COMPARATIVE STUDY OF MODELS USED IN THE ESTIMATION OF RISK FROM FLASH FIRE EVENTS AT MAJOR HAZARD INSTALLATIONS†

Diego Lisbona[a], Brian Briggs[b], Mike Wardman[a,#]
[a]Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK, SK17 9JN
[b]Hazardous Installations Directorate CI5, Health and Safety Executive, Redgrave Court, Merton Road, Bootle, Merseyside, UK, L20 7HS
[#]Corresponding author: mike.wardman@hsl.gov.uk, T: +44 (0) 1298 21 812 3

The quantification of risk from flash fire events, which result from the remote ignition of unconfined flammable clouds, is inherently complex as modelling the distribution of potential ignition sources introduces an additional level of uncertainty, particularly when the flammable cloud extends beyond the site boundary.

A number of approaches for estimating the probability of ignition and the number of potential fatalities have been proposed over the years. These can vary widely in scope and methodology. In terms of delayed ignition modelling, some approaches link the probability of ignition within the area covered by the flammable cloud with the land-use type (rural, industrial, and residential); other approaches consider the geographical distribution of population. There are also variations in the way progressive ignition is handled mathematically. The geographical extent of the flammable cloud, defined as the Lower Flammability Limit (LFL) or $\frac{1}{2}$ LFL concentration contour, is frequently used to mark the extent of fatality impact levels. Some models include variations in the vulnerability factors attributed to the surrounding populations depending on the population type (industrial, residential, and roads), flammable concentration contour chosen and/or distance from the source. An additional factor might be assumptions on the proportion of time the population is indoor or outdoors.

This paper presents the results of a comparison study carried out by the Health and Safety Laboratory to study the effect of the ignition density approach on the overall flash fire risk.

KEYWORDS: Flash fire, Major Hazards, societal risk, QRA, flammable cloud, QuickRisk, land use planning

INTRODUCTION

Flash fires originate from the ignition of unconfined flammable gas clouds by an ignition source remote from the release point. Upon ignition of the cloud, a band of flame travels back to the source as the portion of the cloud between the upper (UFL) and lower flammable limits (LFL) is ignited. The portions of the cloud above the UFL concentration can eventually ignite as the flame promotes air entrainment. Harm to people from materialisation of flash fire hazards has been generally found to occur within the extent of the flammable cloud either defined as the Lower Flammability Limit (LFL) concentration, or $\frac{1}{2}$ LFL concentration contour. It is usually considered that any unsheltered persons within the footprint defined by the flammable cloud become fatalities, and that the energy radiated by the fire is sufficiently low to consider that fatalities do not normally occur beyond the limits of the flammable cloud (Rew et al., 1996). This approach to flash fire consequence modelling, which clearly diverges from the modelling of other flammable events (O'Sullivan & Jagger, 2004), is supported by numerous published studies, as reviewed by Rew et al. (1996).

Consequence assessment of flash fire events in the context of quantitative risk assessment (QRA) normally commences by dispersion modelling to determine the size of the LFL or $\frac{1}{2}$ LFL concentration envelopes at a given time following the start of the release (Energy Institute, 2006). In the context of land use planning (LUP) advice provided by HSE, unless site-specific information indicates otherwise, this time is 1800 seconds. This is based on the assumption that within this time emergency response will have been able to limit the release or begin evacuation. Since the ignition of the cloud may take place virtually at any time from the onset of the release, the assumption that the flammable gas cloud has dispersed to its maximum extent at which point the ignition occurs is a rather cautious approach. A flashfire extending over the maximum possible area will be a very low frequency event. It follows therefore that a cloud ignited early would not necessarily involve a cloud the size of the LFL contour chosen. In order to address this issue HSE developed a risk-based approach for the purpose of providing LUP advice. This was based on the work on ignition likelihood by Spencer, Rew and others (1996, 1997, 1998 and 2004) and was reported by

Rew, Daycock & Rushton (2004). This approach, called the Flashfire Ignition Calculator (FLIC) has been used for providing advice mainly for storage of large quantities of refrigerated flammable substances. More recently, flash fire models have been developed for the risk assessment tool QuickRisk (Lisbona & Wardman, 2011), used in societal risk assessment of major hazard sites by HSL's Major Hazards Unit.

