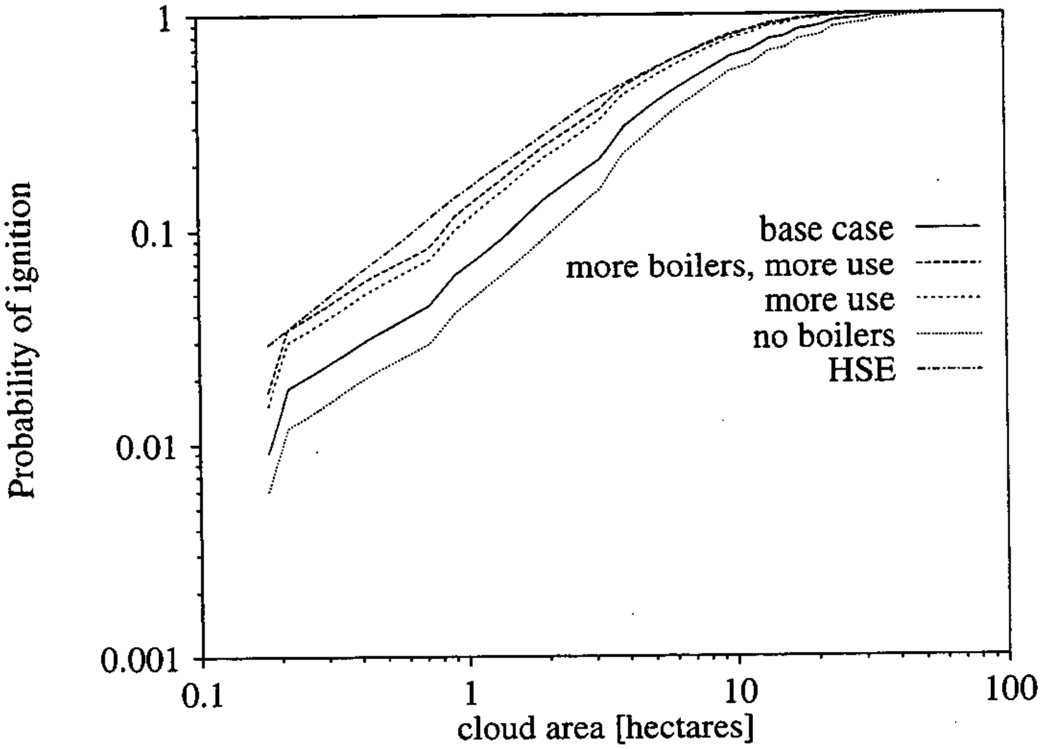

Night

Figure D.3 Comparison of base case, current HSE model and variations of boiler density and use for an industrial area

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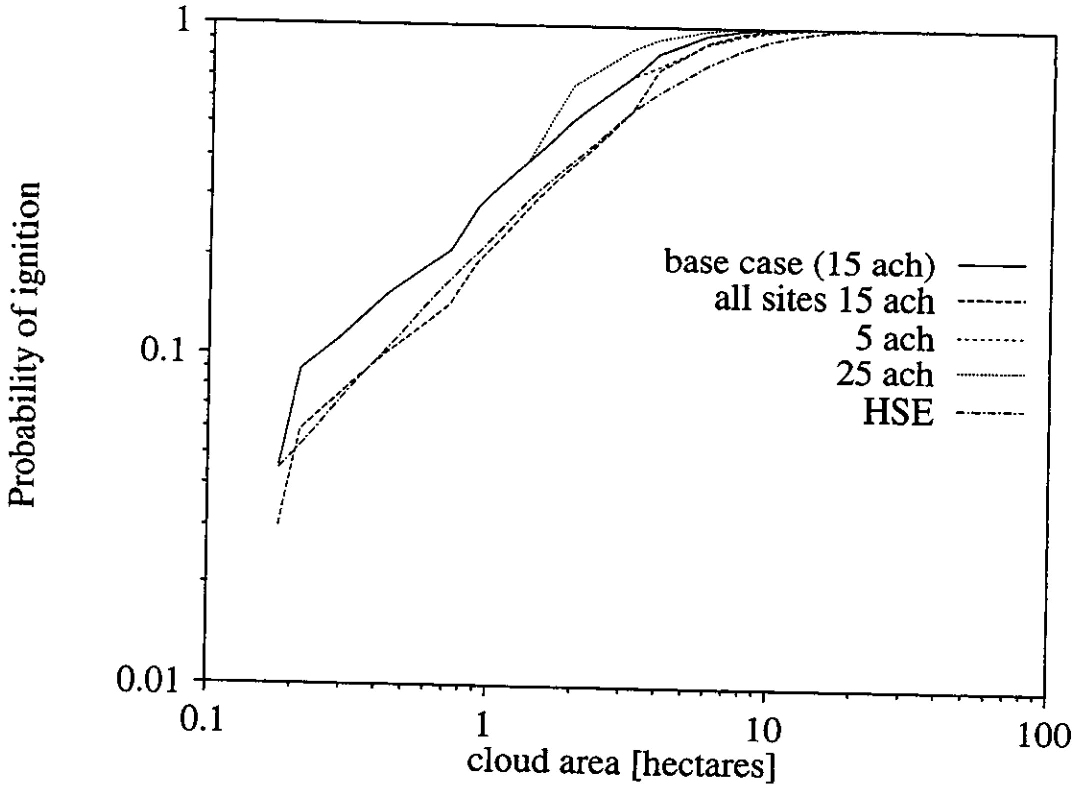

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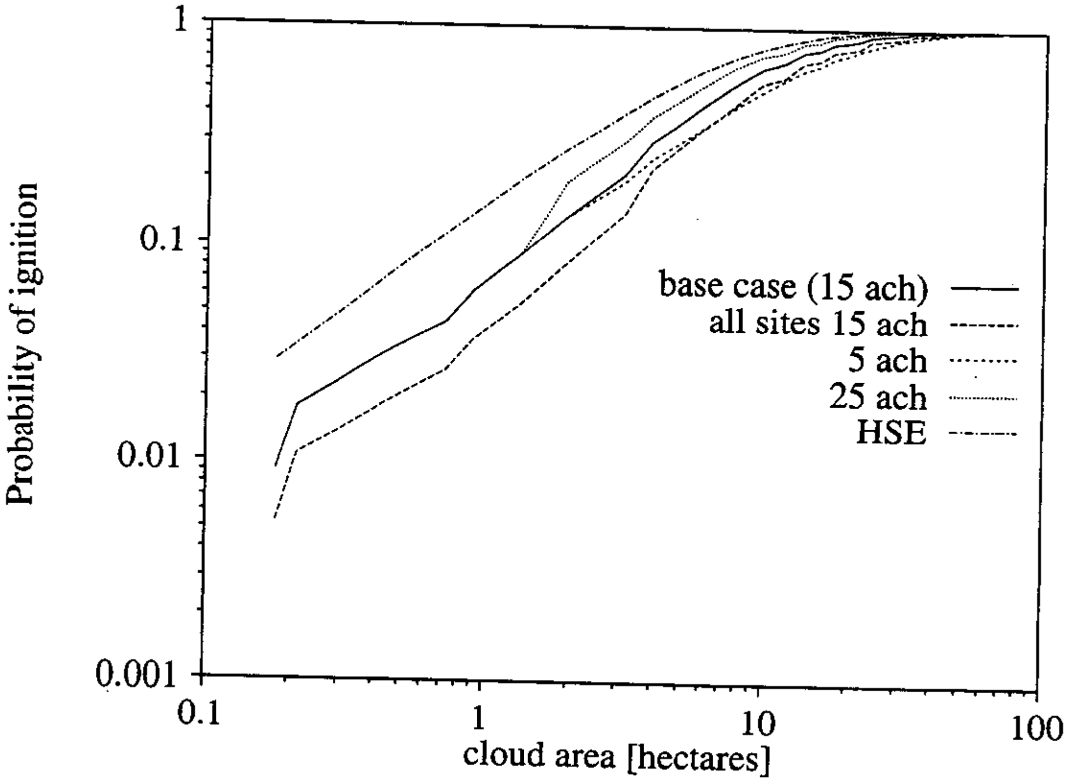

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Figure D.4 Comparison of base case, current HSE model and variations of building ventilation rates for an industrial area

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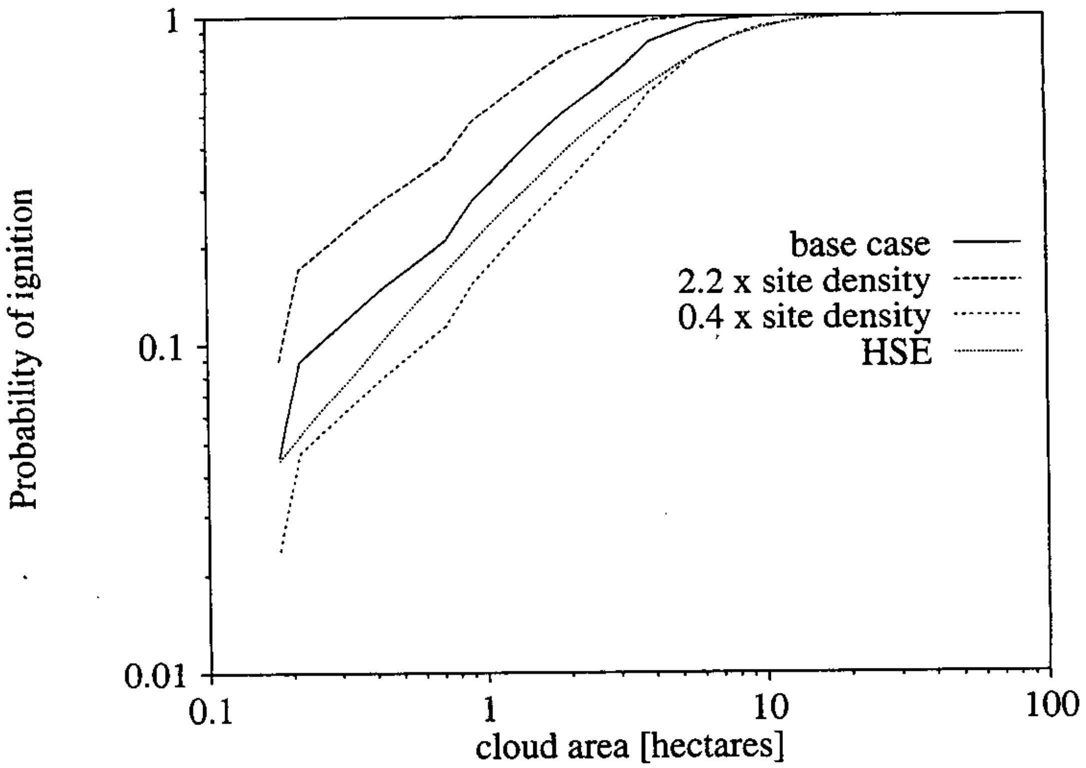

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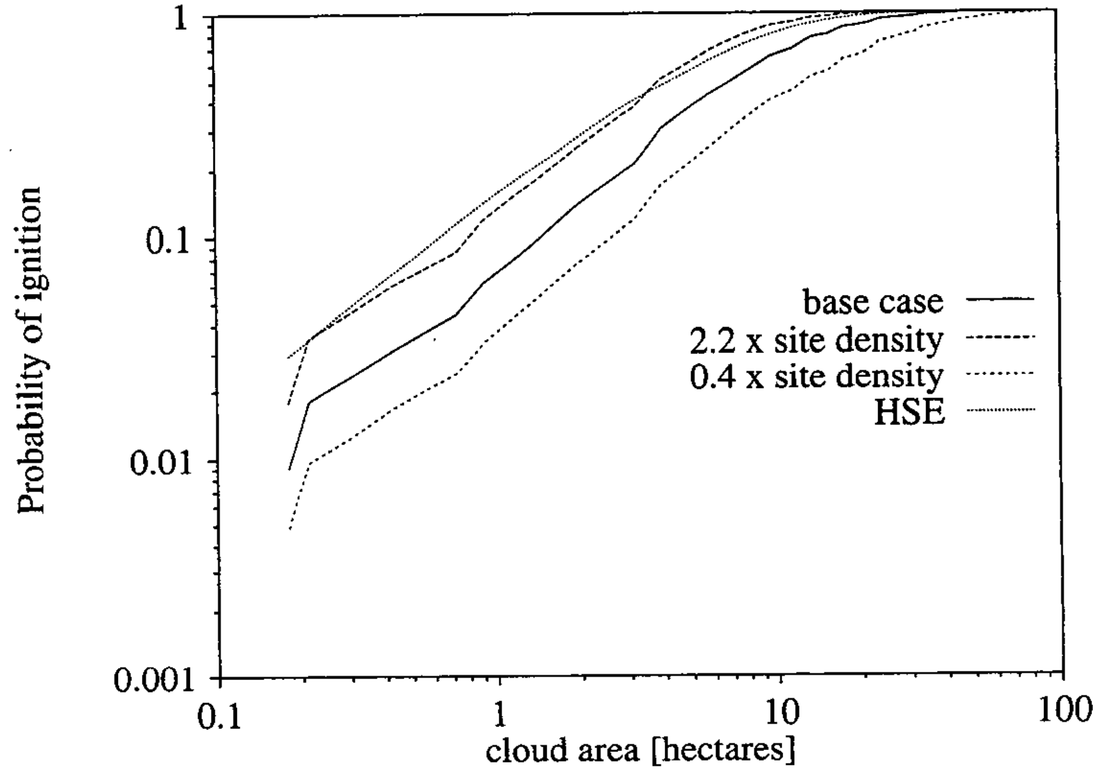

Night

Figure D.5 Comparison of base case, current HSE model and variations of industrial site density for an industrial area

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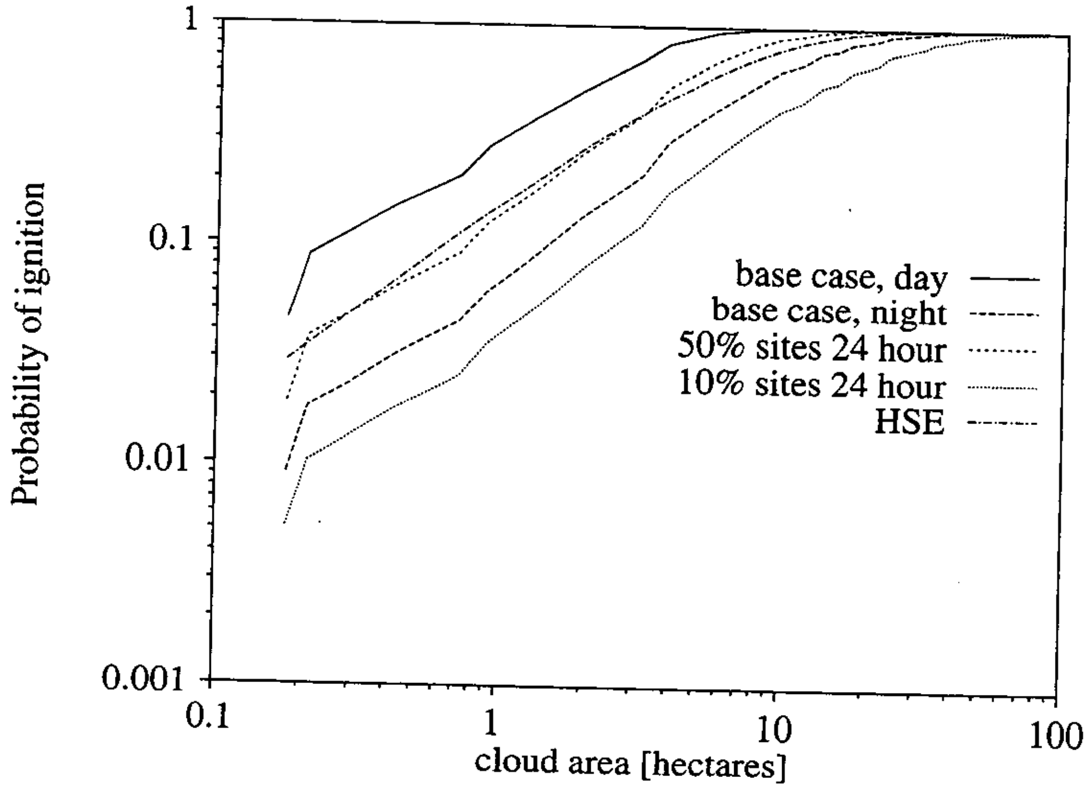

