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Effects of flashfires on building occupants

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RESEARCH REPORT 084

Effects of flashfires on building occupants

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A flash fire, or cloud fire, occurs if ignition takes place within the flammable region of an unobstructed, unconfined gas cloud, generally at a point remote from the source. When modelling the effects of such fires, it is usually assumed that all unprotected personnel caught within the fire boundary are fatalities, but that the proportion of fatalities is significantly lower for those sheltered within buildings.

This report considers the likelihood of secondary ignition of the interior of buildings, based on the incident heat flux from a fire event and the duration of exposure to the event. An assessment is then made of the proportion of occupants who do not escape from the secondary fire. Thus an attempt has been made to incorporate evacuation behaviour into the assessment. Due to the lack of suitable data on the evacuation behaviour relating to external fires, selected case studies have been used to estimate particular behaviour patterns.

The key finding of this study is the increased probability of fatalities of building occupants due to multi-point ignition events, as compared to that for single point ignition. Multi-point ignition refers to events which engulf the complete building, i.e. flash fires, for which secondary ignition of all rooms and flame penetration is possible, whereas single point ignition refers to events such as pool fires, where only one elevation of the building is exposed to the incident flux.

Typical case studies have been applied to the model. For a steady-state fire remote from the building (single-point ignition), producing sufficient radiation to cause ignition of the interior as well as the exterior, the probabilities of fatality range from 0.4% for a office building to 3.5% for a dwelling at night. For flash fire events (multi-point ignition), the corresponding probabilities for office buildings and dwellings are 2.2% and 21.5%, respectively.

It is noted that the above probabilities of fatality relate to the effects of secondary fires only and do not include the direct effects of flame penetration on occupants. This report considers the contribution of blast and flame penetration through windows and concludes that these effects may be significant when determining risk to building occupants. However, it is noted that simple models are currently not available for assessing such effects..

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CONTENTS

1. INTRODUCTION

1.1 Background

In a study of the modelling of flash fire effects (Rew et al,1997), it was concluded that the assessment of off-site risk for flash fire events is most sensitive to:

a) the modelling of ignition probability;

b) the maximum burn area of the cloud (dependent on both dispersion modelling and fraction of mean LFL at which combustion occurs);

c) the proportion of people within shelter who are fatalities.

This report is concerned with item (c). Based on a preliminary analysis provided in the above study, it was suggested that, in the event of a flash fire, approximately 5% of those who are sheltered by typical domestic housing will be fatalities as a result of secondary fires. However, there was much uncertainty in the derivation of this value:

Uncertainty in modelling blast effects and flame penetration:

- possibility of gas ingress to buildings resulting in internal explosions;
- likelihood of external blast effects and flames penetrating the building boundaries.

Uncertainty in modelling ignition of buildings:

- use of ignition criteria based on radiative heat (Lawson & Simms, 1952), when heat transfer will also occur due to convection for an engulfed building;
- variation in ignition criteria for different building materials;
- likelihood of fire spread within buildings after ignition.

Uncertainty in estimating likelihood of escape from buildings:

- differences in characteristics between fires caused by process accidents (generally highly flammable hydrocarbons) and those which are included in the Home Office data (on which the 5% estimate is based). Fire characteristics which may vary include the rate of fire development, localised blast effects and intensity of heat flux on external surfaces of building;
- intervention of the fire brigade, which may not be as effective for aiding escape from the potentially large number of properties which may become involved in a major fire.

This report further investigates the effects of flash fires (and other external hydrocarbon fires) on buildings and their occupants, with the aim of reducing the above uncertainties.

1.2 Objectives and scope of work

The objectives of the study reported here were to:

a) define a method for estimating the proportion of fatalities within buildings due to secondary fires resulting from external process fires (noting that the scope of this project is limited to dwellings and typical office buildings);

b) assess the requirement for more detailed analysis of the effects of blast and flame penetration into buildings during flash fire events.

1.3 Methodology

The study was broken down into a number of distinct tasks as described below:

Task 1: Identification of key modelling issues

The key modelling issues in the determination of fire effects on buildings and their occupants are identified. Thus each of the following are considered:

- properties of hydrocarbon process fires (intensity, duration etc.);
- proximity of the fire to the building and whether heat transfer is by radiation alone or else the building is engulfed or impinged upon by flames;
- range of building types and their construction materials;
- definition of ignition criteria (piloted or non-piloted, radiative or convective heat transfer, effect of material thickness etc.);
- fire spread mechanisms after ignition;
- modes of escape from different building types;
- effect of fire brigade intervention;
- building ventilation rates and gas ingress.

Task 2: Evaluation of direct fire effects on buildings

In practice, process fires are likely to produce direct effects (gas ingress, blast, flame penetration) on buildings and their occupants as well as producing secondary fires. The severity of these effects is evaluated and consideration given to their significance within flammables risk assessments. Related fire effects which may increase fatality levels include the following:

- minor blast damage from the weak deflagrative effects of flash fires (window breakage etc.);
- flame penetration into buildings (through open windows or doors, or those damaged by heat or blast effects);
- gas ingress to buildings (or well-ventilated parts of buildings) and effect of internal explosions;
- radiative heat transfer to occupants through windows.

The report assesses the availability and applicability of simple methods for evaluating the direct effect of blast and flame penetration on building occupants. The value of more detailed modelling of these direct fire effects is considered.

Task 3: Definition of ignition criteria for selected building types

Many data are available on the ignition of building materials, whether based on laboratory or larger scale experiments. This data has been used in developing models for ignition of individual materials, or used in larger scale studies which consider the spread of fires to and between buildings. Some work has also been done in the assessment of fire spread after natural disasters.

Ignition and the subsequent spread of fire within a building is dependent on a wide range of factors such as material properties, proximity of combustible building components and the intensity and duration of the exposure to the fire event. Based on a review of the identified literature, criteria are developed relating the probability of a secondary fire developing in a building to the properties of the process fire.