Additionally, although some sources of ignition are static and easily identifiable (e.g. a boiler house, an open flare) the location of other potential sources of ignition can be uncertain or transient (lightning strike, combustion engines in vehicles). In order to address this, models have been developed that attempt to calculate the probability of delayed ignition as a function of the area covered by the cloud and the estimated density of ignition sources (Spencer & Rew, 1997; Spencer et al., 1998; Daycock & Rew, 2004). In this paper, one of QuickRisk's flash fire models has been used to study the effect of the ignition density model on the overall flashfire risk.

THE FLASH FIRE MODEL IN QUICK RISK

Following the public consultation on societal risk CD212 (HSE, 2007), the Government decided to continue with the technical development work in this area and HSE commissioned HSL to develop a framework and tool for estimating societal risk around major hazard installations. As part of this work, HSL developed the risk assessment tool QuickRisk (Lisbona and Wardman, 2011), to enable risk assessments to include an extended set of major accident scenarios, up to Quantified Risk Assessment (QRA) level, and to consider multiple population data, time periods, and toxic dispersion and flammable risk models, as well as producing graphical and geographical representations of societal risk. As part of this work, new flash fire models were developed by HSL and incorporated into QuickRisk.

Table 1. Number of ignition sources per hectare typically used in LUP

Land use type	Values typically used in LUP
Developed areas	0.1
Undeveloped/rural areas	0.001
Over water	0

In QuickRisk the conditional probability of ignition at each point in the grid is calculated according to Eq. (1):

$$P = 1 - e^{-\mu \cdot A} \tag{1}$$

where P is the conditional probability of ignition, μ is the density of ignition sources (per hectare) and A is the area of the cell in hectares (typically 1 ha [100 m x100 m] but smaller cell sizes can be used).

The individual risk of flash fire at a point distant from the release location is calculated according to Eq. (2).

$$IR = F_{event} \times P_{not\ imm.\ ign.} \times P_{no\ early\ ign.} \times P_{ignition\ at\ location} \times P_{weather} \times P_{wind\ direction}/N_{sub} \tag{2}$$

where N_{sub} is the number of sub-sectors or resolution in which wind directions are dealt with computationally. N_{sub} is typically chosen at 360 (1 degree intervals). $P_{weather}$ is the probability of the weather category (atmospheric Pasquill stability class and wind speed combination) being considered (e.g Probability of D5 or F2 weathers). F_{event} is the frequency of the initiating event, such as, for instance,