Figure D.6 Comparison of base case, current HSE model and variation of 24 hour sites for an industrial area

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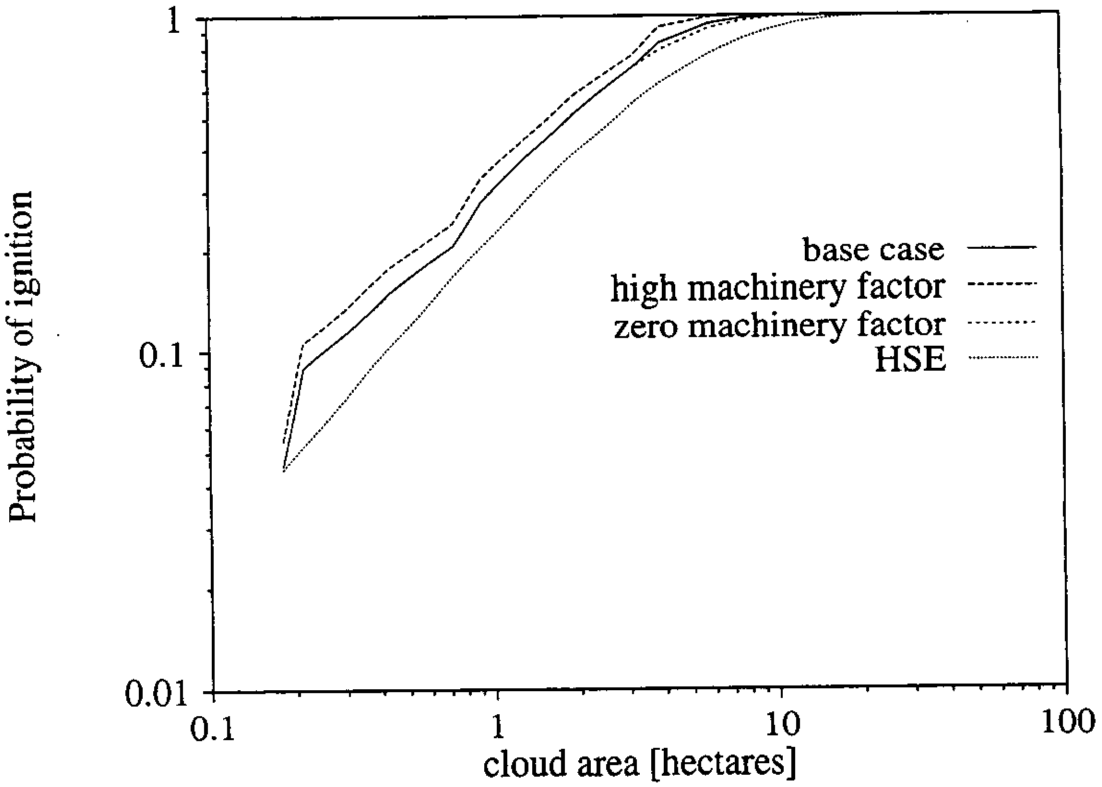

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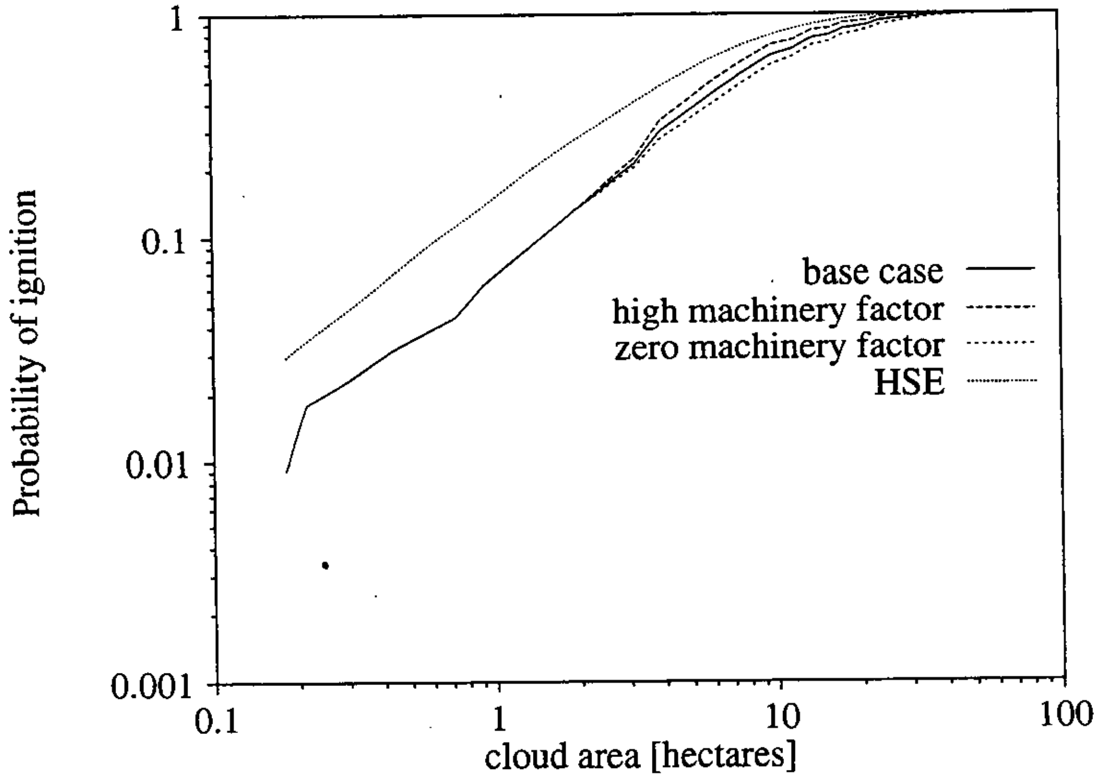
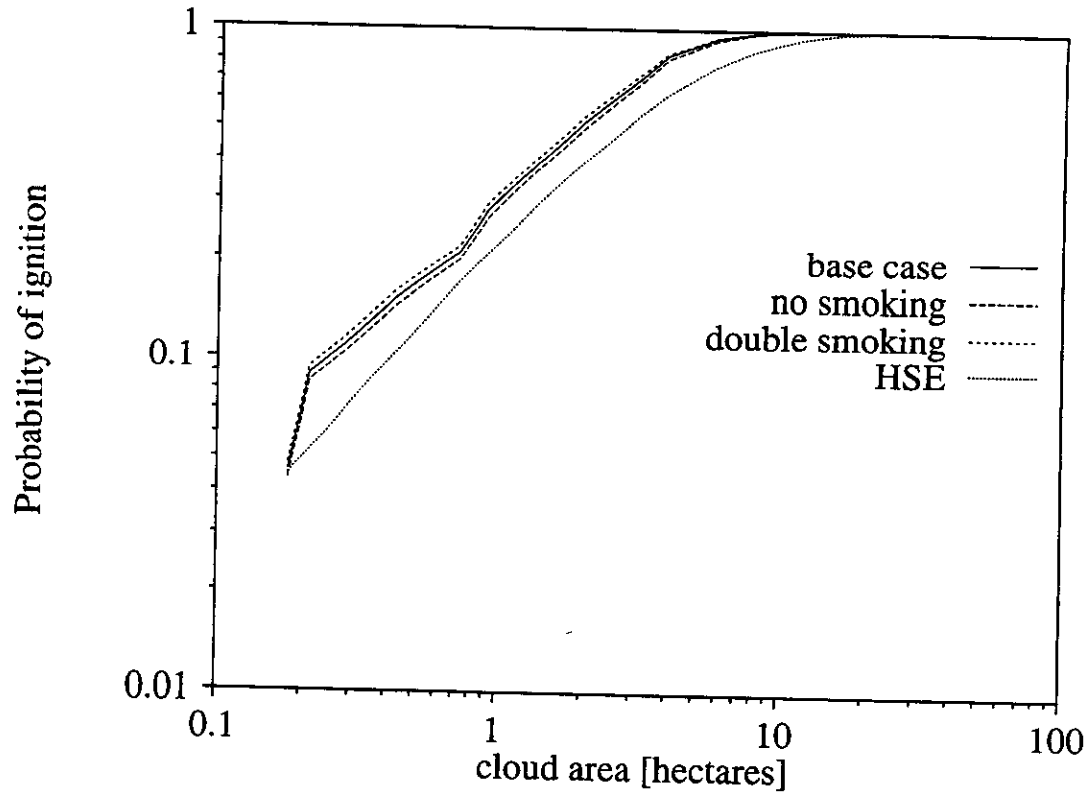


Night

Figure D.7 Comparison of base case, current HSE model and variations of probability of ignition from machines of an industrial area



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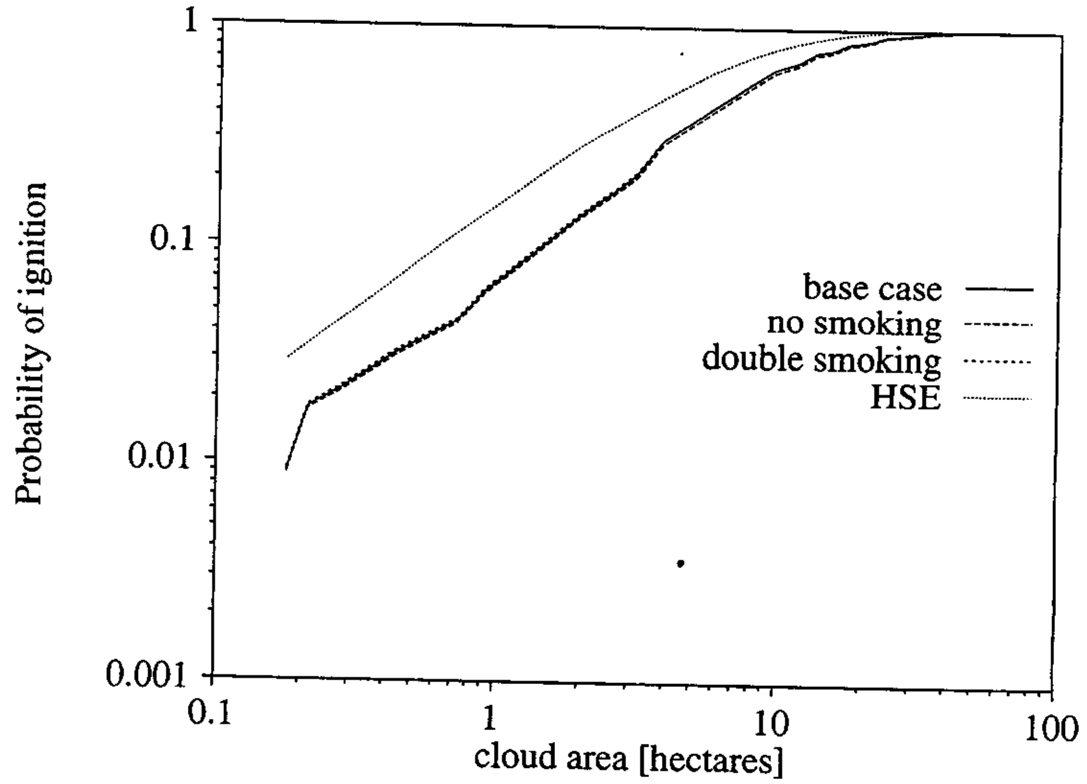

Night

Figure D.8 Comparison of base case, current HSE model and variations of smoking frequency for an industrial area

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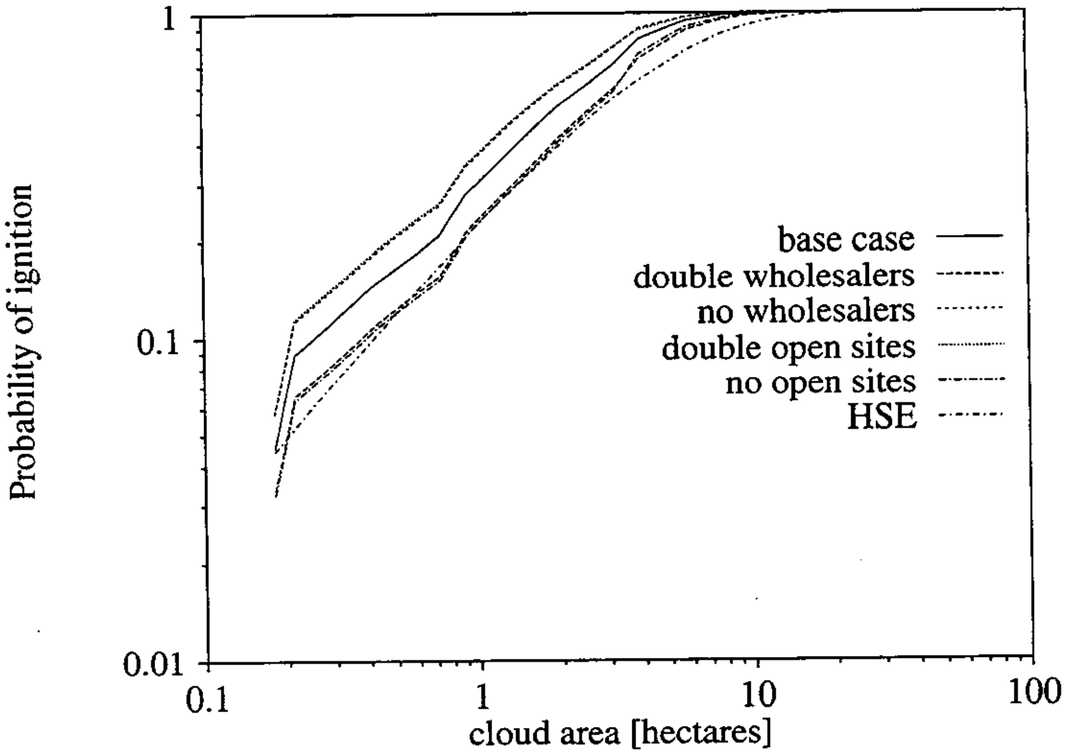