Task 4: Definition of proportion of occupants escaping from secondary fires

Having obtained criteria for the likelihood of a secondary fire developing in a building, the proportion of people escaping from the building is considered. Thus a review of literature and data relating to escape from building fires has been undertaken. Based on interpretation of incident data, an estimate of the probability of people escaping from secondary fires is produced. Modifications are made to this data through reference to guidance relating to fire safety design in buildings.

Task 5: Implementation of method within risk assessment studies

Having defined the method for evaluating the effects of process fires on buildings and their occupants, consideration is given to its implementation within flammables risk assessments.

The method is evaluated against the characteristics of selected process fires, including those for a typical flash fire. The sensitivity of risk assessment to any assumptions or uncertainties in the method is determined.

1.4 Report outline

Section 2 identifies the key factors determining effects of fire on building occupants. It also outlines and illustrates the process adopted for the development of the model.

Section 3 discusses the direct effect of flash fires on buildings, including the influence of blast damage, flame penetration and gas ingress.

Section 4 investigates the ignition of buildings and the development of secondary fires. A review of ignition modelling is outlined and a framework for modelling the ignition of buildings and the development of secondary fires is presented.

Section 5 assesses the proportion of occupants escaping from secondary fires. A review of human behaviour in evacuation is outlined, and key issues are discussed.

Section 6 outlines the application of the proposed model within risk assessment studies, and also evaluates the sensitivity of the proposed model to the key input parameters, considering occupant response and building type.

Section 7 summarises the key findings of the study and provides a recommended approach to the modelling of effects of flash fires on building occupants. It also outlines any significant remaining uncertainties in the modelling and discusses how these may be addressed.

2. KEY MODELLING ISSUES

2.1 Factors determining effects of fire on building occupants

The factors determining the effects of fire on building occupants can be divided into two areas: factors relating to the characterisation of the fire incident and factors relating to the response of people exposed to the fire incident.

<u>Fire incident</u>

- Fire intensity; the higher the incident heat flux to which the building is exposed, the greater the likelihood of secondary ignition of the building.
- Incident duration; the longer the incident duration, the higher the thermal dose to which the buildings are exposed, and therefore the higher the probability of secondary ignition.
- Type of fire incident; if the building is engulfed, multi-point ignition may occur, i.e. all elevations of the building are exposed to the incident flux. Alternatively, single point ignition would occur when only one elevation of the building is exposed to a distant fire source, e.g. pool fire or jet fire.
- Speed of incident; the more sudden the incident, the less time building occupants have to respond to the incident.
- Construction of the building; if the building is constructed of combustible materials the probability of secondary ignition will be high. Also the presence of unprotected areas in the external envelope will increase the probability of secondary ignition of the interior of the building.

<u>Response to the fire incident</u>

- Occupant characteristics; the mobility of the building occupants, and their behavioural characteristics, will have an important effect on their response and evacuation time for an external fire event.
- Occupant education and awareness, i.e. the actions which occupants are trained to take in the event of an external fire.
- Pre-warning, i.e. whether the occupants have been pre-warned of an incident, therefore reducing the information gathering phase of evacuation behaviour, and hence reducing the pre-movement time.
- Occupant activities; the occupant's behaviour at the time of the incident will influence their reaction to the incident.
- Use of building (dwelling or office). If the occupants own the building at risk, they may be reluctant to evacuate the building and they may also be involved in non-evacuation activities, e.g. fighting the fire. Alternatively, office occupants, who have less of an association, may evacuate more quickly.
- Time of the day; occupants who are asleep when the fire first affects them will have a slower response time to evacuation than occupants who are awake and fully alert.
- Fire brigade intervention; this may assist in the evacuation of occupants from a building fire.

All the factors outlined above have been incorporated within the proposed model to varying degrees. The degree to which each factor has been incorporated is related to the considered influence of that factor on the probability of fatality of building occupants due to an external fire event.

2.2 Framework for modelling effects of fire on building occupants

The framework for modelling the effects of fire on building occupants is illustrated in Figures 2.1 and 2.2. Figure 2.1 provides the framework for estimating the probability of secondary fires, and Figure 2.2 provides the framework used to determine the probability of fatality of an occupant given that a secondary fire has occurred. The flow charts illustrate both the framework of the model and the source of input for each event.

Note that, before undertaking the assessment outlined in Figures 2.1 and 2.2, the possibility of fatalities due to direct fire effects must be considered. These direct effects include blast damage, gas ingress (and thus internal explosions), radiative transfer to occupants through windows and flame penetration into buildings (through open or broken windows and doors). These effects are discussed in Section 3.

Having determined the significance of direct fire effects, and in particular whether flame penetration occurs, the probability of secondary fires is estimated. The output from the flash fire model, given in terms of incident heat flux and duration of the incident, is input to the model, which determines whether secondary ignition will occur, either of the exterior (i.e. cladding, refuse, vegetation) or of the interior of the building (i.e. furnishings, finishes etc.). Ignition of the interior is also influenced by transmission of radiation through the glazing system. If the incident heat flux is significant, failure of the glazing may occur, in which case 100% of the heat would be transmitted. If ignition of the interior of the building occurs, the ability of the fire to escalate is related to the information outlined in UK fire statistics (Home Office, 1995), which is further discussed in Section 4.4.6.

The output from the secondary ignition model provides the input to the building evacuation model for determining the probability of fatality due to secondary ignition (Figure 2.2). Single point ignition refers to a fire incident where the radiation from a remote fire source only affects one side of the building, e.g. a pool fire. Multi-point ignition refers to a fire incident where heat transfer effects more than one elevation, e.g. a flash fire may totally engulf the building, therefore exposing all elevations of the building to heat transfer from the flame.