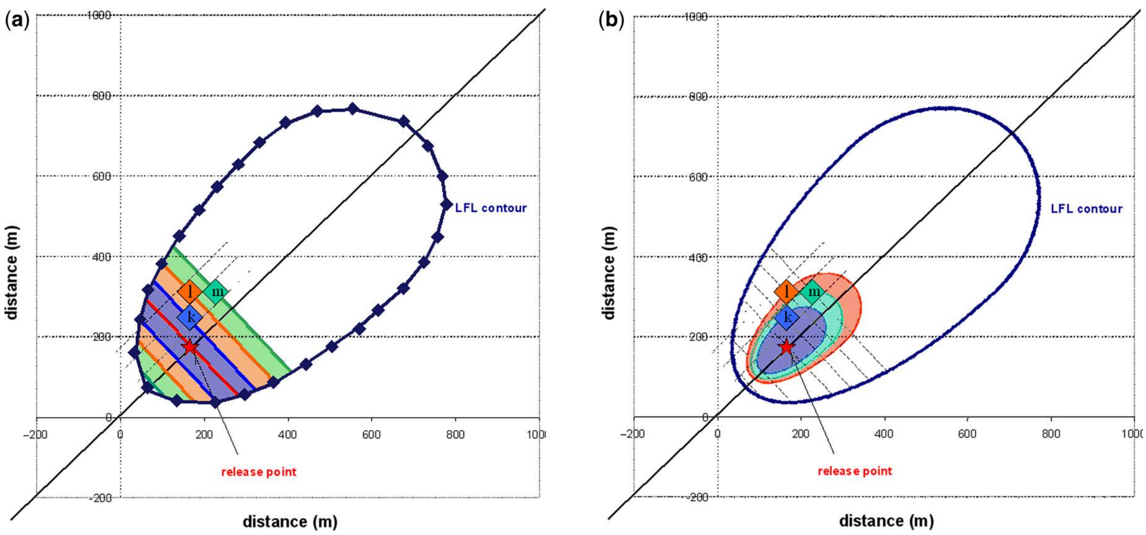

Figure 1. Representation of progressive calculation of ignition probability for three grid locations k, l, m using (a) one-dimensional model, (b) QuickRisk approach

Table 2. Density of ignition sources per hectare and land-type (μ) according to Spencer and Rew (1997)

Land use type	μ (Spencer and Rew, 1997)
Industrial	0.125
Urban	0.1
Rural	0.05

the failure frequency associated with the catastrophic loss of vessel integrity, or a vessel/pipework hole failure frequency. $P_{not\ imm.\ ign}$. is the probability of the release not being ignited immediately. The probability of the release not being ignited immediately is entered by the user and the value can be chosen based on historical data, or site specific information. For example, a decision could be made to consider no immediate ignition. Alternatively, empirical correlations for the probability of immediate ignition can be found in the open literature (International Association of Oil and Gas Producers, 2010). Recently, Moosemiller (2011) proposed methods to estimate both the probabilities of immediate and delayed ignition. In the approach proposed to estimate the probability of immediate ignition, Moosemiller considered that the probability of immediate ignition is *proportional to the cube root of the source pressure*, according to the relationship in Eq. (3)

$$P_{II} = [1 - 5000 \cdot e^{-9.5(T/AIT)}] + \left[0.0024 \cdot \frac{P^{1/3}}{MIE^{2/3}}\right] \quad (3)$$

where P_{II} is the probability of immediate ignition, P is the source pressure at the point of release, AIT is the autoignition temperature in degrees Fahrenheit, T is the temperature in degrees Fahrenheit and MIE is the minimum ignition energy.

Other examples of probability of immediate ignition are available from the Energy Institue (2006), which refers to work carried out by the DNV TDIM project. The probability of self-ignition can be calculated, for instance, using the correlation in Eq. (4).

$$P_{self\ ignition} = 0.01 \times m/100 \quad (4)$$

where m is the mass release rate in kg/s.

If the release is not ignited immediately, e.g. by fragments of the containment that generate sparks or by contact with electrical equipment in the immediate vicinity of the release point, then the flammable cloud can progress and/or disperse un-ignited for a period of time. If the latter is the case, then there is a chance that the flammable cloud will extend so far as to cover a "location of interest" where harm to individuals may take place (due to flash fire) if the unconfined release ignites. For this to take place it is therefore necessary that the release has not ignited *early* or *before reaching the point of interest*. The probability of the release not having ignited early, i.e. upwind from the point of interest, was introduced in Eq. (2) as $P_{no\ early\ ignition}$, and determines the flash fire risk at a given location. To calculate $P_{no\ early\ ignition}$, HSE uses a simplified version of the Atkins ignition model (Daycock & Rew, 2004; Spencer et al.,