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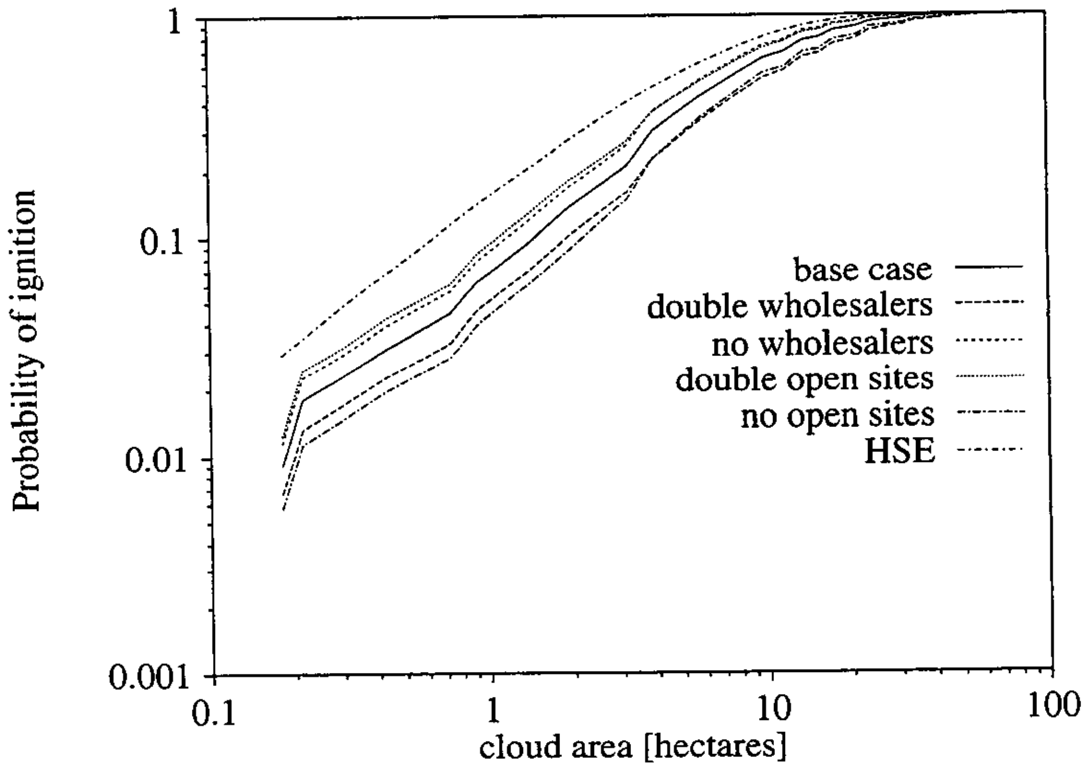
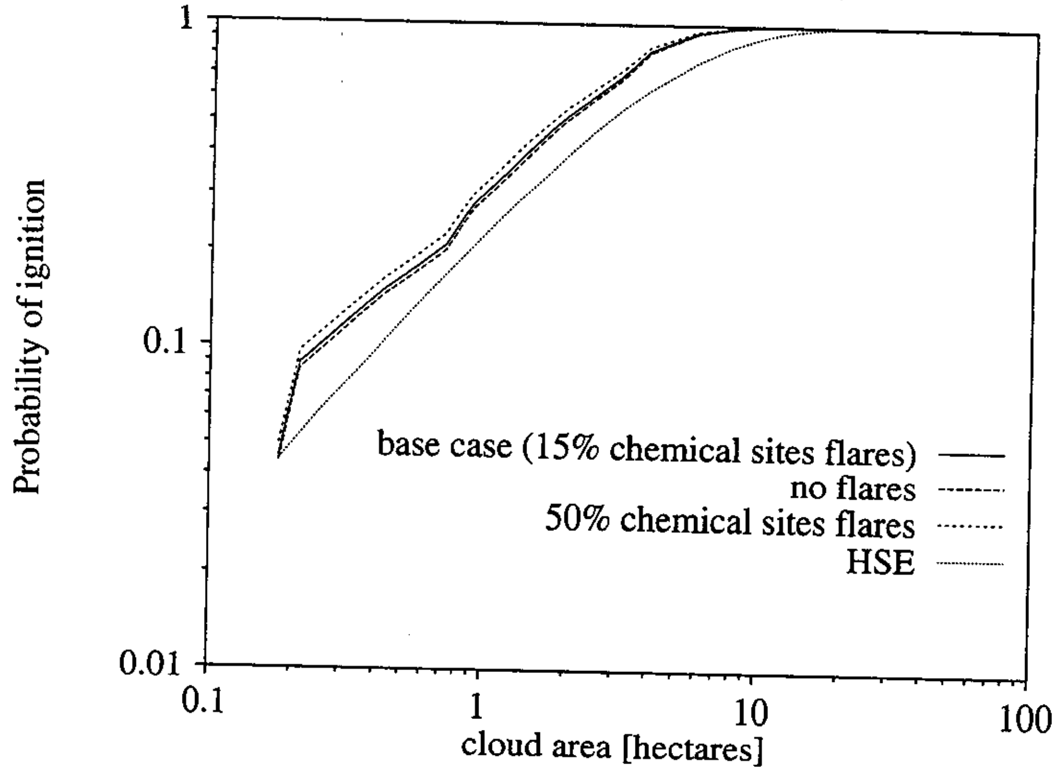


Night

Figure D.9 Comparison of base case, current HSE model and variations of composition of an industrial area



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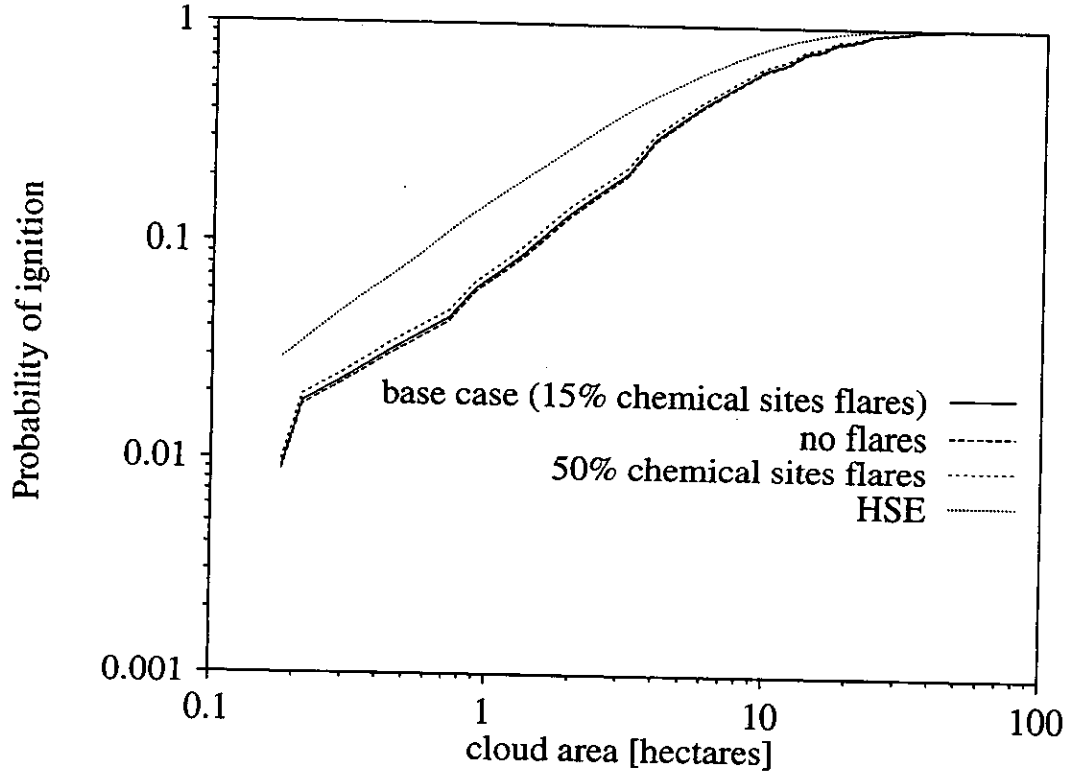

Night

Figure D.10 Comparison of base case, current HSE model and variations of flares on chemical sites for an industrial area

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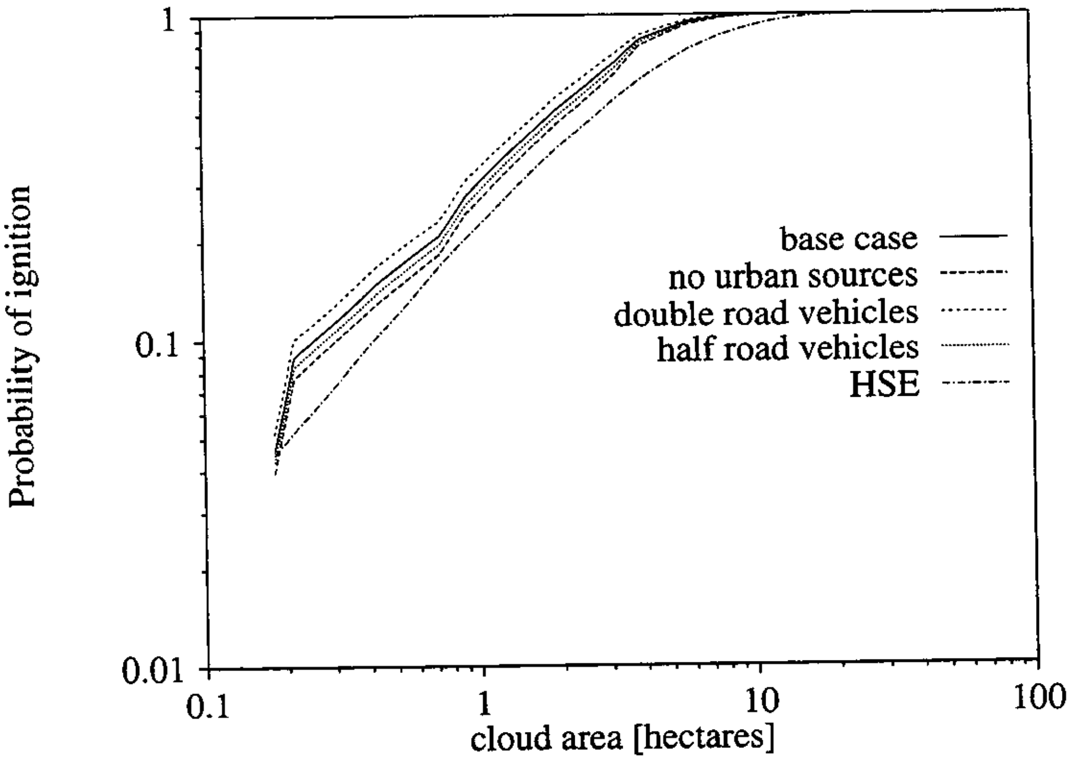
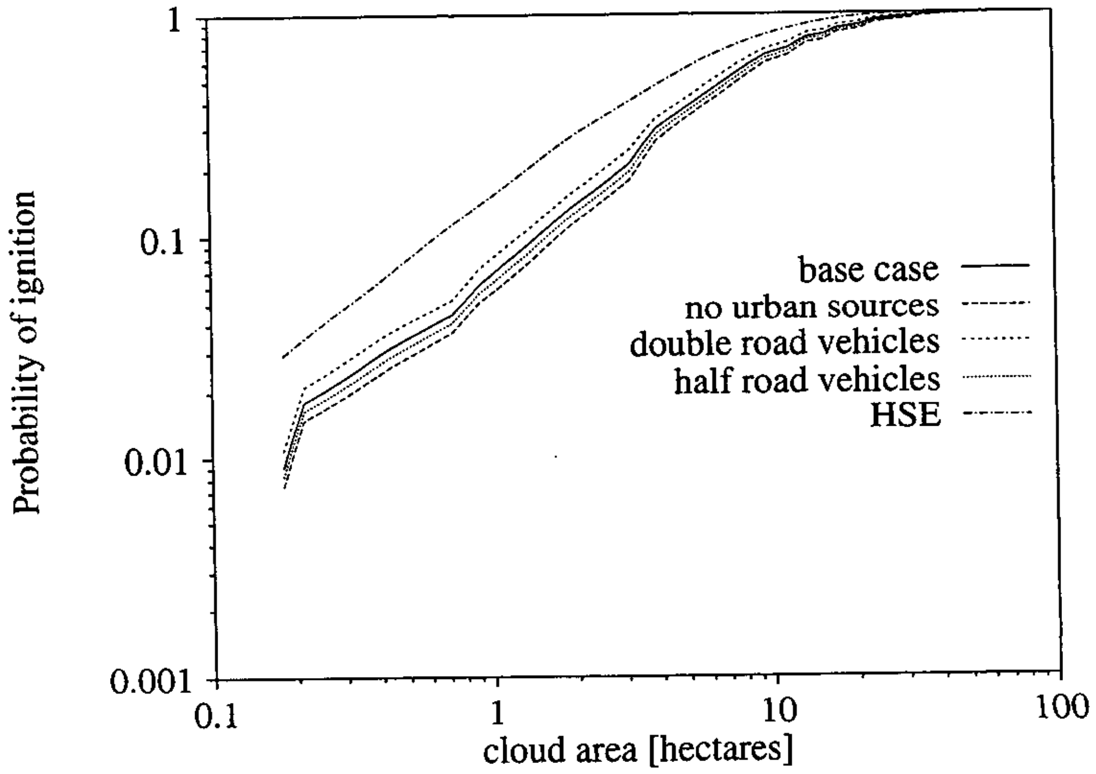


Day



Night

Figure D.11 Comparison of base case, current HSE model and variations of urban sources for an industrial area

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D.4 Sensitivity Study for Urban and Rural Areas

A number of variations on the base cases are considered in order to evaluate the sensitivity of the probability of ignition to various parameters.

D.4.1 Variation 1: Ventilation rates of Buildings

The building ventilation rate varies significantly between different buildings and wind conditions. The concentration does not reach the lower flammability limit inside any building within the dispersion time with a ventilation rate of only 2 ach, therefore for the base case, ignition sources inside buildings are insignificant. The probability of ignition is therefore calculated for ventilation rates of 5, 10 and 20 air changes per hour in order to assess the effect of internal ignition sources. The results of these are shown in Figure D.12. The results for buildings with 2 and 5 ach are identical for both day and night time results because, for neither ventilation rate does the concentration reach LFL inside the buildings within the dispersion time. However, for buildings with 10 and 20 ach, the probability of ignition sharply increases once the concentration reaches LFL inside the buildings, where it is assumed that the probability of ignition is one for a certain proportion of the time, depending on the building type.

D.4.2 Variation 2: Density of Balanced Flue Boilers (BFBs)

Balanced flue gas boilers are the strongest and most prevalent ignition source in urban areas and there is some uncertainty surrounding their prevalence. Therefore the probability of ignition is calculated assuming their density is halved and also ignoring this ignition source. The results of these calculations are shown in Figure D.13. With only half the number of balanced flue boilers, the probability of ignition is slightly reduced whereas for no balanced flue boilers the probability of ignition is significantly reduced. For the rural base case it is assumed the proportion of housing with balanced flue boilers is significantly lower than in urban areas. However, if the same proportion of households have these boilers in rural as in urban areas, the probability of ignition in rural areas is significantly increased, especially at night. The results of these are also shown in Figure D.13.

D.4.3 Variation 3: Density of road vehicles

There is a significant amount of uncertainty associated with the probability of ignition from and the density of road vehicles. Since road vehicles are treated as continuous ignition sources, doubling the probability of ignition from a road vehicle has the same effect as doubling the density of road vehicles. Therefore the sensitivity of the probability of ignition to the density of road vehicles only is investigated, since the effect of varying the probability of ignition from a single vehicle, p, is identical to the effect of varying the density by the same amount.

The probability of ignition for a number of different road vehicle densities is shown in Figure D.14. Increasing the density of road vehicles increases the probability of ignition more during the day than at night in urban areas since at night the probability of ignition is predominantly dependent on the balanced flue boilers. In rural areas

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increasing the density of vehicles significantly increases the probability of ignition during the day and night. The effect is more marked at night since there are fewer other ignition sources at night in rural areas. During the day there are more occasional fires in rural areas than at night.