Information provided in the DD240 Fire Safety Engineering in Buildings document (BSI, 1997) gives guidance on the probability of fire spread beyond the room of origin, which has been determined from UK fire statistics. Whether occupants attempt to evacuate their building is a complex issue; various case studies have therefore been used as guidance, to determine the portion of occupants attempting to evacuate. These case studies are outlined in Section 5.2.2. Whether occupants are awake or asleep when first affected by the fire will affect their pre-movement time.

The proportion of fatalities for the various fire incidents is estimated using a deterministic analysis, involving fire and evacuation models. Discussion of the deterministic model is outlined in Section 5.3.

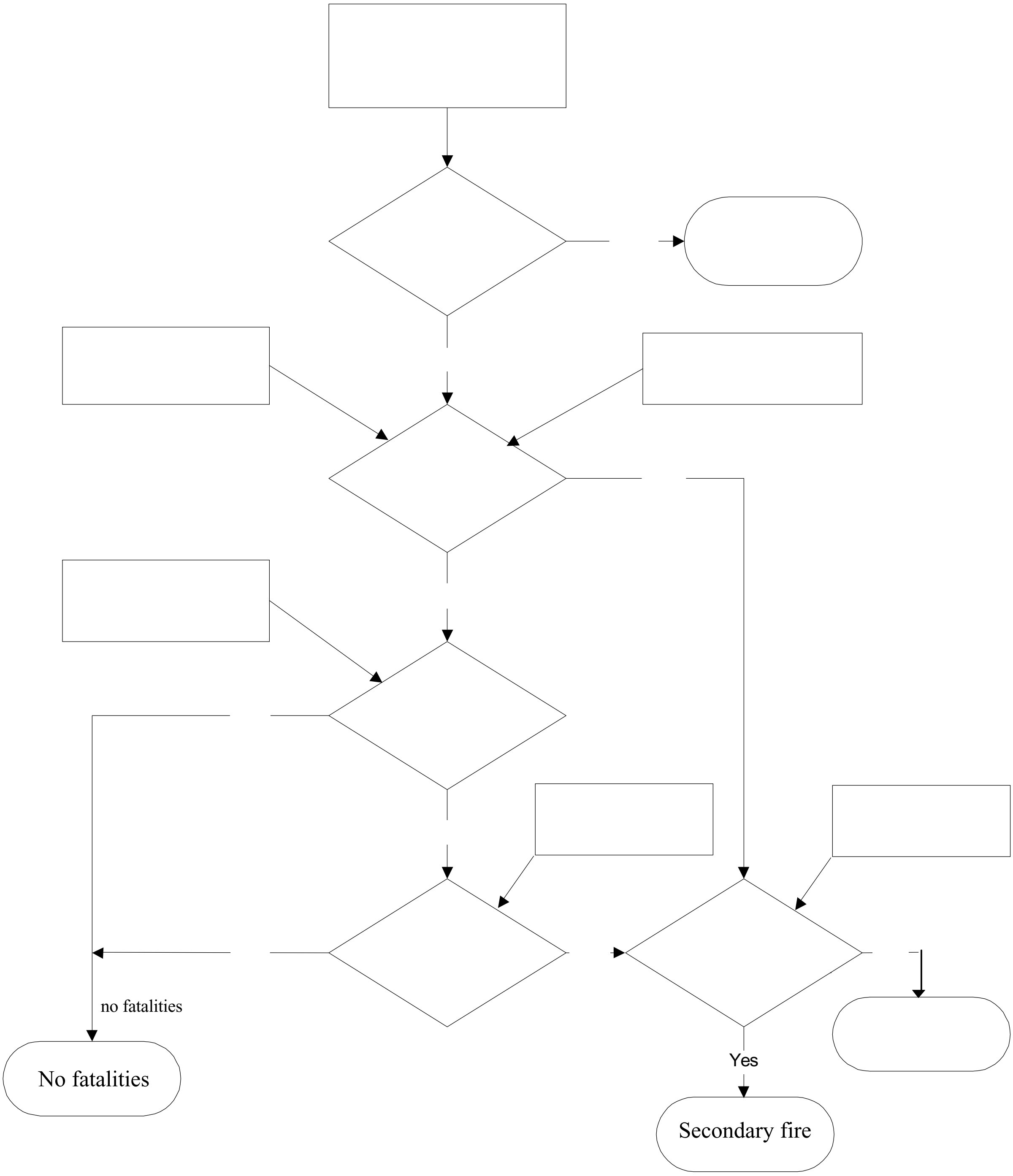

Figure 2.1 Sub-model framework for determining occurrence of secondary fires

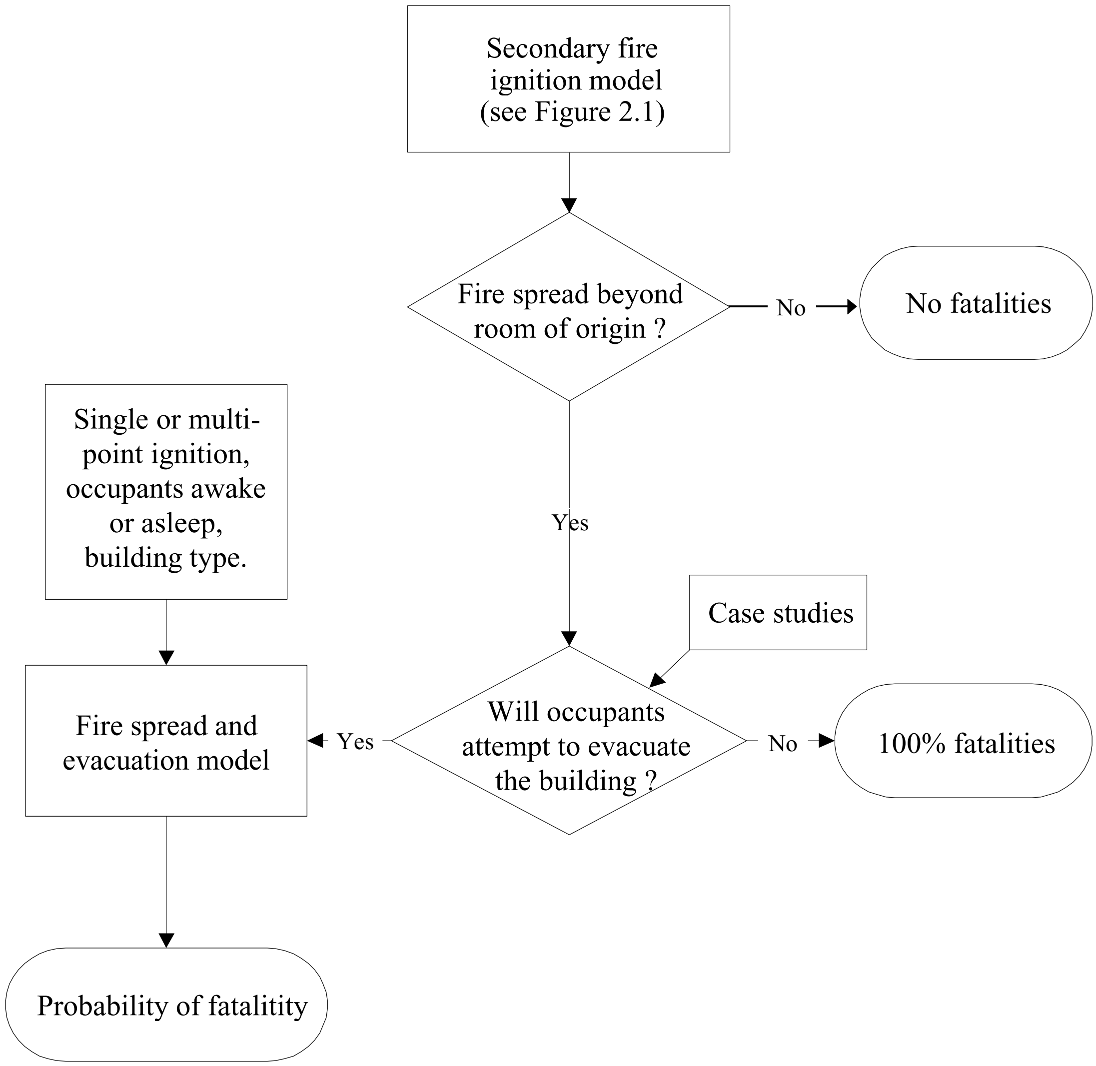

Figure 2.2 Sub-model framework for determining probability of a fatality due given a secondary ignition fire

3. DIRECT EFFECTS OF FLASH FIRES ON BUILDINGS

3.1 Flame penetration

3.1.1 Blast effects on windows

Jeffries et al (1997) have assessed the fatality of building occupants subject to blast loads and have considered the failure probability of glass using the method proposed by Mainstone (1971). Failure pressures are dependent on the area and aspect ratio of the window and the thickness of the glass. For a single sheet glass window with an area of $2m^2$ and an aspect ratio of 1 (which is worst-case in terms of breakage), Mainstone gives failure pressures of approximately 10 to 60 mbar for “24oz to ¼ inch” panes. The failure pressures rise to between 20 and 100 mbar for bonded double glazing units. These failure pressures correspond to a pulse duration of 1 second, which is considered to be same order of magnitude as the pulse duration of flash fire events. Mainstone also considers the effect of variation in the pulse duration on failure pressures; increasing the duration from 1 second to 10 seconds only reduces failure pressures by approximately 20%.

Flame-generated overpressures produced during flash fire events were measured during the Maplin Sands trials and found to be less than 1 mbar for all LNG and LPG releases (Blackmore et al, 1982). These overpressure levels are consistent with flame speeds of order 10 m/s, which are typical of the combustion of gas clouds over flat unobstructed regions; the Maplin Sands trials were conducted on mud flats with the only obstructions being sparsely located instrument pontoons. Thus comparison with Mainstone’s predicted failure pressures would suggest that the blast produced by a flash fire should not cause windows to fail.