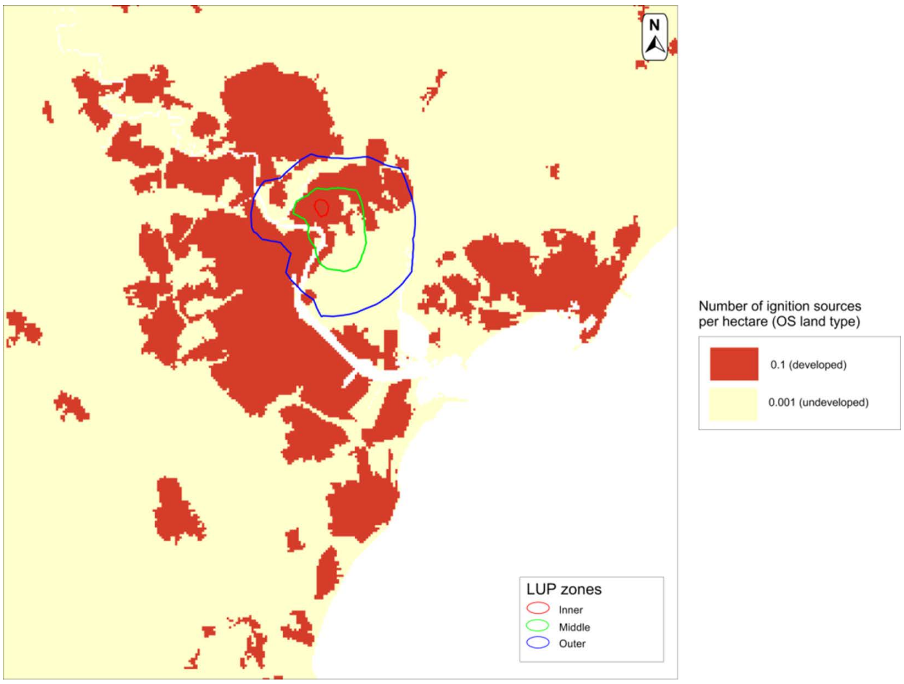

Figure 2. Density of ignition sources using land-type information and μ values typically used in LUP (Table 1).

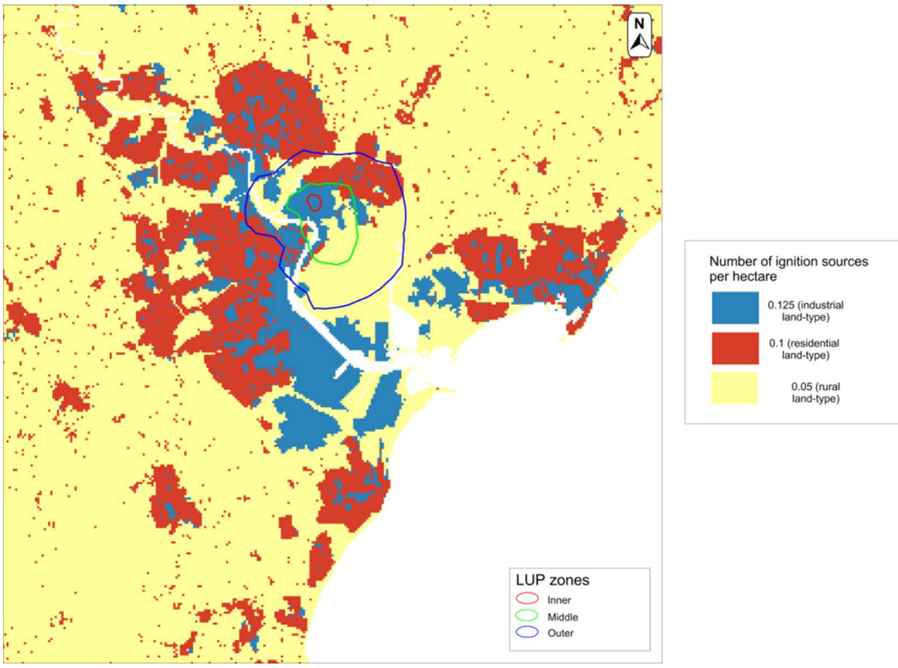

Figure 3. Density of ignition sources using land-type information and μ values from Spencer and Rew (1997).