D.4.4 Variation 4: Density of Housing

For houses with low ventilation rates, such as those considered, and for short duration releases, again such as those considered, the density of housing affects the probability of ignition only through the density of balanced flue boilers in urban areas and the density of occasional fires in rural areas. Therefore, as with studying the density of balanced flue boilers directly, the density of housing affects the probability more at night than in day for urban areas. In rural areas, since occasional fires are predominantly during the day, the density of housing affects the probability of ignition more during the day than at night. The probability of ignition for different housing densities and therefore different balanced flue boiler and occasional fire densities is shown in Figure D.15.

D.4.5 Strongest Components of Ignition Probability

For a short duration release, such as the instantaneous release simulated, and for low ventilation buildings, such as those considered in the base case, the probability of ignition is not dependent on any indoor ignition sources since the concentration does not have time to build up to the lower flammability limit inside the buildings. Furthermore, some outdoor ignition sources are insignificant due to their scarcity or infrequency of use. In fact, in urban and rural areas, for the release considered and for the base case parameters, the probability of ignition is only dependent on two ignition sources in each area. In urban areas, the probability of ignition is only dependent on the balanced flue boiler and road vehicle densities and in rural areas the probability of ignition is only dependent on the occasional fire and vehicle densities.

Comparisons between the full base cases, the reduced models (with only vehicles and balanced flue boilers or fires) and each strong source individually are shown in Figure D.16. In urban areas there is a small difference between the reduced model and the full model due to the small probability of ignition due to traffic lights. In urban areas, balanced flue boilers are the strongest and most prevalent ignition sources, but road vehicles are also significant. In rural areas, during the day, occasional fires are the most prevalent ignition source whereas at night road vehicles are the most prevalent.

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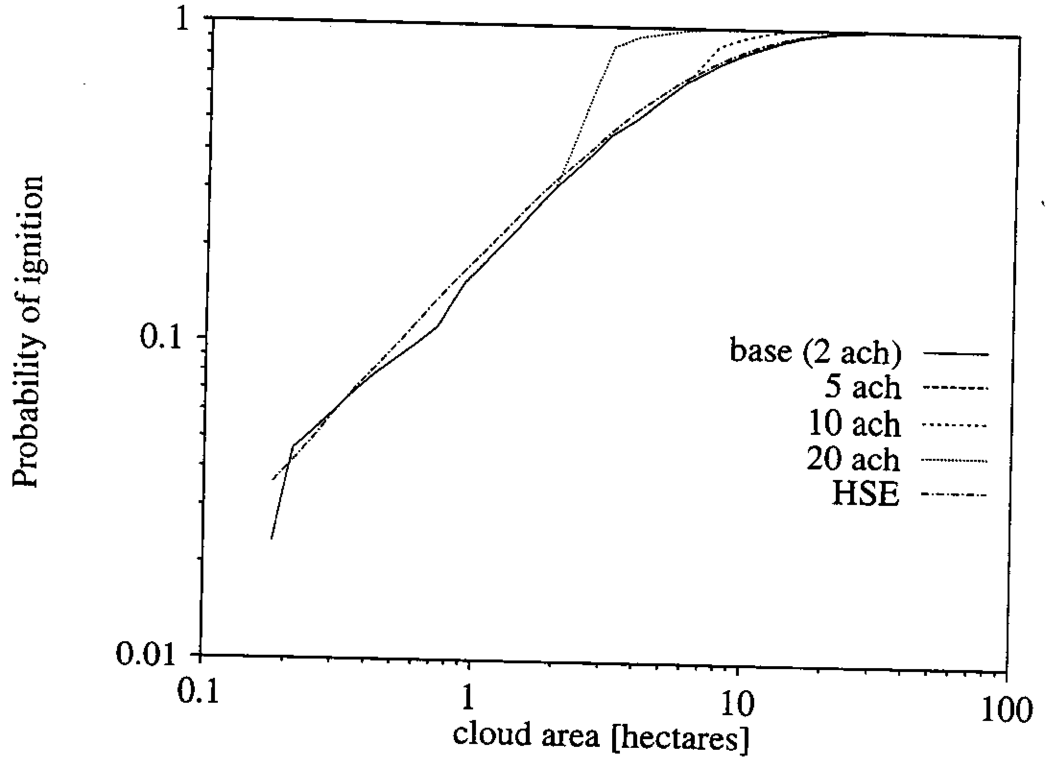
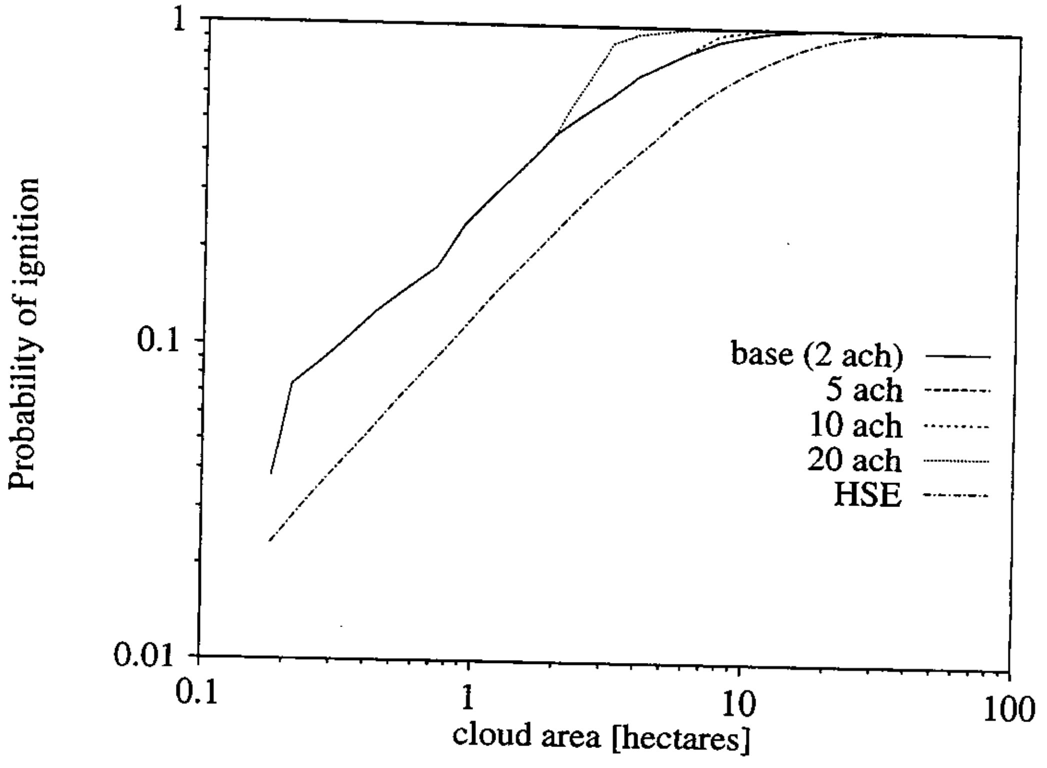


Urban Day



Urban Night

Figure D.12a Comparison of base case, current HSE model and variations with buildings with 5 ach, 10 ach and 20 ach

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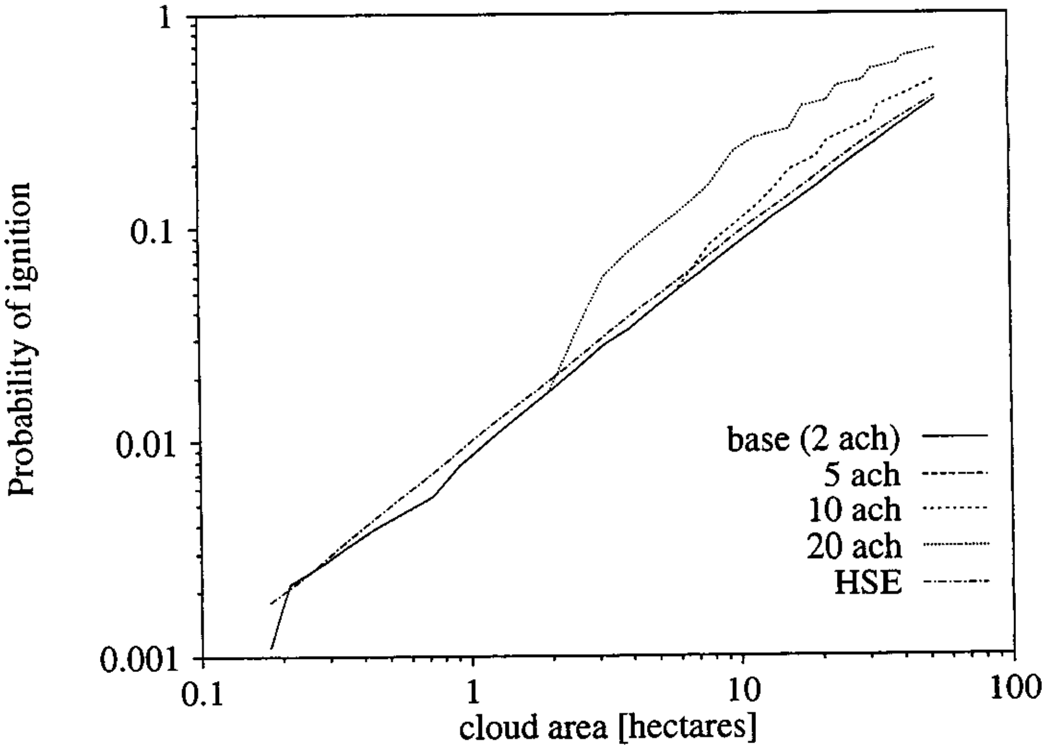
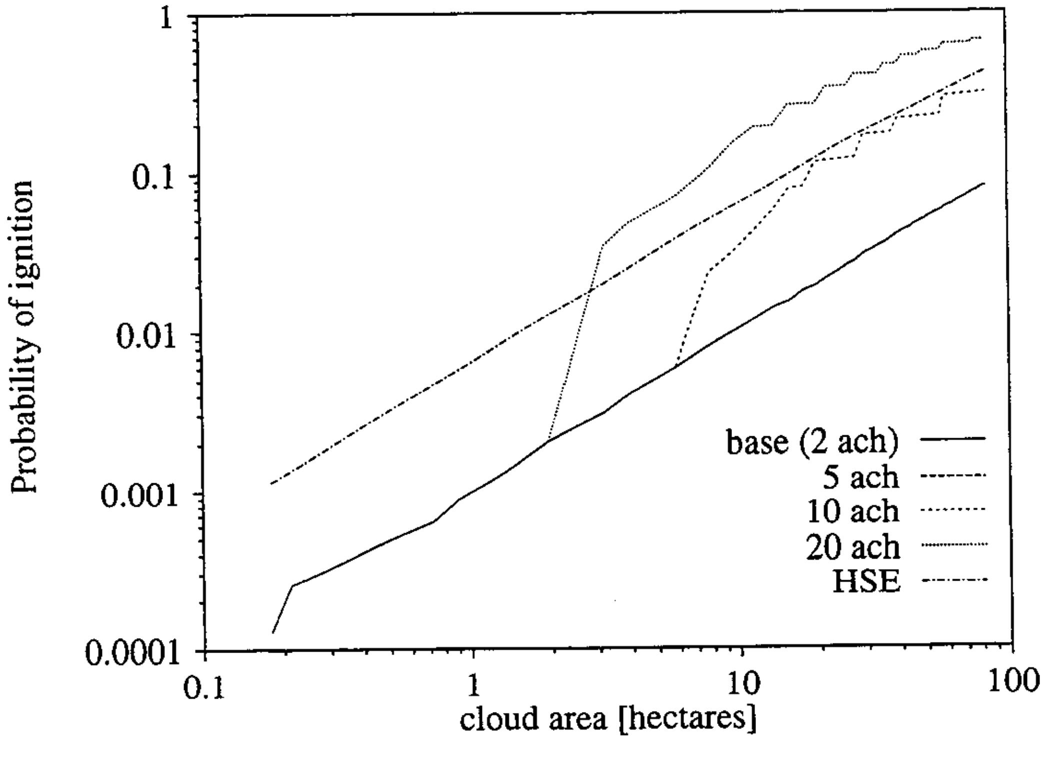
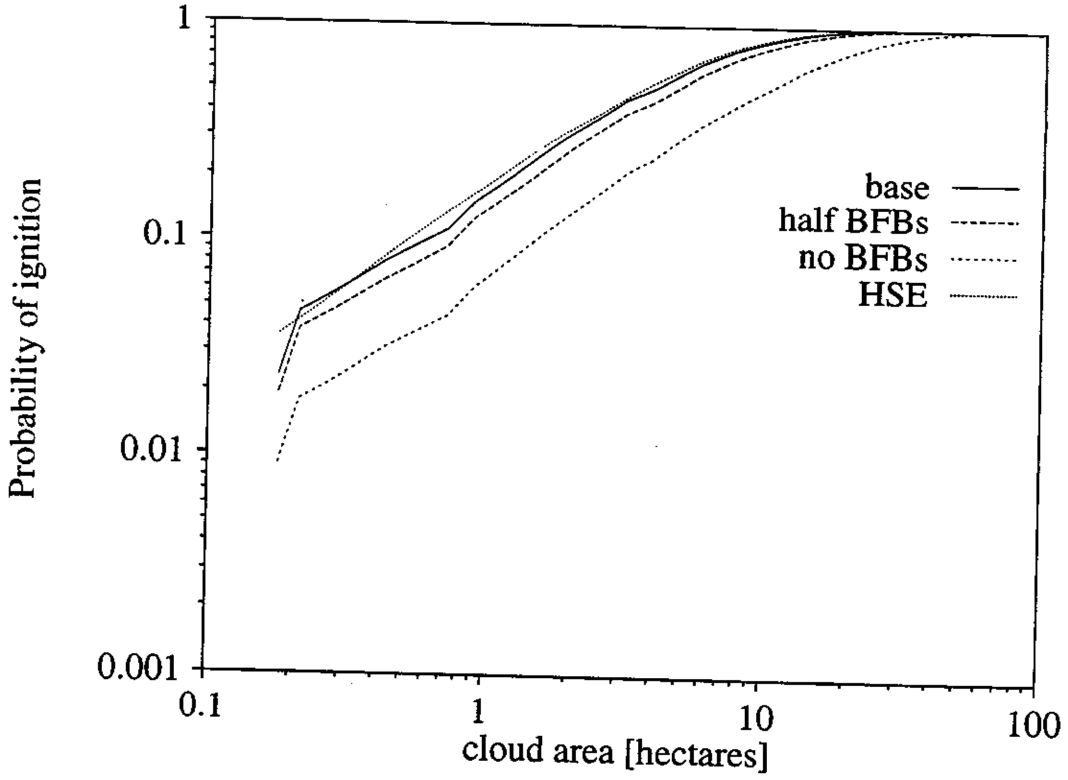


Rural Day



Rural Night

Figure D.12b Comparison of base case, current HSE model and variations with buildings with 5 ach, 10 ach and 20 ach (continued)