However, the overpressure within a flash fire may not always be as low as that observed during the Maplin Sands trials due to presence of obstructions within the flammable cloud. Stock & Barth (1991) correlate overpressure with flame velocity within a burning gas cloud. Although the prediction of overpressure and duration within an explosion is highly complex, their analysis indicates that an increase in flame speed to 40 m/s could result in an overpressure of around 20 mbar. Such an overpressure would be sufficient to cause failure of windows. Rew et al (1997) have developed a model for flash fire flame propagation and suggest that, for energetic releases or releases containing sparse obstructions typical of chemical process sites (but not highly congested plant areas), flames may reach speeds of 40m/s. Such predictions are to be validated in a series of flash fire trials to be undertaken as part of a collaborative project (CERC, 1999). Thus there is a requirement for more detailed assessment of flash fire events with high flame speeds. Such events may not produce blast damage sufficient to be classified as vapour cloud explosions (VCEs) but may still damage buildings sufficiently to allow flame penetration and subsequent occupant fatalities.

3.1.2 Thermal effects on windows

Flame penetration into buildings may occur through open windows or doors, or those damaged by heat or blast effects. Even if blast effects on their own are not sufficient to cause failure of windows, exterior fires may still penetrate building envelopes via a number of pathways to become interior fires and one pathway is through windows and other glazed openings that have been broken by fire induced stresses.

Most of the previous research into the performance of glazing systems has addressed glass exposure to interior fires, not to exterior fires. The distinction is in the conditions to which the window is exposed. For an interior fire, a layer of hot, buoyant gases forms beneath the ceiling and descends, subjecting the inside of the window to a two layer convective and radiative environment. For an exterior fire, the window is subjected to a fairly uniform heat flux.