1998; Spencer & Rew, 1997), as defined in Eq. (5):

$$P_{no\ early\ ignition} = 1 - P_e \qquad (5)$$

where P_e is the probability of early ignition calculated according to Eq. (6)

$$1 - P_e = \prod_{Upwind} e^{-\mu_{i,j} \cdot A_{i,j}} \qquad (6)$$

and $\mu_{i,j}$ is the density of ignition sources at the geographical locations of interest i,j (x,y) in sources per hectare and $A_{i,j}$ is the area of the geographical locations of interest (in hectares). Typical values for $\mu_{i,j}$ are shown in Table 1.

To calculate the probability of early ignition at each grid location, the product defined by Eq. (6) is evaluated considering all the cells within the corresponding plume segments that are *upwind* from the point of interest. Eq. (2) also requires $P_{ignitionat\ location}$ which is the probability of ignition at the point of interest, evaluated with Eq. (1).

There are a number of approaches to dealing with the progressive likelihood of ignition as the flammable vapour cloud spreads out over the surrounding area. These approaches depend on a number of factors including: the complexity of the dispersion model, available computing resources and the assumptions that have to be made in respect of the releases event, dispersion condition and sources of ignition. The FLIC model uses a one dimensional approach as indicated in Figure 1a. During the development of the flashfire model in QuickRisk a number of different approaches were considered before a two dimensional approach as indicated in Figure 1b was adopted. As it can be seen in the pictorial representations, grid locations do not necessarily follow the cloud growth in the same sequence, nor would the area covered (which determines the density of ignition sources and cumulative probability of ignition) be the same. Alternative QuickRisk flash fire models have been produced and used in societal risk calculations. An example of these is the possibility of considering radial distances from the source to mark the extent of the progressive ignition calculation intervals. Both the ellipsoidal and radial cloud growth models can be evaluated at a set of pre-defined distances or, alternatively, at the spacing determined by the grid resolution.

As shown by the introduction of $P_{wind\ direction}$ and N_{sub} in Eq. (2), the cloud footprint is gradually rotated one degree at a time and the probabilities for each point re-calculated. The actual probability of ignition at any one particular point is finally obtained by adding up the values for that point from each plume orientation.

The QuickRisk method shows how grid locations away from the centreline could be reached generally later than in one-dimensional models, with the area shaded also extending further away along the centreline than in the one-dimensional method (see Figure 1). As a result, neither approach can be generally considered to be the definitive 'conservative best estimate' in individual risk and societal risk terms, as both individual risk and societal risk values will be affected by the irregularly distributed density of ignition sources and population, and the differences in the geometrical progression used to simulate cloud growth.