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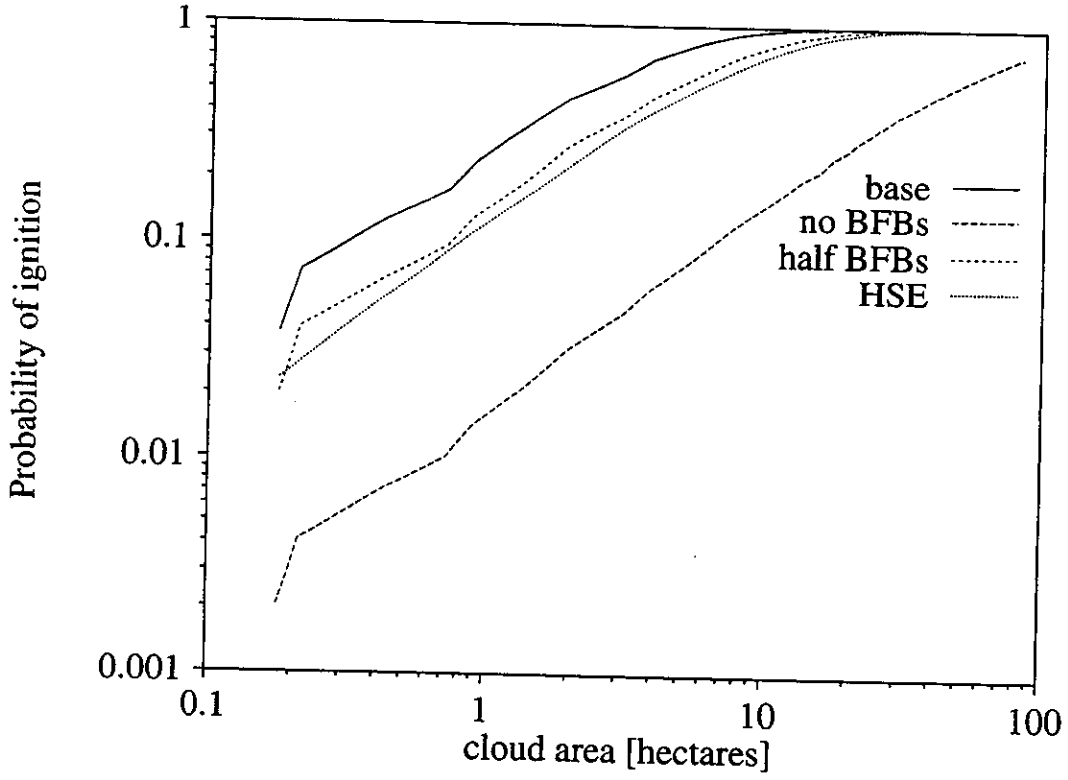

Urban Night

Figure D.13a Comparison of base case, current HSE model and variations of densities of balanced flue boilers (BFBs)

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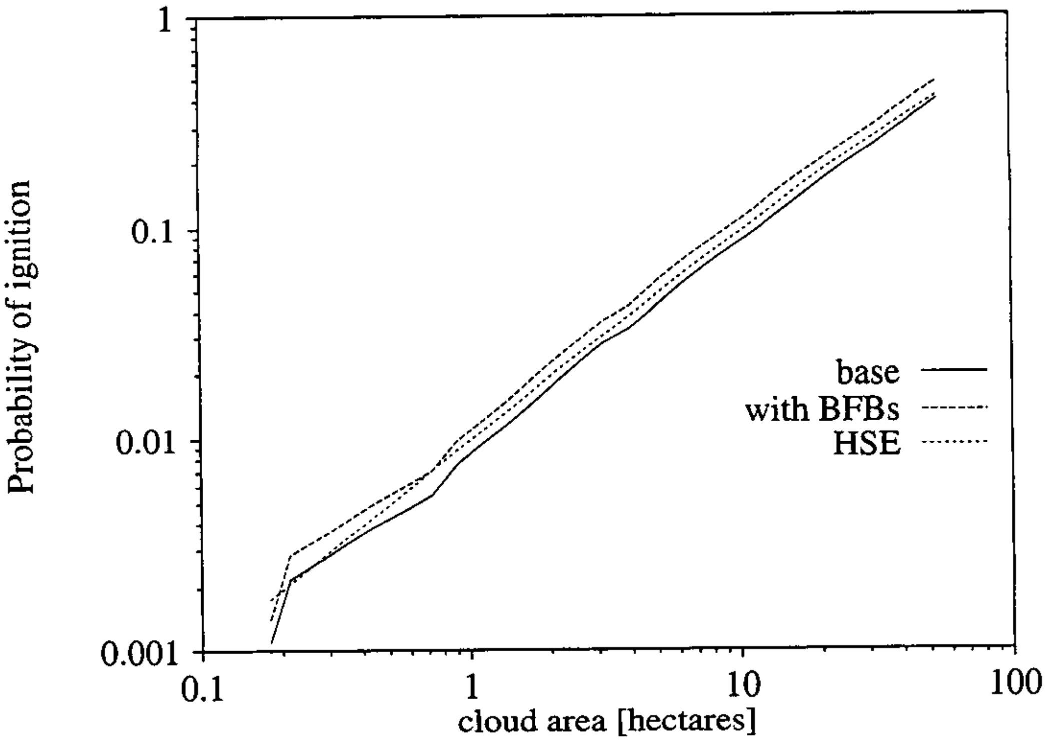

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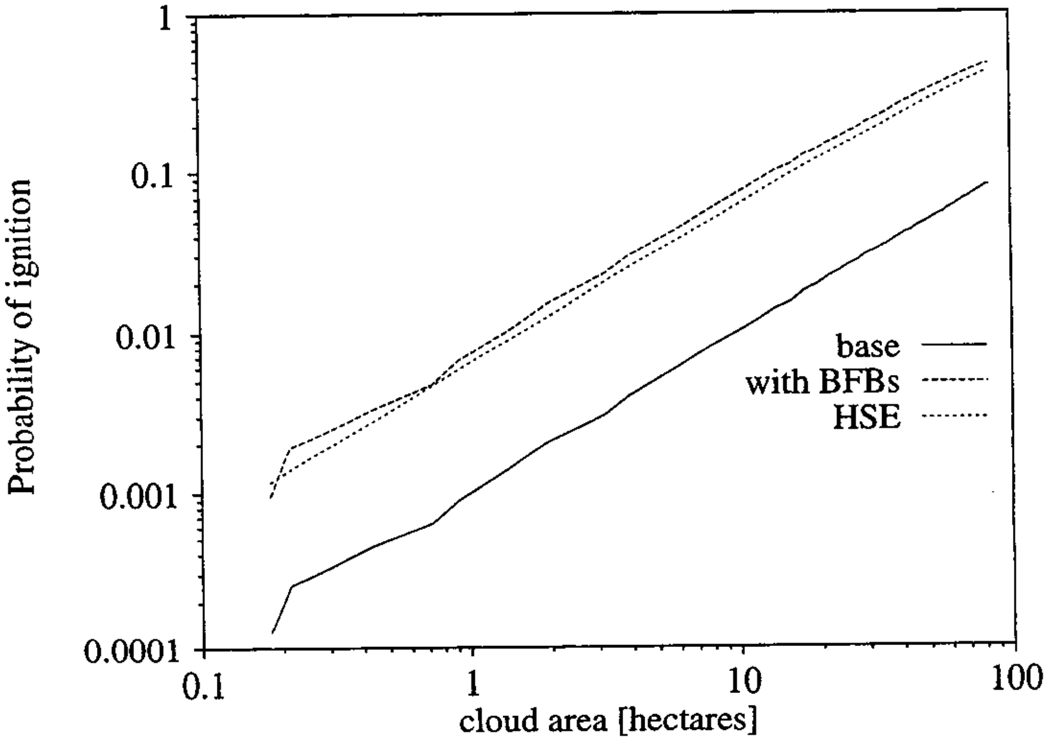

Rural Night

Figure D.13b Comparison of base case, current HSE model and variations of densities of balanced flue boilers (BFBs) (continued)

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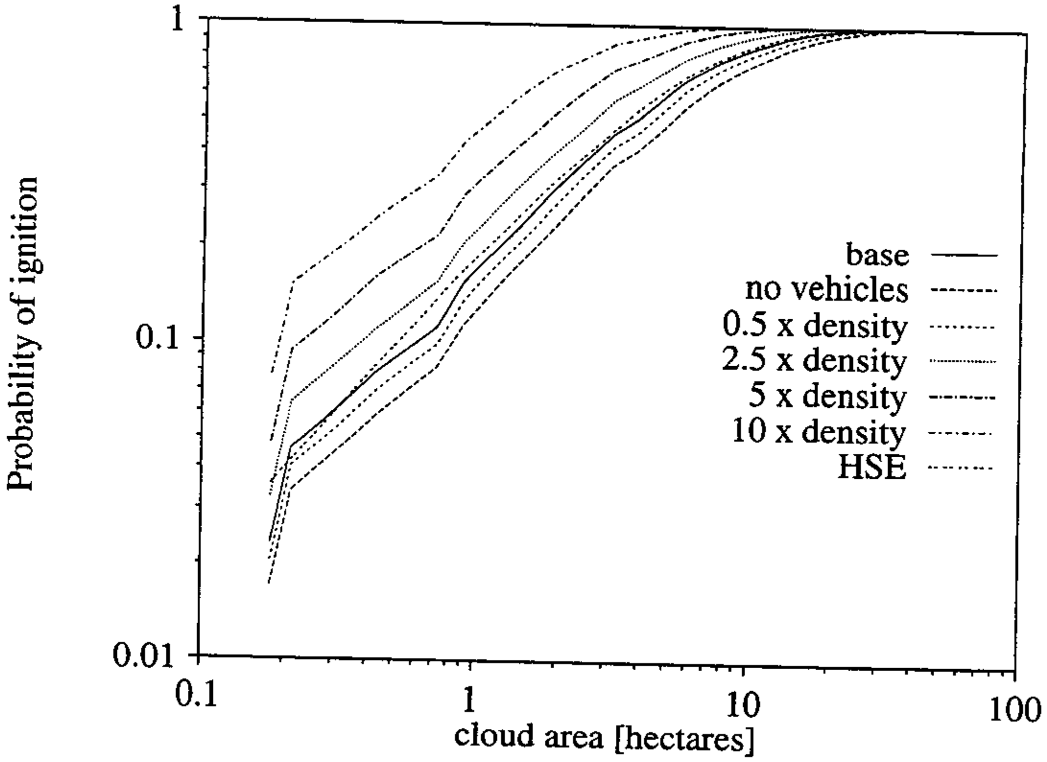

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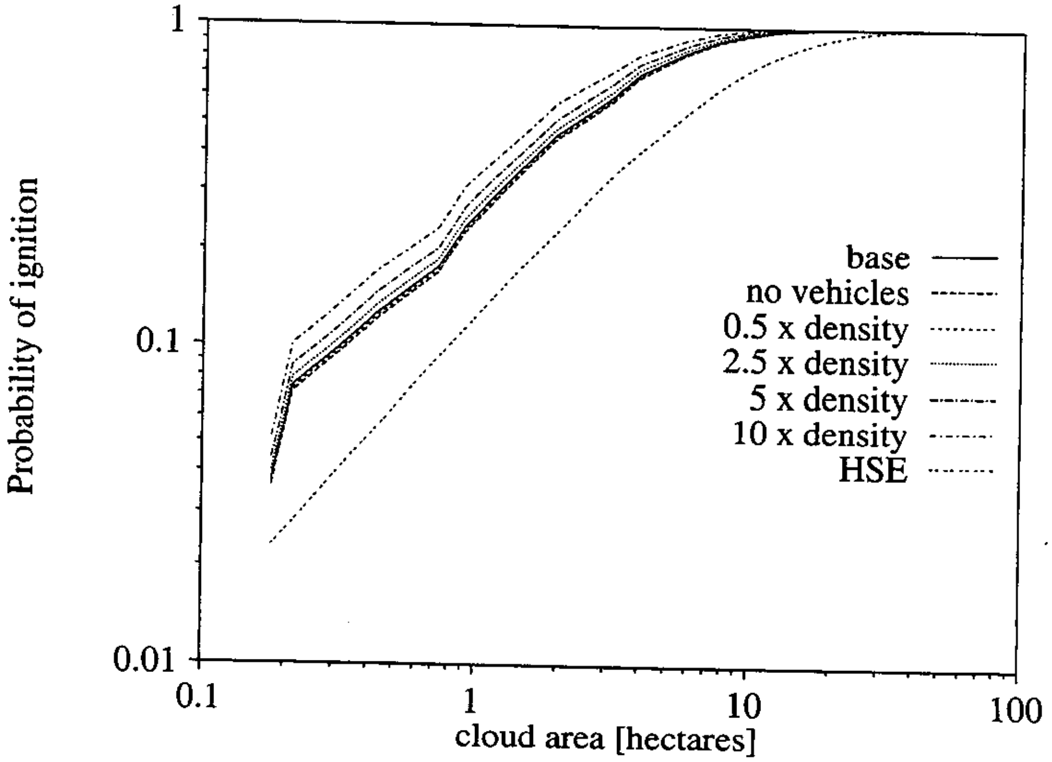
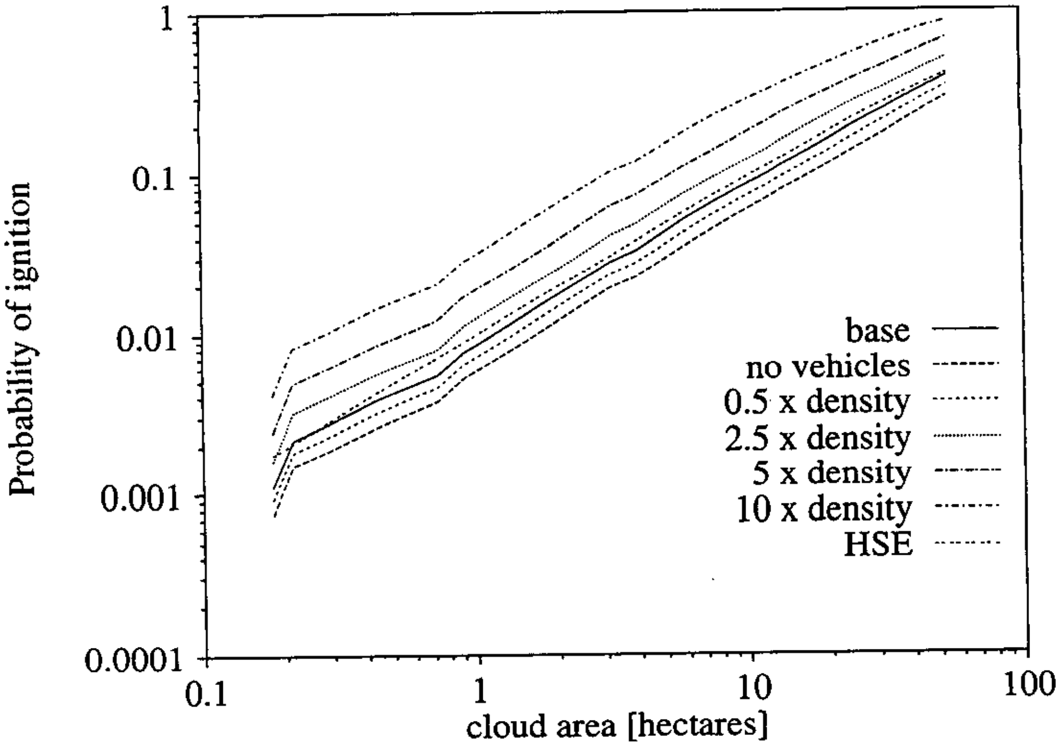


Urban Night

Figure D.14a Comparison of base case, current HSE model and variations with different densities of road vehicles