Research by Mowrer (1997) to analyse window breakage induced by exterior fires considered a wildland or other exterior fire approaching a building from some distance, such that the target building envelope is exposed to a uniform radiant heat flux (but of relatively low intensity compared to flash fire events). This research focused on the exposure of the exterior of window assemblies. The heat flux absorbed by the glass causes the exposed glass to heat up, while the shielded glass border remains cool. With sufficient heating, the thermally induced stresses exceed the yield stress of the glass and the glass cracks.

Mowrer found that single-pane wood frame windows failed at fluxes greater than 7 kW/m^2. The heat load at failure had an average value of 0.96 MJ/m^2 for the upper light and 0.77 MJ/m^2 for the lower light. The corresponding ranges for window failure were between 0.44 and 1.67 MJ/m^2 for the upper light and 0.42 and 1.23 MJ/m^2 for the lower light. It was noted that there was a slight trend towards lower heat loads at higher heat fluxes, although the scatter in the data made this observation inconclusive. The question of whether the panes of a broken window will fall out after it breaks remains unanswered. In the experiments conducted for this program, windows tended to remain in place after fracturing, but field experience suggests that broken windows frequently fall out.

Research undertaken by FRS (Shipp, 1991) relating to fire spread between adjacent caravans, also gave some indication of the performance of glazing. Although plate glass in a window can absorb some 40 to 60% of the radiation from a building fire, it cannot be relied on to afford protection to the contents of the room as large areas are liable to crack and fall out. No figure of a maximum 'safe' intensity for glass can be given with confidence since such variable factors as restraint at the edges and stresses in the glass itself affect its behaviour. Therefore, Shipp recommends that the worst case of immediate cracking and falling out must be assumed. A summary of the results from the study suggests that single pane wood frame windows always failed at heat fluxes above $10kW/m^2$ and did not fail at heat fluxes of less than $7kW/m^2$. The unexposed (inside) panes of double glazed wood frame windows failed in all tests in which imposed fluxes ranged from $10kW/m^2$ to $18kW/m^2$. However, it should be noted that, in the FRS study, the glazing elements would have been exposed to low incident heat fluxes for a long duration, which is in contrast to most flash fire events where the incident duration is short, and the incident heat flux is high. Therefore, the validity of the above values for the loss of integrity of the glazing systems may be misleading in the present context.

Previous analysis provided by Rew et al (1997) suggests that doses of up to 43,000 TDU (thermal dose unit $(kW/m^2)^{4/3}$ s) may occur at the centre of a flash fire, falling to 3200 TDU at the edge of the cloud. The corresponding exposure duration are approximately 15 seconds at the centreline of the cloud and 4 seconds at the edge of the cloud, giving equivalent heat loads of 5.9 MJ/m^2 and 0.6 MJ/m^2, respectively. However, the thermal doses provided by Rew et al (1997) were derived from CFD analyses, which were undertaken primarily to study flame propagation rather than heat transfer. Internal heat flux measurements taken during the Coyote trials (CCPS, 1994) provided heat load estimates of the order of 0.5 MJ/m^2, suggesting that the higher values provided by the CFD analyses are pessimistic. However, even if the heat load within a flash fire is as low as 0.5 MJ/m^2, comparison with the data of Mowrer (1997) suggests that some or all windows of a building engulfed within a flash fire will fail.

3.1.3 Effects of flame penetration on building occupants

As noted in Section 3.1.2, flame penetration may occur through open windows or doors or through windows that fail as a result of thermal damage, blast effects or a combination of both. Assuming that a window is open or fails, the effect on building occupants will depend on the extent to which flames enter the building and on how close the occupants are to the window.

During the day it might be expected that some of the occupants may actually be at the window, watching the growth of the flammable cloud (which appears as a mist for releases of liquefied gases). If windows break or are open, then it is reasonable to assume that the effects of flame penetration on these people will be the same as if they were unprotected by the building and engulfed in the flash fire, i.e. they would have a 100% probability of fatality. For people not adjacent to the window, the direct effects of flame penetration are not so easily defined. No published research on the penetration of flames from flash fires into buildings has been identified. There are some events which produce similar flame effects (e.g. venting of flames from explosions or from backdraft events). However, the processes by which these flames are produced are not similar to flash fire events.

Thus further detailed assessment would be required to resolve fully the effects of flame penetration on building occupants. Note that the analysis that follows in Sections 4 and 5 relates to the effects of secondary fires only and does not consider direct flame penetration effects on building occupants.

3.2 Gas ingress and internal explosion

The issue of gas ingress to buildings has been considered, in relation to the ignition of flammable gas clouds, by Spencer & Rew (1997). A simple model for the prediction of gas ingress into buildings (Davies & Purdy, 1986) was used to assess whether flammable concentrations would build up in dwellings for typical LPG release scenarios. It was concluded that instantaneous releases (of up to 200 tonne) would not have a sufficient duration to produce flammable concentrations (i.e. mean concentration above the lower flammable limit) within buildings with typical ventilation rates (2 air changes per hour). However, continuous releases are capable of creating flammable concentrations within buildings. For example, for an external gas concentration of 3.5%, it would take 30 minutes for the mean concentration within a building to reach the lower flammable limit (2.1% for LPG).

Such a model could be used to determine whether gas ingress to buildings could result in internal explosions and would be consistent with that used for modelling ignition probability of flammable gases. If an explosion occurred it would be conservative to assume that 100% of occupants are fatalities. The weakness in using such an approach is that the gas ingress model uses an average building ventilation rate whereas in practice there will be a distribution of ventilation rates, with ventilation rate varying with time of year, with external wind speed, between different buildings and between rooms within buildings. The model also assumes uniform mixing within the building, whereas, if mixing is incomplete, flammable pockets of gas may occur within a room before the mean concentration within the room reaches the lower flammable limit. For these reasons, the model may be non-conservative for certain scenarios.