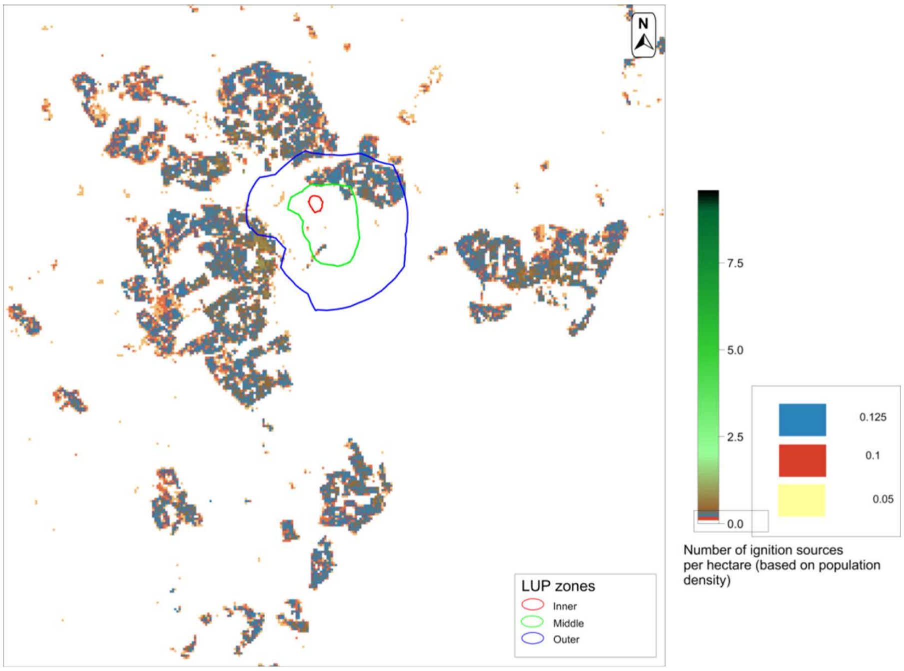

Figure 4. Density of ignition sources based on daytime population density and an average number of 0.005 ignition sources per person. The colour code scale from Figure 2 has been used (for 0.005, 0.1, 0.125 sources per ha) and extended to show that the density of ignition sources could be as high as 7.5-9 per ha in densely populated areas.

Estimating the Density of Ignition Sources

The number and location of ignition sources can be estimated analytically, e.g. following the methodology described by Daycock and Rew (2004), for a major hazard site storing flammable substances, where control of ignition sources by hazardous area zoning, permit to work systems

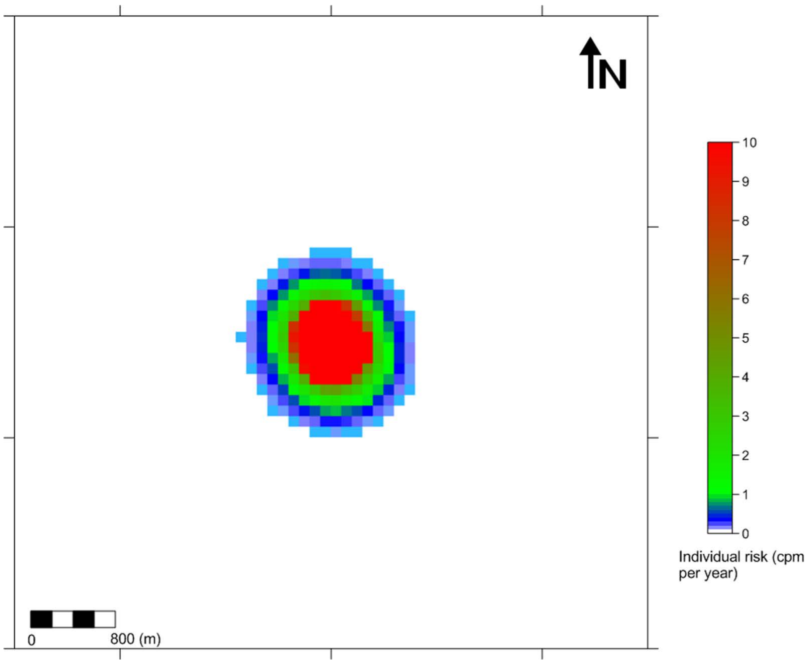

Figure 5. Individual risk values per cell (in chances per million per year) when using ignition source densities as per Figure 2.