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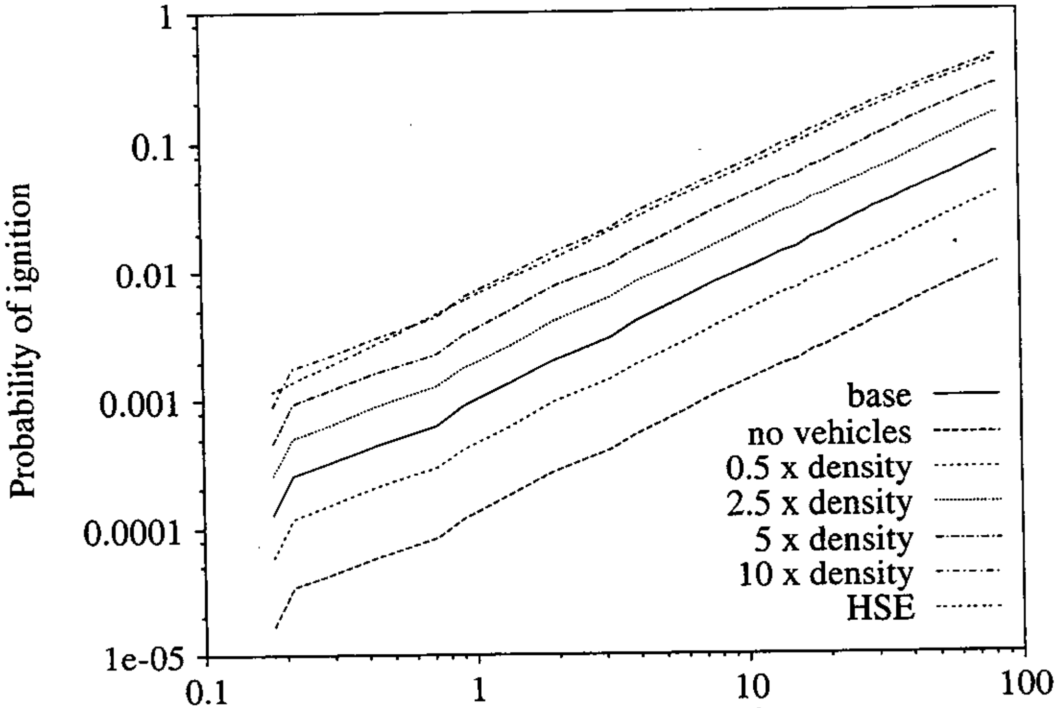
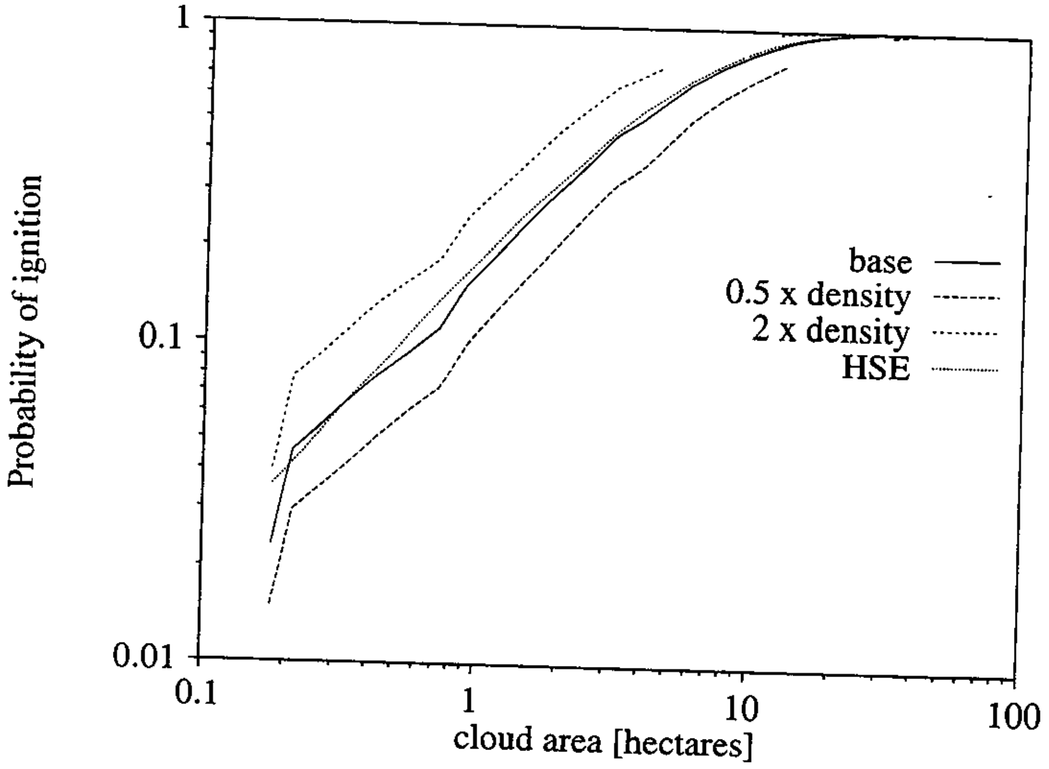


Rural Night

Figure D.14b Comparison of base case, current HSE model and variations with different densities of road vehicles (continued)



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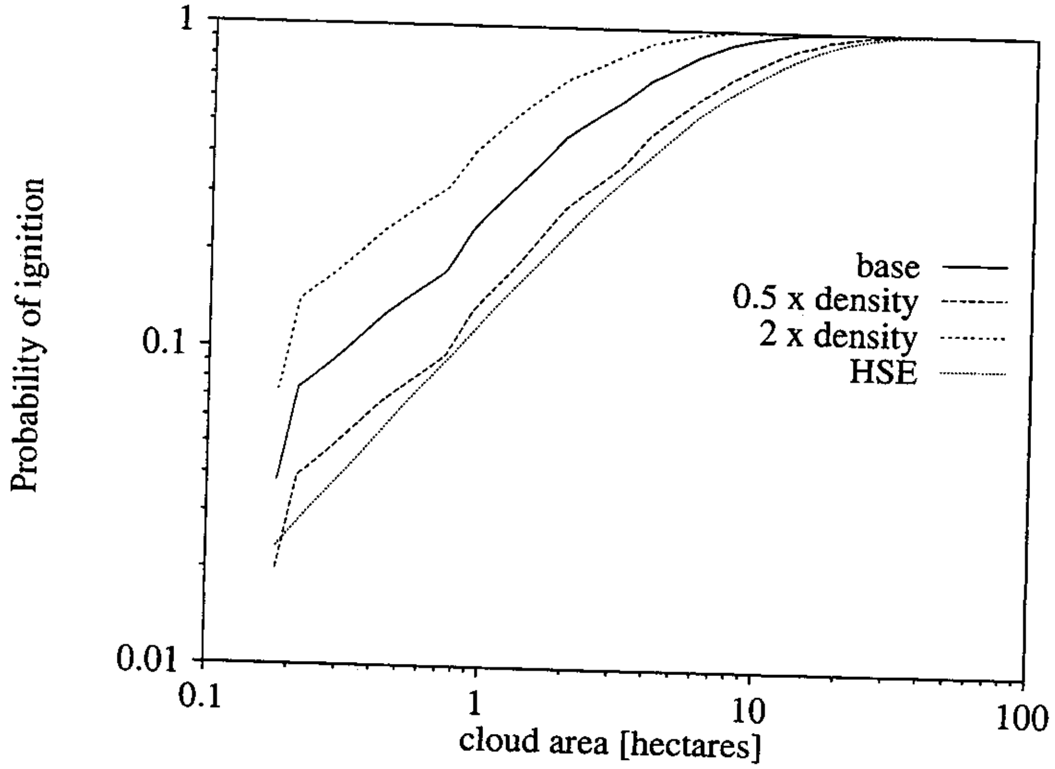
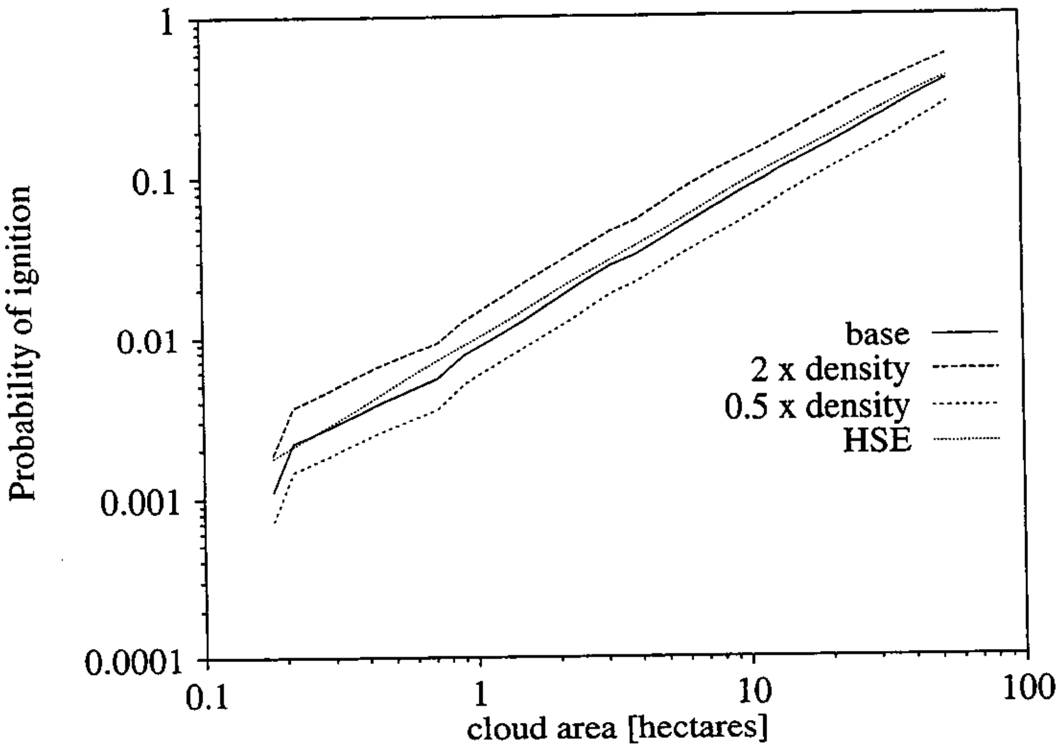
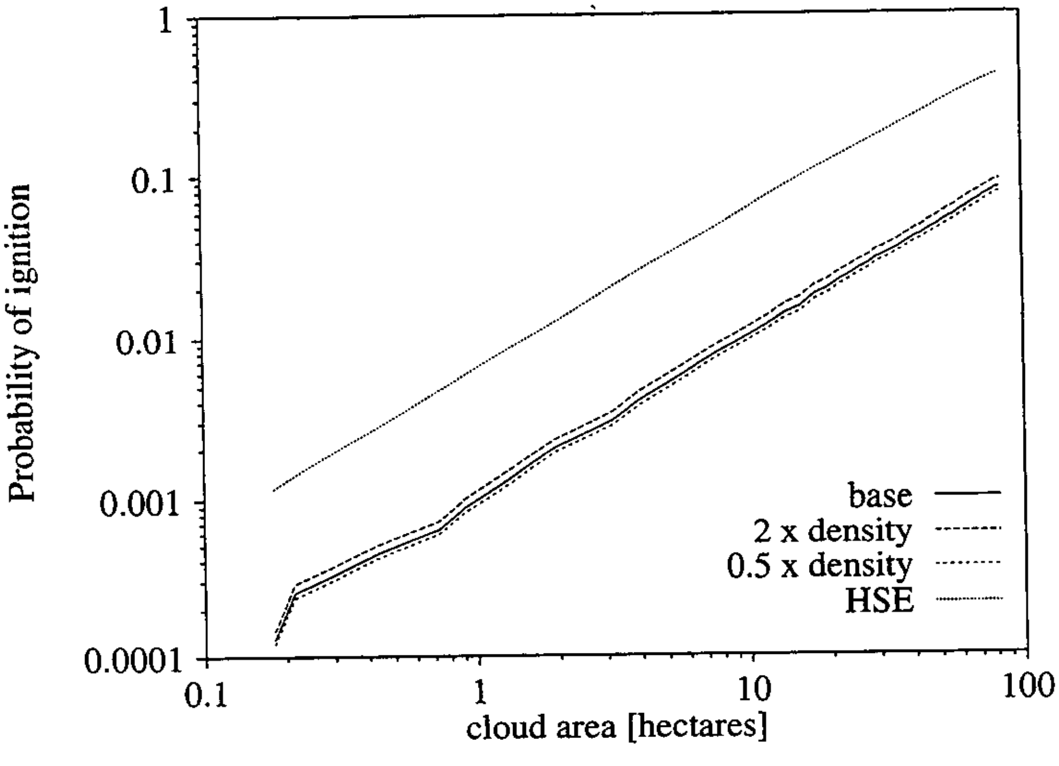


Urban Night

Figure D.15a Comparison of base case, current HSE model and variations with different densities of housing

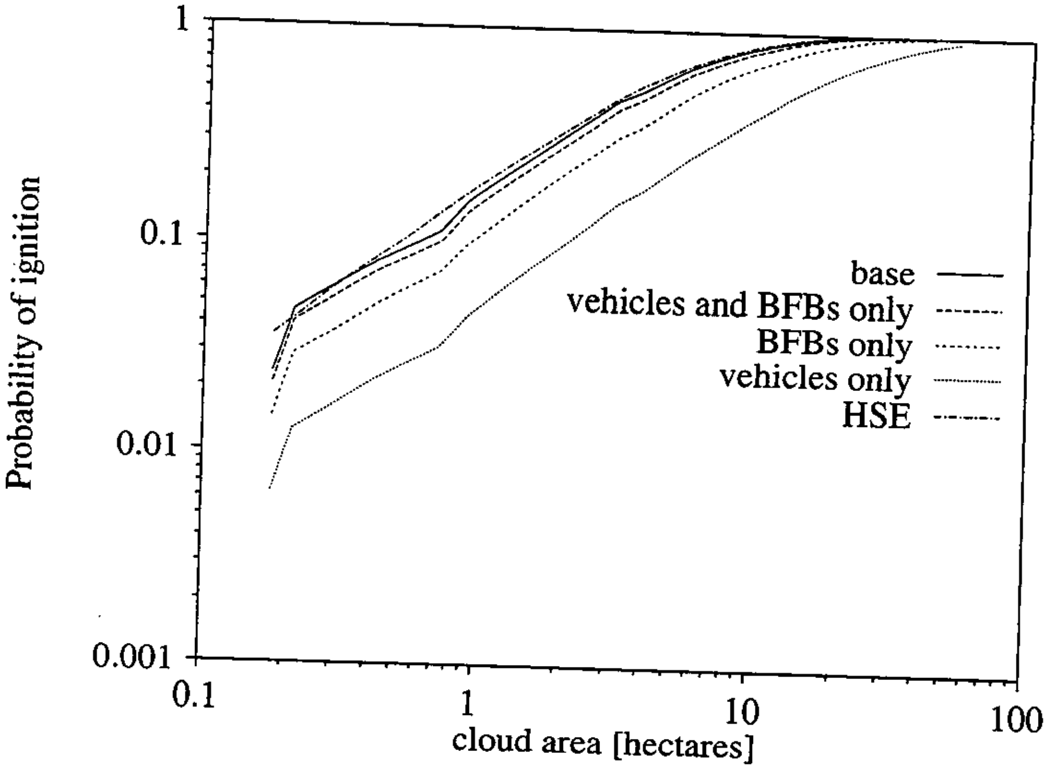


Rural Day



Rural Night

Figure D.15b Comparison of base case, current HSE model and variations with different densities of housing (continued)