3.3 Direct heat transfer to occupants

Even if there is no flame penetration into a building, occupants may be exposed to heat radiated through windows, at least during the day. At night it is assumed that curtains would block transmission of radiation, noting that the effect of secondary fires caused by ignition of curtains is considered separately in Sections 4 and 5.

Glass does not transmit 100% of the infrared radiation incident upon it. Hymes et al (1996) consider the transmission of thermal radiation through normal window glass based on a report by Wenzel & Spitzer (1955). They suggest that, for typical pane thicknesses, of 2 to 3 mm, approximately 70% of infrared thermal radiation is transmitted. Shipp (1991) suggests that the transmission factor for single and double pane glazing systems is 0.82 and 0.62, respectively (the transmission factor is the proportion of incident heat flux transmitted through a particular glazed component). In the analysis described below, the values provided by Shipp are used as they are the more conservative.

As discussed in Section 3.1.2, the thermal dose to an object within a flash fire, based on CFD analyses by Rew et al (1997), ranges from 3200 to 43,000 $(kW/m^2)^{4/3}s$, although the upper end of this range is considered pessimistic when compared with heat transfer measured within flash fire trials. The thermal dose of 3200 $(kW/m^2)^{4/3}s$ comprises 2800 $(kW/m^2)^{4/3}s$ of radiative and 400 $(kW/m^2)^{4/3}s$ of convective heat transfer. Thus, for a single pane window with a transmission factor of 0.82, the thermal dose received by a person standing adjacent to the window would be 2100 $(kW/m^2)^{4/3}s$, assuming a 4 second event duration. This thermal dose is just above that required to cause 50% fatality for an average population (1800 $(kW/m^2)^{4/3}s$) as defined by Rew (1997). Figure 3.1 shows the variation in dose received as the distance is increased from the centre of a $2m^2$ window. It can be seen that, at 0.7m, the thermal dose has dropped below 1000 $(kW/m^2)^{4/3}s$, which is the Dangerous Dose level defined by Hockey & Rew (1996) and which is equivalent to fatality levels of approximately 1% for an average population. This would suggest that, unless people are standing at the window, the effect of transmission of thermal radiation through windows can be neglected. If people are standing at the window then window breakage and flame penetration are likely to be the more serious event.

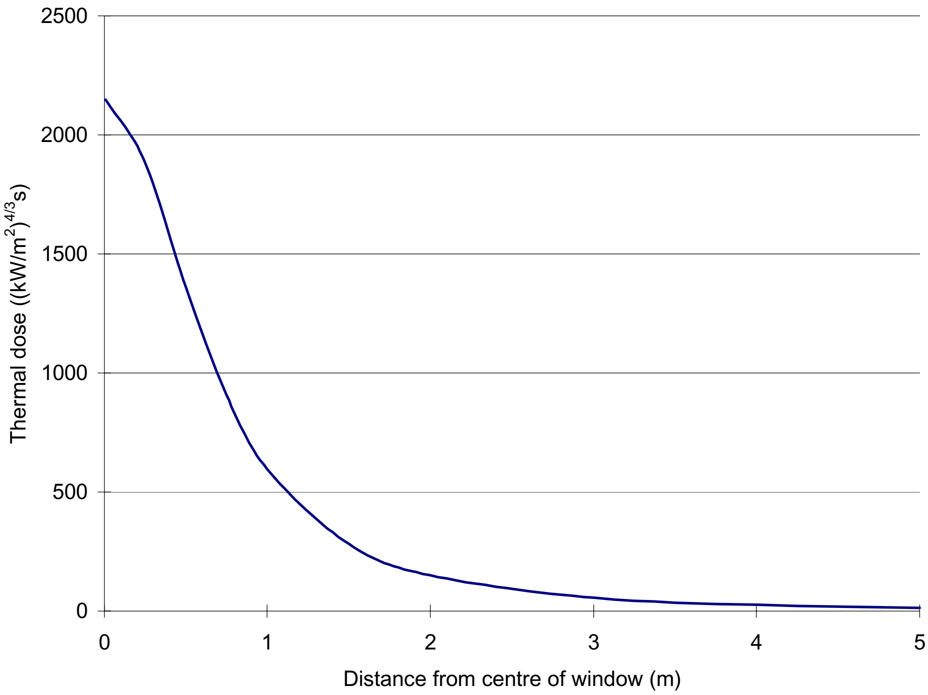

Figure 3.1 Reduction in incident thermal dose with distance from centre of window

4. IGNITION OF BUILDINGS AND DEVELOPMENT OF SECONDARY FIRES

4.1 Introduction

Exterior fires can penetrate a building envelope via a number of pathways to become interior fires. The main pathway is through unprotected areas. The term 'unprotected area' is often used in the assessment of fire spread between detached buildings and is defined as an area with limited or no fire resistance. Unprotected areas include glazed areas, external doors, roof coverings and service penetrations.

Fire transmission from the exterior to the interior of a building is a significant aspect of wildland-urban interface fires, earthquake-induced fires and other conflagrations in developed areas (Mowrer, 1997).

Ignition and the subsequent spread of fire within a building is dependent on many factors such as material properties, proximity of combustible building components and the intensity and duration of exposure to the fire event.

The following section reviews ignition criteria and data for building materials. A model is then developed for the ignition and development of secondary fires within selected building types (i.e. dwelling, office), taking due consideration of the following:

- secondary ignition of the exterior of the building;
- mitigation provided by glazing systems to exterior fires;
- fire spread from exterior to interior;
- ignition of the interior;
- ability of secondary fire to escalate.