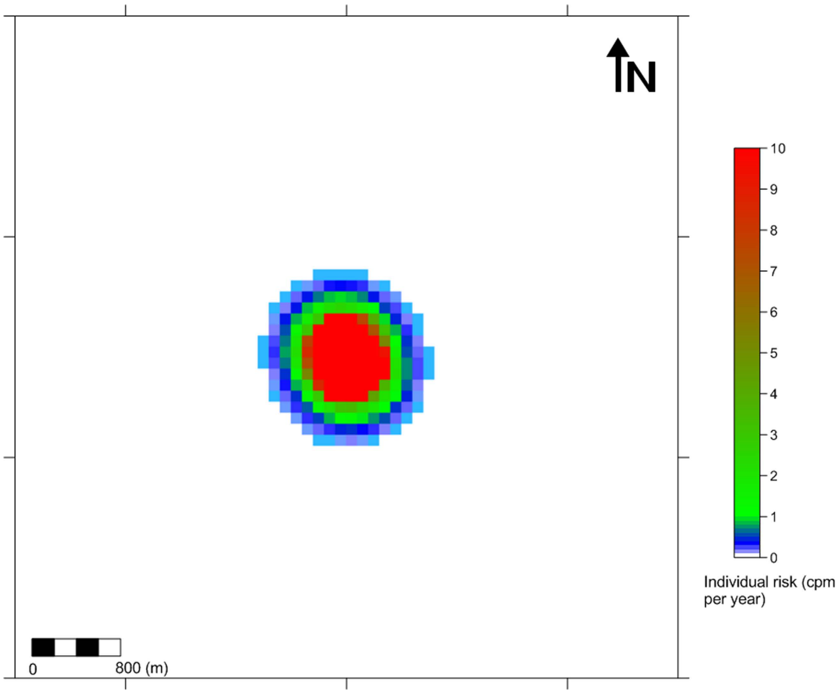

Figure 6. Individual risk values per cell (in chances per million per year) when using ignition source densities as per Figure 3.

and hot work controls is likely to be in force. Beyond the site boundary, the absolute number and location of ignition sources is subject to considerable uncertainty.

Three options have been considered for obtaining the ignition probability:

1. Using estimates of the number of ignition sources according to the level of land development (Table 1);
2. Using the Spencer and Rew (1997) estimates of μ as a function of land type (Table 2);
3. Using estimates based on population density.

Approximations such as those presented in Table 1 may be the only feasible approach for LUP purposes. However, HSL holds geographically referenced land-type information with UK-wide coverage that can be used to consistently assign μ values to areas of land according to Table 2. Figure 2 shows the density of ignition sources in a UK area using land-type information based on undeveloped and developed land-types, and the μ values typically used in LUP (Table 1). Figure 3 shows the density of ignition sources in a UK area based on the land-type and the μ values from Spencer and Rew (1997). Another option could be to assume that the number of ignition sources is linked to the population density and to assign an average value to the number of ignition sources per person. This originates from the fact that, the road population estimates are linked to the number of vehicles on roads, which can act as ignition sources. Similarly, density of residential populations can be estimated from the number of housing units, each likely to have a central heating boiler that may act as a source of ignition. The National Population Database, developed by Staffordshire University (Smith et al., 2005; Smith and Fairburn, 2008) and hosted by HSL, contains estimates of road and residential populations that could therefore be used to consistently generate an approximated distribution of offsite ignition sources in the UK. The density of ignition sources in Figure 4 is the result of applying an average value of 0.005 ignition sources per person to the road and residential population density values from the NPD for the same geographical area. This value has been chosen as a basis of discussion only and does not reflect any current HSE policy. The apparent level of detail that is derived from the NPD can give a false sense of accuracy, particularly considering that an averaged value for the number of ignition sources per person has been used regardless of the population type. Also this approach does not take account of other ignition sources that are not clearly linked to people as recorded in the residential and road information in the NPD. Examples might include temporary workplaces, agricultural machinery, and other forms of transport, temporary accommodation or events.

EFFECT OF IGNITION SOURCE DENSITY DEFINITION ON THE INDIVIDUAL RISK LEVELS USING QUICKRISK'S FLASH FIRE MODEL

The effect of the ignition density approach on flash fire risks has been studied using one of QuickRisk's flash fire models. The model chosen handles progressive ignition using ellipsoidal contours as defined in Figure 1b at 50 m spacing. An LFL contour (representative of a 30min, 3000 kg/s release