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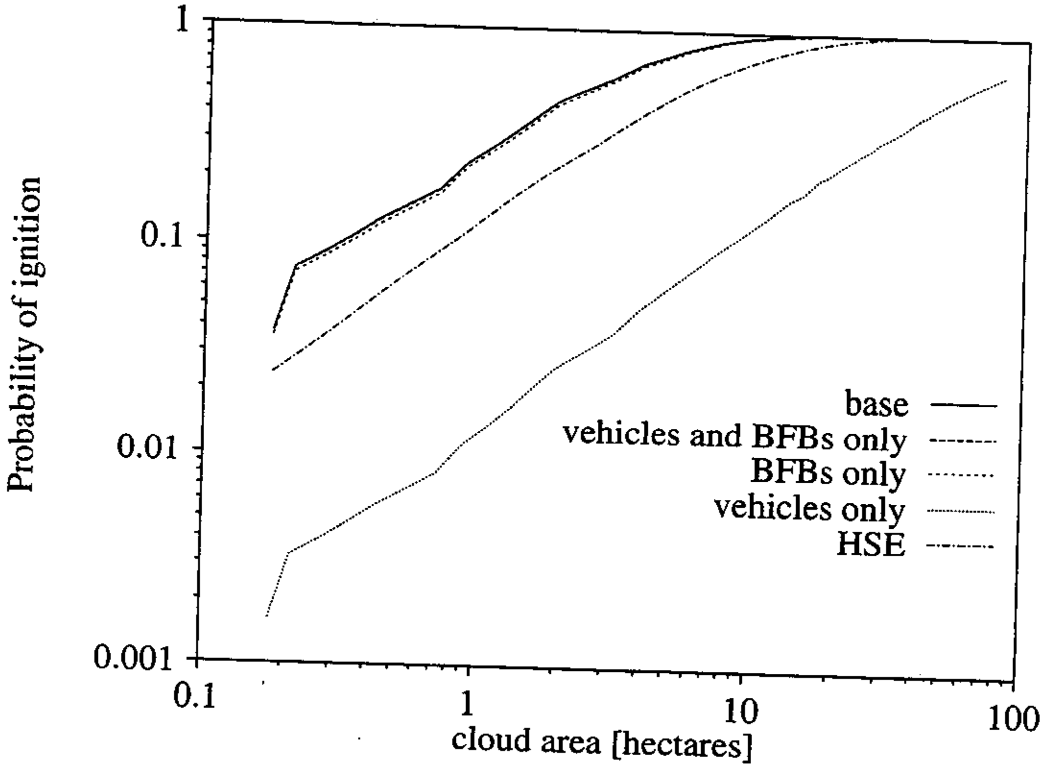

Urban Night

Figure D.16a Comparison of base case, current HSE model and reduced models

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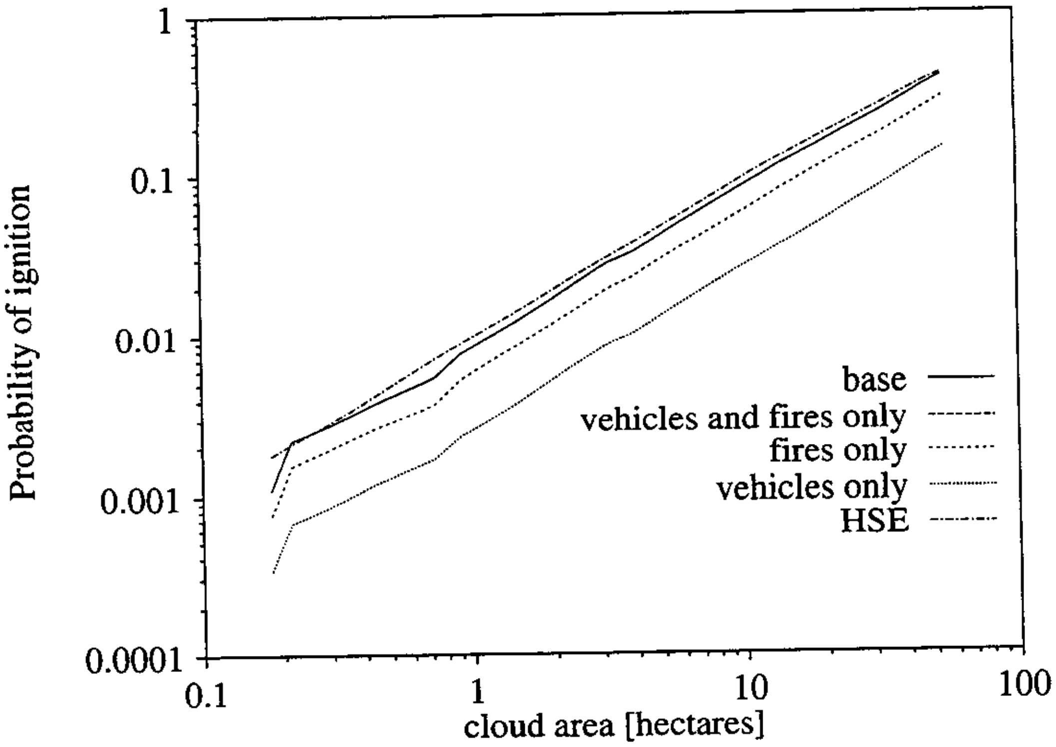
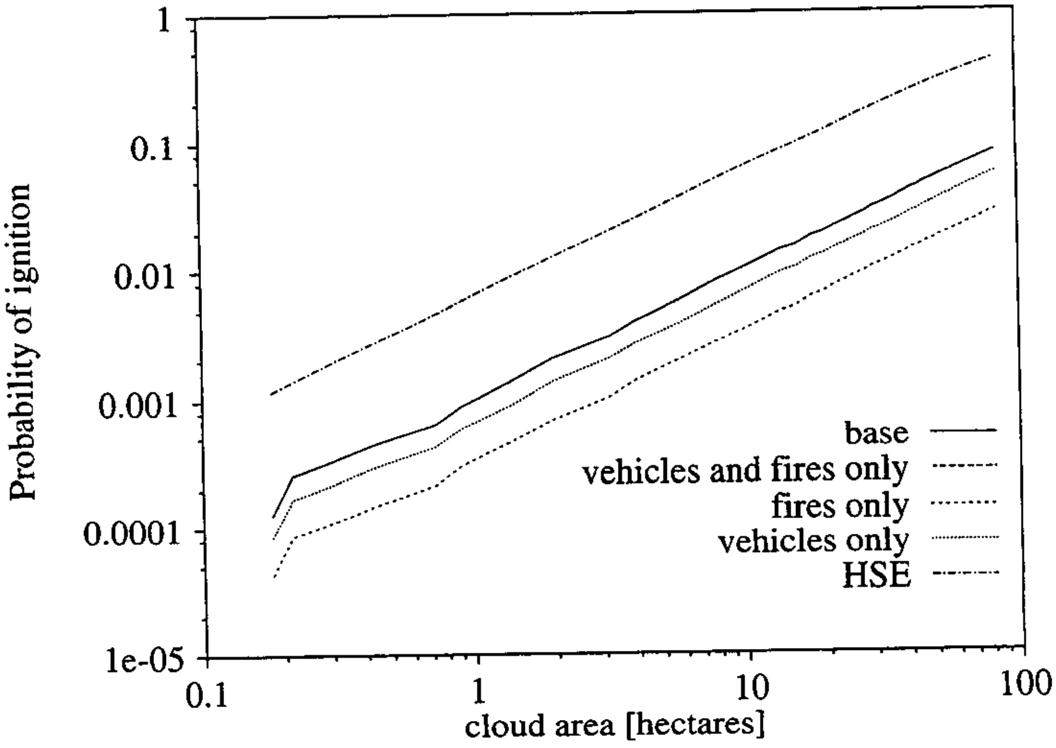


Rural Day



Rural Night

Figure D.16b Comparison of base case, current HSE model and reduced models (continued)

D.5 Sensitivity to Dispersion Modelling

D.5.1 A continuous release

Two, 30 minute duration, continuous releases of propane are simulated using HEGADAS-T (Post 1994), the transient, dense gas dispersion model, one during the day time and one during the night time. The input conditions used and some key results are given in Table D.3. The total area swept by the cloud as a function of time is shown in Figure D.17. The clouds formed are much smaller than those from the instantaneous releases shown in Figure D.1, but the duration of the releases is much longer. In night time conditions, the release is much slower to reach its maximum size but grows to a much larger size than in day time conditions. There is a slight discontinuity in the results for the night time release at 200 seconds. This is due to a change in time step used in HEGADAS-T at this point in order to simulate a long release with high temporal resolution at the beginning of the release.

Release parameter	Day time	Night time
Wind speed	5 m/s	2 m/s
Stability	D	F
Air and ground temperature	20°C	20°C
Ground roughness	0.1 m	0.1 m
Release rate	50 kg/s	50 kg/s
Release duration	30 minutes	30 minutes
Key results		
Maximum area of ground level LFL contour	1.04×10^4 m^2	1.42×10^5 m^2

Table D.3 Input conditions for a continuous release of propane and key results

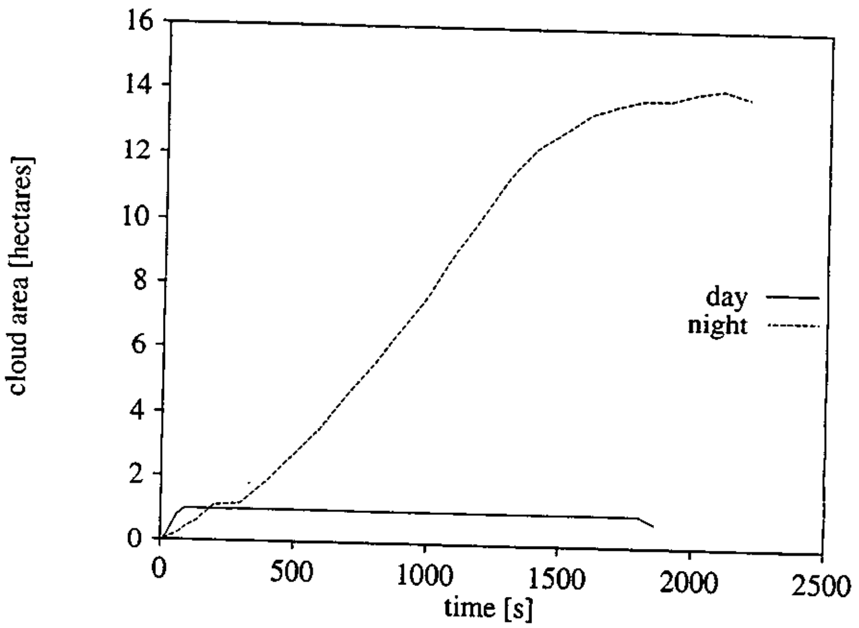


Figure D.17 Area of external cloud from continuous release during day and night time conditions

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D.5.2 The probability of ignition in all areas

The probability of ignition in all areas for the two continuous releases is shown in Figure D.18 against time and cloud area (area of the ground level LFL contour). Since the cloud is small and long lasting in comparison to the instantaneous releases, both internal and intermittent ignition sources are more significant for the continuous releases.

Due to the long duration of the releases, the concentration has time to build up to LFL inside all buildings, regardless of the ventilation rate. Therefore internal ignition sources are significant even for the base case model parameters. Since the concentration varies throughout the flammable cloud, the concentration reaches LFL inside buildings at different times in different locations, depending on the external concentration history. Therefore there is no sharp jump upwards when the concentration reaches LFL inside all buildings, as for the instantaneous release. Instead, the probability of ignition rises more gradually as the internal concentration reaches LFL in different locations.

The effect of intermittent ignition sources can be seen for the day time release for which the cloud reaches its maximum area quite quickly in comparison to the total dispersion time. However the probability of ignition continues to rise once the cloud has reached a fixed area due to the intermittent sources.

The probability of ignition is increased at night in comparison to the day due to the larger final cloud size at night for the continuous release. The cloud size during the day is initially bigger, therefore the initial probability of ignition in urban areas is higher during the day than at night. For an instantaneous release in a rural area, the probability of ignition is consistently higher during the day than at night. However, for the continuous release, the cloud area at night becomes so much bigger than during the day that the probability of ignition eventually becomes higher at night than during the day in rural areas.

D.5.3 Comparison with other models in an industrial area

The probabilities of ignition for the continuous releases in an industrial area in comparison with the current HSE model and the Simmons model are shown in Figure D.19. The probability of ignition is higher during the day than during the night for the first half of the release. The probability of ignition then becomes higher at night due to the larger size of the cloud. The probabilities of ignition during the night and day are higher than the current HSE model in comparison to the instantaneous release, since the current HSE model does not include any effects of time, only cloud area. During the first half of the release, the Simmons model gives much higher probabilities of ignition. During the second half, the proposed model catches up due to the effects of the long release time while the Simmons model includes no effects of time.

D.5.4 Comparison with other models in an urban area

The probabilities of ignition for the continuous releases in an urban area in comparison with the current HSE model and the Simmons model are shown in Figure

D.20. During the day, the probability of ignition is initially higher using the current HSE model. However, since the cloud reaches a fixed size quite quickly, the probability of ignition from the current HSE model flattens out, while the probability from the proposed model continues to rise due to the intermittent ignition sources and increasing contributions from internal sources as the concentration reaches LFL inside buildings in different locations. During the night, the probability of ignition using the proposed model is consistently higher than the current HSE model, as was the case for the instantaneous release, due to the high probability from balanced flue boilers. The difference becomes more marked later in the release due to contributions from indoor and intermittent ignition sources. The probability of ignition from Simmons' model is initially higher than from all other models. However the probability at night based on the proposed model becomes higher than that from the Simmons model due to the time dependent factors.

D.5.5 Comparison with other models in a rural area

The probabilities of ignition for the continuous releases in a rural area in comparison with the current HSE model and the Simmons model are shown in Figure D.21. During the day, the probability of ignition is again initially higher using the current HSE model, but the probability from the proposed model becomes higher due to intermittent and indoor ignition sources. Also, during the night, the probability of ignition is initially higher using the current HSE model. However, the probability calculated by the proposed model increases rapidly to a higher value than the current HSE model due to a sudden contribution from internal sources. The probability of ignition from Simmons' model is consistently higher than other models. As was mentioned in Section D.2.4, Simmons' model does not differentiate between different areas and Simmons studied reported incidents due to transportation accidents, where ignition sources could be clustered, leading to a high probability of ignition.