4.2 Models and data for ignition of building materials

4.2.1 Review of ignition modelling

A flash fire, or other type of process fire, may cause direct ignition of building materials. Alternatively ignition may occur to items in close proximity to the building which may put the building occupants at risk. Janssens (1991a) describes the process of ignition as follows. When a combustible material is exposed to an external heat flux (radiative, convective or a combination), its surface temperature starts to rise. The temperature inside the material also increases with time, but at a slower rate. Provided the net heat flux into the material is sufficiently high (i.e. above a critical heat flux), eventually the surface temperature reaches a level at which pyrolysis begins. The fuel vapours generated emerge through the exposed surface and mix with air in the boundary layer. Under certain conditions, the concentration of this mixture of fuel vapour exceeds the lower flammability limit and ignites.

The initiation of combustion as described above is called 'flaming ignition'. For some materials, or under certain conditions, combustion is not in the gas phase but in the solid phase. In such cases no flame is observed and the surface glows. This phenomenon is termed glowing ignition. The ignition process depends on factors such as temperature, composition and the velocity of the surrounding gases and the magnitude and spectral quality of the incident radiation. In addition to those external factors, internal factors such as thermophysical properties (i.e. thermal conductivity, density and specific heat capacity) and moisture content are considered to control the ignition process. The following definitions are introduced to distinguish between various types of ignition:

Piloted ignition: Initiation of flaming combustion in the presence of a pilot flame, e.g. incandescent particles, flying brands etc.

Spontaneous ignition: Initiation of flaming combustion without a pilot flame.

Sustained ignition: Initiation of flaming combustion, with or without a pilot flame, but persisting even after the external heat source is removed.

Most theoretical and experimental investigations have concentrated on ignition brought about by radiative heat transfer. The original impetus for this followed the realisation that thermal radiation levels from a nuclear explosion would be sufficient to ignite materials at great distances from the blast centre. However, more recently it has become apparent that radiation is also of fundamental importance in the growth and spread of fire in many situations, such as external fire spread between detached buildings. The high level of interest in radiative ignition has been maintained although ignition by convective heat transfer cannot be neglected.

In the case of flash fires, i.e. direct flame impingement, piloted ignition is assumed to be the predominant ignition mode. In the case of remote fires, i.e. pool or jet fires, fire brands from burning buildings and vegetation are assumed to act as the pilot flame. The exception is for ignition of internal materials through glazing, where brands or flame are unable to reach the material. In this case spontaneous ignition is assumed to be the predominant ignition mode.

A detailed review of the various ignition models is presented in Appendix A. The following paragraphs give a summary of this review, outlining the research undertaken, the various materials tested, and the different approaches to the problem of ignition prediction. The review focuses on piloted ignition, for which most research has been conducted.

A considerable number of studies of piloted ignition of wood and plastic products have been reported in the literature. The objective of most of these studies was to relate the time taken to ignite the material, when subjected to various irradiance levels, with the thermal properties of the material, and to determine the irradiance below which piloted ignition no longer occurs. In the following review, emphasis is on ignition models which can practicably be used in conjunction with models for flash fires and other process fires.

The first published study into the ignition characteristics of materials exposed to various incident fluxes was undertaken by Lawson & Simms (1952). The focus of their research was to estimate the separation distance required to prevent external fire spread between detached buildings, which is a key component in fire regulations worldwide. As a result of an experimental program, Lawson & Simms (1952) deduced a minimum heat flux required for ignition, termed the critical heat flux (q_{cr}). They also developed a relationship between the incident heat flux (q_e) and the time to ignition (t_{ig}). Values of q_{cr}, q_e and t_{ig} were derived for various wood species, for both piloted and spontaneous ignition.

Following the work by Lawson & Simms, further studies were undertaken which adopted a similar approach, e.g. Buschmann (1961), Koohyar et al (1968), Wesson et al (1971), Magnusson & Sundstrom (1981) and Janssens (1991b). All resulted in similar relationships, with increased complexity to accommodate the complex thermal and chemical processes that exist at ignition.

Smith & Satija (1981) introduced the Flux Time Product (FTP) concept to predict the time to ignition of materials subjected to an external flux. The FTP is characteristic of the material, which is derived by experimental means. Silcock & Shields (1995) used dimensional analysis to determine which dimensionless groups are relevant to piloted ignition. They proposed a protocol for the analysis of ignition data for combustible materials based on the Flux Time Product.

The research mentioned above focused on combustible construction materials used in typical building stock, i.e. timber and plastics. Wulff et al (1973) developed a semi-empirical relationship to relate the performance of various fabrics to an incident heat flux over time, i.e. the ignition or melting time of the fabric. The issue of ignition of clothing and resulting fatality has been dealt with in detail by Hymes et al (1996), who refer to the research undertaken by Wulff et al.

The various models outlined above, and the results obtained from the various experimental programs, are similar in many respects. However, the practicality of the more complex relationships is limited, i.e. the input parameters required for the models, such as temperature at ignition (T_{ig}), Flux Time Product (FTP), are only available from experimental data. Therefore the earliest models developed by Lawson & Simms (1952) and Buschmann (1961) tend to be the most practical, despite also being the most empirical. Section 4.2.2 compares selected models and data from ignition tests.

4.2.2 Typical results for ignition of various materials

Tables 4.1 and 4.2 outline selected results of ignition tests on various materials.

Incident flux (kW/m^2)	Time to ignition, t_{ig} (s), for various material types			
	Particleboard[1] (thermally thin)	Spruce[1] (thermally thick)	PVC (extruded) 3mm (grey)[2]	PVC (pressed) 5mm (white)[2]
50	40	15	26	55
40	53	30	43	95
30	82	60	71	209
20	166	625	184	332
15	400	~1200	655	653
10	(no ignition)	(no ignition)	(no ignition)	(no ignition)

1. Mikkola & Wichman (1989)
2. Silcock & Shields (1995)

Table 4.1 Typical results from ignitability tests for solid materials

Incident flux (kW/m²)	Time to ignition, t_{ig} (s), for various material types[1]			
	Cotton (white)	Cotton (white) Fire Retardant[2]	Polyester / Cotton[3] (65/35)	Polyester / Cotton[3] (50/50)
198	3	2	3	6
118	7	4	8	15
87	12	6	15	26
70	19	8	26	43
52	41	13	(no ignition)	(no ignition)

1. Hymes et al (1996).
2. Fire retardant in this context refers to the resistance to flame spread and not the resistance to ignition. This explains why ignition of fire retardant cotton occurs before the untreated cotton.