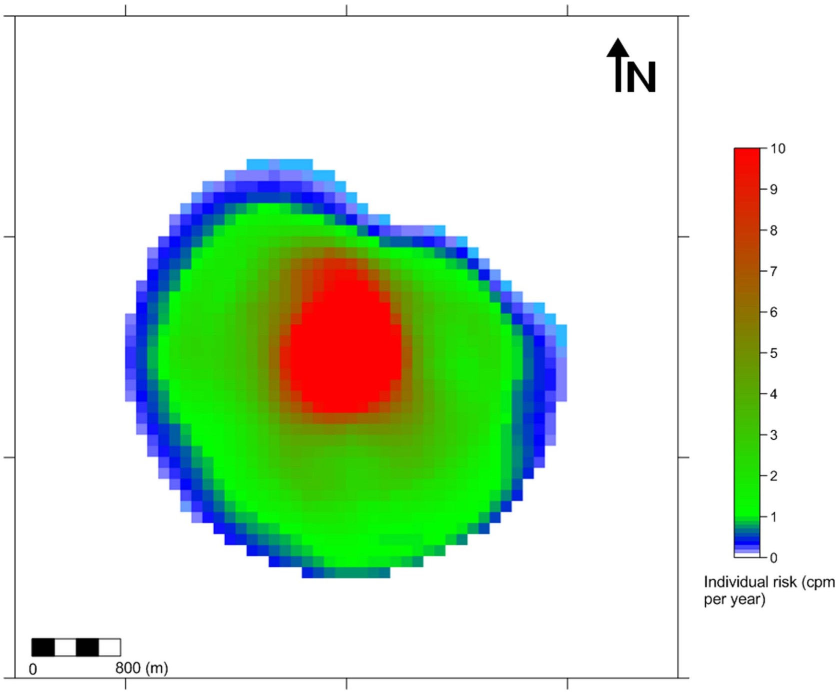

Figure 7. Individual risk values per cell (in chances per million per year) when using source densities as per Figure 4.

of refrigerated propane modelled with DRIFT v3 (Tickle & Carlisle, 2008, 2011)) has been used to define the extent of the flammable cloud. The frequency of the initiating event was considered to be 80 chances per million (cpm) per year and the probability of immediate ignition was considered negligible (assumed good control of ignition sources on site).

The individual risk contours obtained with QuickRisk (in cpm per year) and the developed/undeveloped land-type approach are shown in Figure 5. Figure 6 shows individual risk contours obtained with QuickRisk when the ignition source density values were defined according to the land-types by Spencer and Rew (1997). The introduction of this approach results in generally smaller individual risk contours when areas of land within the LFL contours are re-classified as industrial, which have higher allocated ignition source density values.

Figure 7 shows the individual risk of flash fire when the population density approach is used to model the density of ignition sources. In this case, the dominant factor is the effect of large unpopulated areas of land, with no allocated ignition density, which has the effect of *postponing* ignition until the progressive ignition has reached larger contours or segments. Conversely, the presence of areas of very high population density can result on the probability of ignition quickly reaching high values thus resulting in flashfire risks not extending beyond that location. Further investigation of the significance of zero ignition sources allocated to "unpopulated" land and the allocation of density of ignition sources to different types of population data from the NPD is therefore required.

CONCLUSIONS

In this paper, a QuickRisk flash fire risk model has been presented. A test case major hazard scenario (3000 kg/s release of refrigerated propane) has been used to study the potential impact on flash fire risks from changing the ignition source density model.

Two alternatives that depart from the current approach used to estimate ignition source density values for LUP have been introduced:

1. Allocating ignition source density values according to the land- use type (industrial, urban, rural).
2. Linking the density of ignition sources to daytime or night time population density values from the National Population Database (NPD).

This paper demonstrates that both approaches, for any given progressive ignition model, can result in significantly different flash fire risks from those currently obtained using estimates of ignition source densities linked to the level of land development. However all approaches rely on making assumptions that link the likelihood of ignition sources to the presence of people. It is important that the level of accuracy is appropriate with the other assumptions that have to be made in modelling these low frequency but potentially high consequence events.

DISCLAIMER

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of the authors alone and do not necessarily reflect HSE policy.

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