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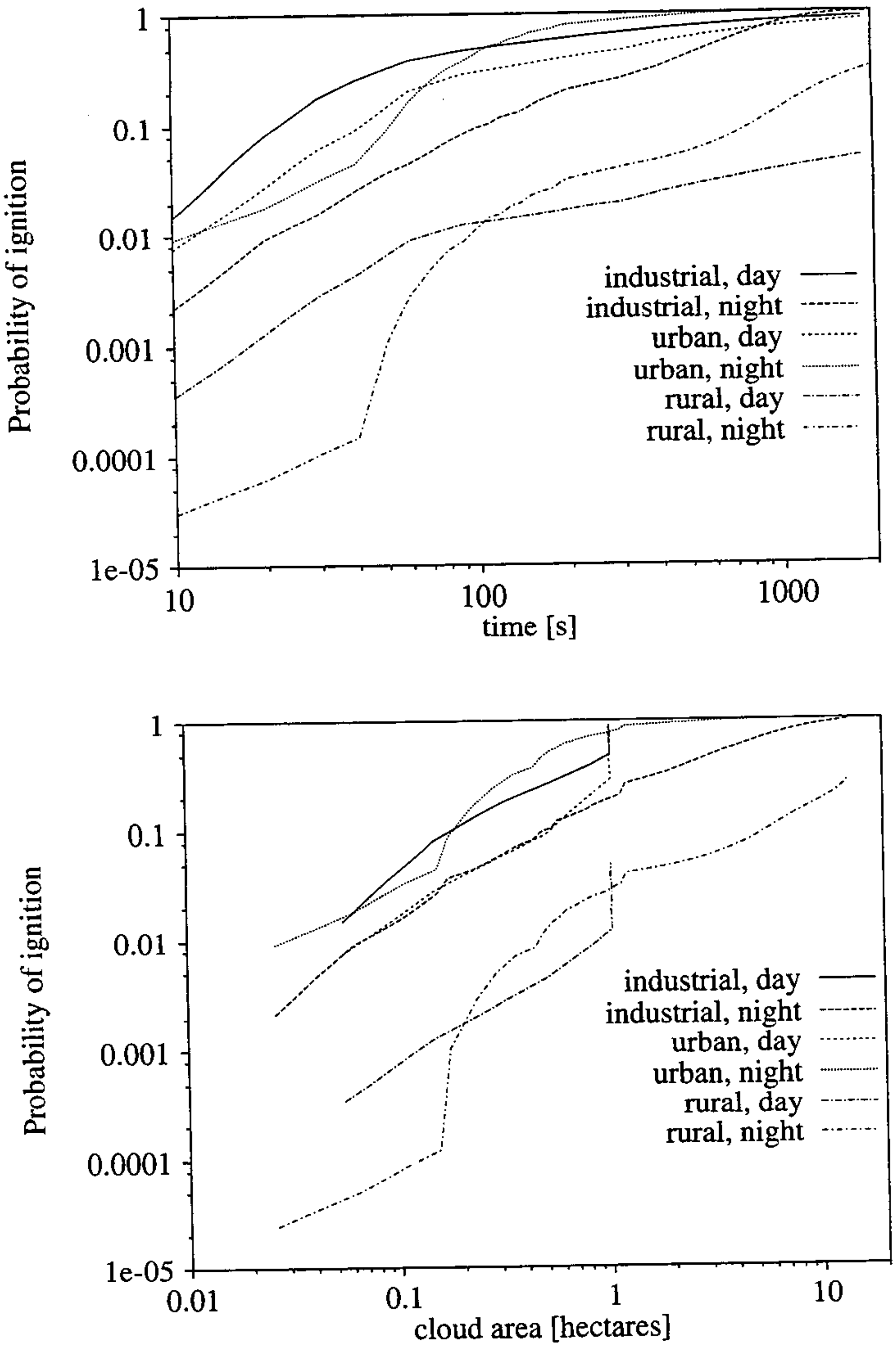

Figure D.18 Base case probability of ignition for a continuous release

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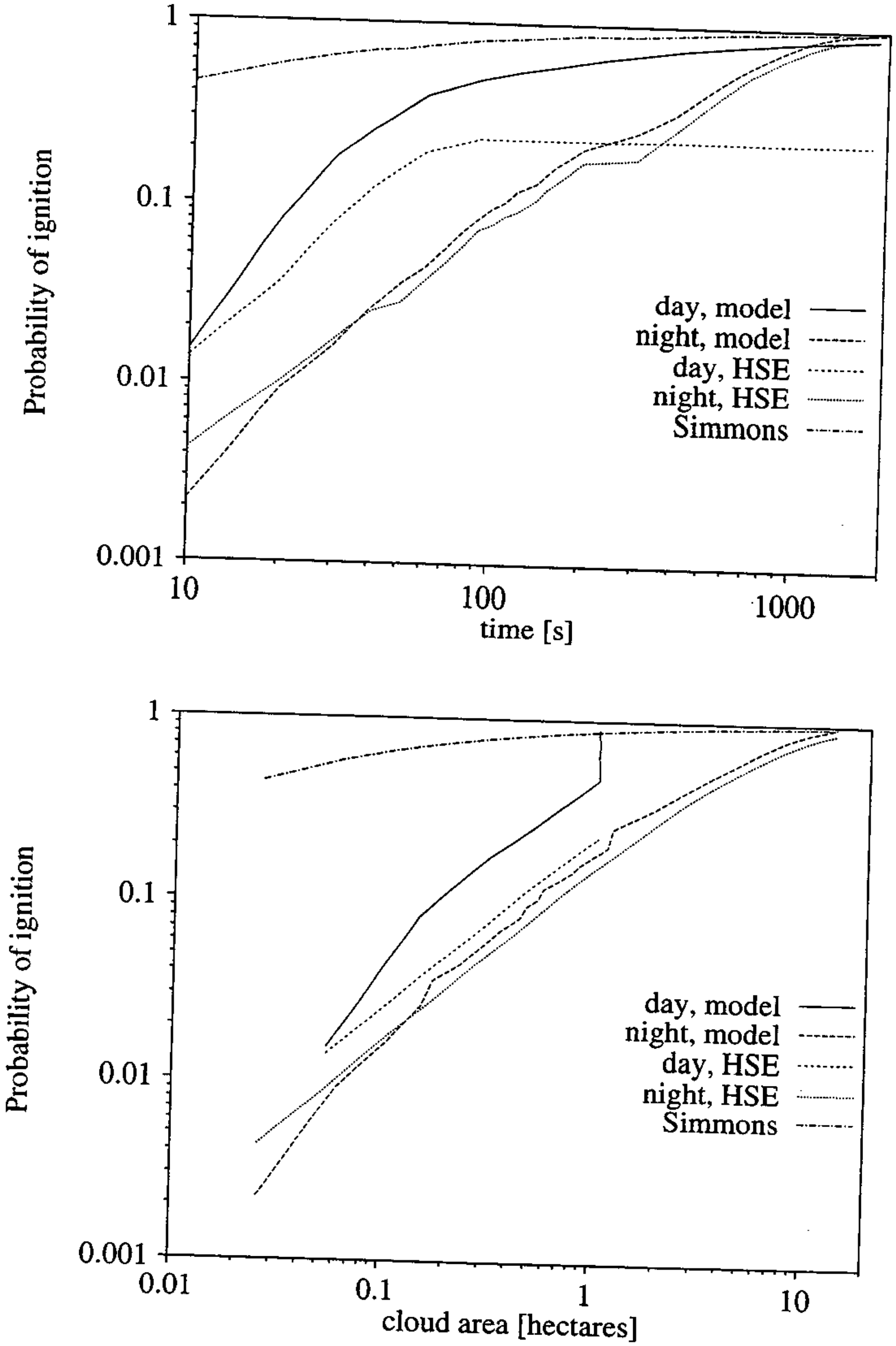

Figure D.19 Comparison of base case for an industrial area with current HSE model and Simmons' model for a continuous release

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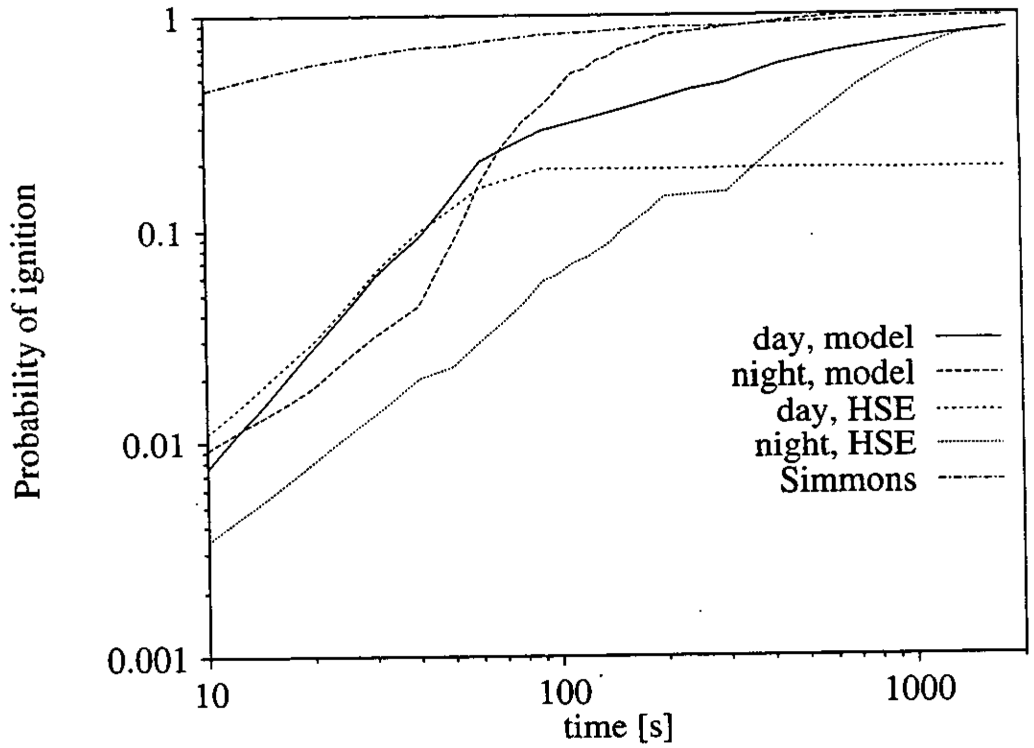

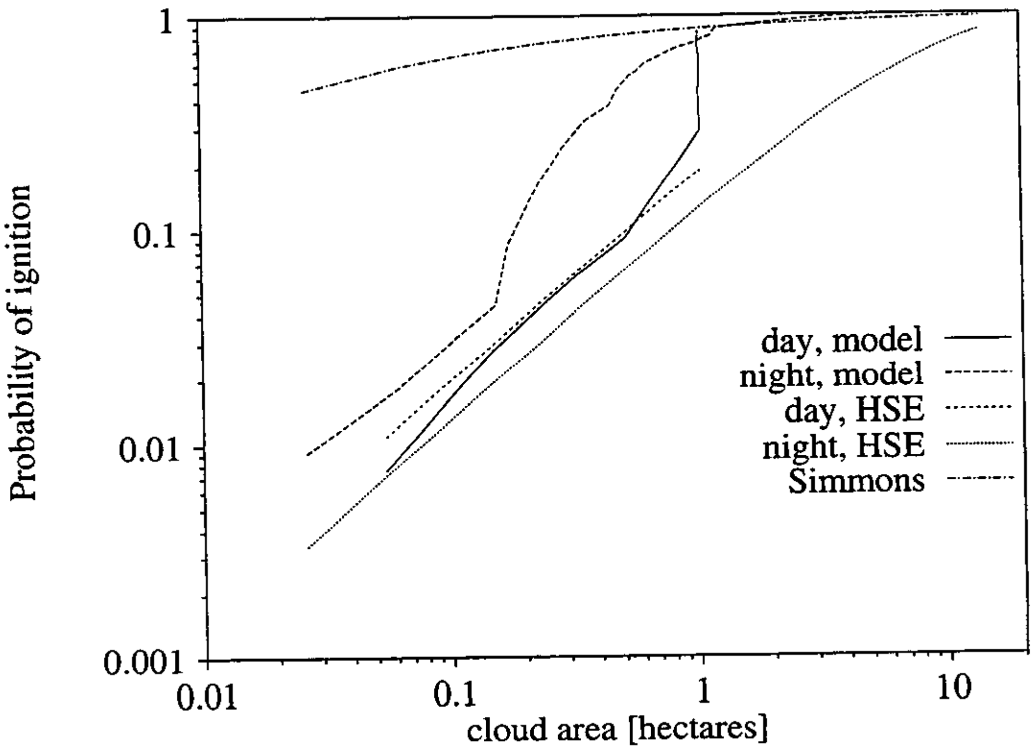

Figure D.20 Comparison of base case for an urban area with current HSE model and Simmons' model for a continuous release

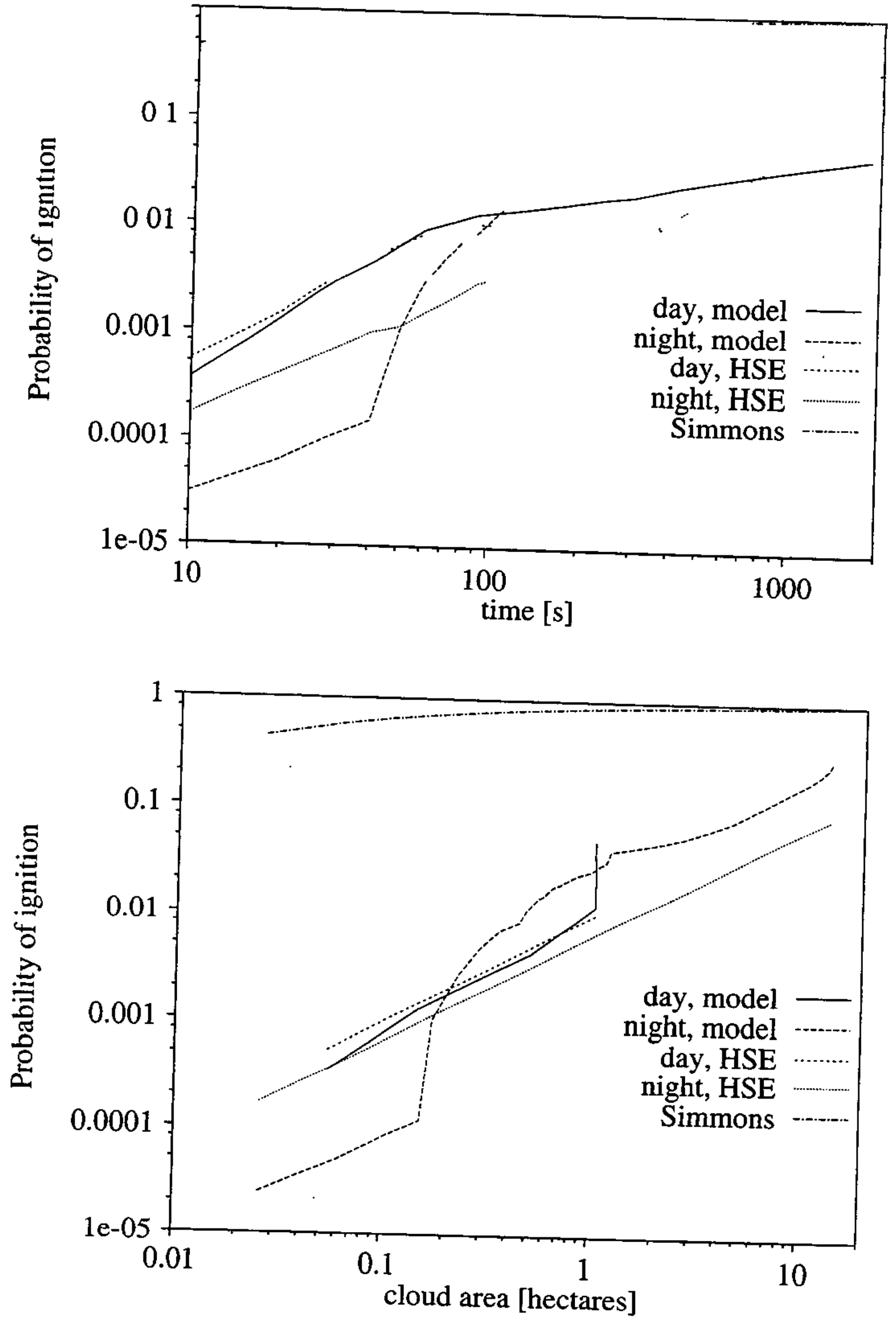

Figure D.21 **Comparison of base case for a rural area with current HSE model and Simmons' model for a continuous release**

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