Table 4.2 Typical results from ignitability tests for fabric materials

From the evidence outlined in Table 4.1, secondary ignition of typical building materials only occurs at incident heat fluxes greater than 10kW/m² (critical flux). Considering the likely exposure duration to a typical flash fire event, i.e. of order 5 seconds, secondary ignition of solid materials will only occur at incident heat fluxes greater than 50kW/m², and probably of the order of 100kW/m², although data is unavailable to verify this figure. Note that the maximum incident heat flux used in the experimental research relating to ignition of building materials outlined in Section 4.2.1 and Appendix A is 80kW/m². The reason for this maximum incident heat flux is because the research relates to fire spread between detached buildings. Furthermore, there is the practical difficulty in working with high heat fluxes, i.e. greater than 100kW/m².

Table 4.2 outlines the time to ignition of various fabrics exposed to an incident heat flux. The maximum heat flux tested is 198 kW/m². From the results in Table 4.2, for a typical flash fire event, i.e. of order 5 seconds exposure duration, secondary ignition of the fabrics considered will only occur at fluxes greater than approximately 90 kW/m².

The information outlined in Tables 4.1 and 4.2 for incident fluxes of 50 or 52 kW/m², suggests that, for the range of materials presented, ignition occurs at similar exposure times for fabrics as for solid materials. Intuitively it would be expected that fabrics were more easily ignited than solids, although the ignition times could possibly be explained by increased heat loss via the unexposed face for fabrics causing the material to take a longer time to reach its ignition temperature. However, this effect should not be as significant for high intensity incident heat fluxes, over short duration, i.e. as would be expected in a flash fire event.

4.2.3 Choice of ignition model

Many of the models for the prediction of piloted ignition can only be used for materials for which experimental studies have been undertaken, i.e. they require input data such as temperature at ignition, Flux Time Product etc. The earliest models developed by Lawson & Simms (1952), and Buschmann (1961), appear to be the most flexible, i.e. if required, the model constants can be derived from the material properties of thermal conductivity (k), material density (ρ), and the specific heat capacity (c), which are easily obtainable for materials at ambient temperature. The model developed by

Janssens (1991b) also appears to be suitable. However it requires the heat transfer coefficient from the surface at ignition, h_{ig}, and material properties averaged between ambient and the ignition temperatures. Although the value of h_{ig} is difficult to calculate, the results of the experiments of Janssens (1991b) suggest use of a value in the range 30-36 W/m^2 K for the materials tested, which included hardwoods and softwoods.

Figure 4.1 compares the results of two ignition models for the exposure time period relevant to a flash fire, i.e. 1-5 seconds. The Janssens (1991b) model appears to underpredict the secondary ignition of the material, (i.e. overpredict the time to ignition) in comparison to the Lawson & Simms (1952) model. The results from experiments undertaken by Hymes et al (1996) for cotton and for a polyester/cotton mix (being the only ignition data identified for exposure duration of less than 5 seconds) are also plotted on Figure 4.1. Both models are conservative with respect to this data.

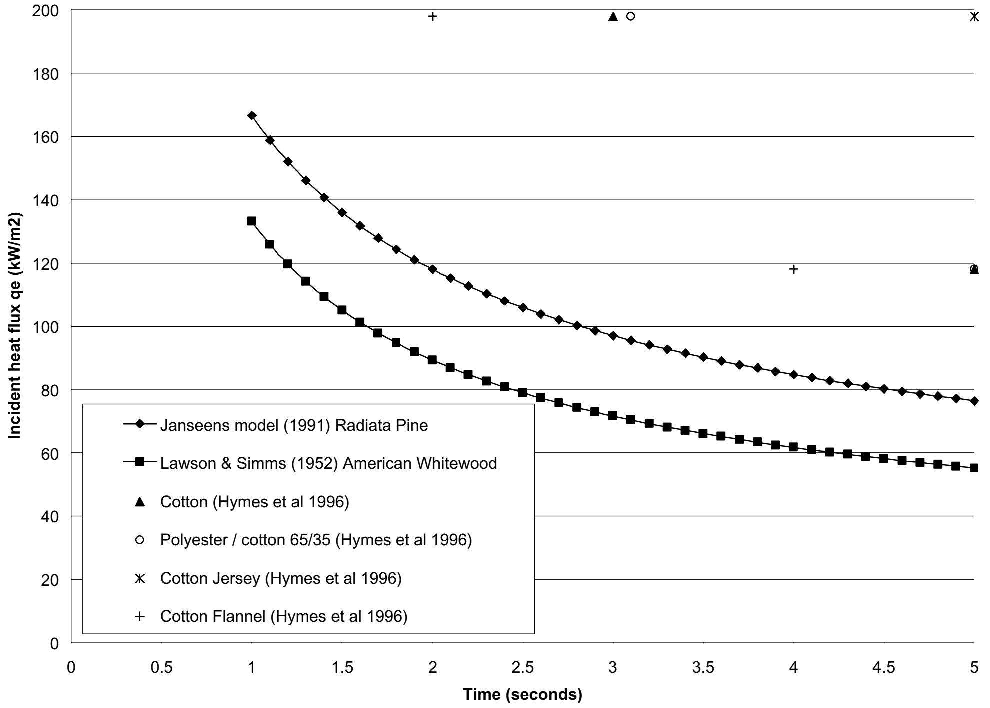

Figure 4.1 Comparison of t_{ig} for softwood materials and various fabrics, in the incident range 1-5 seconds

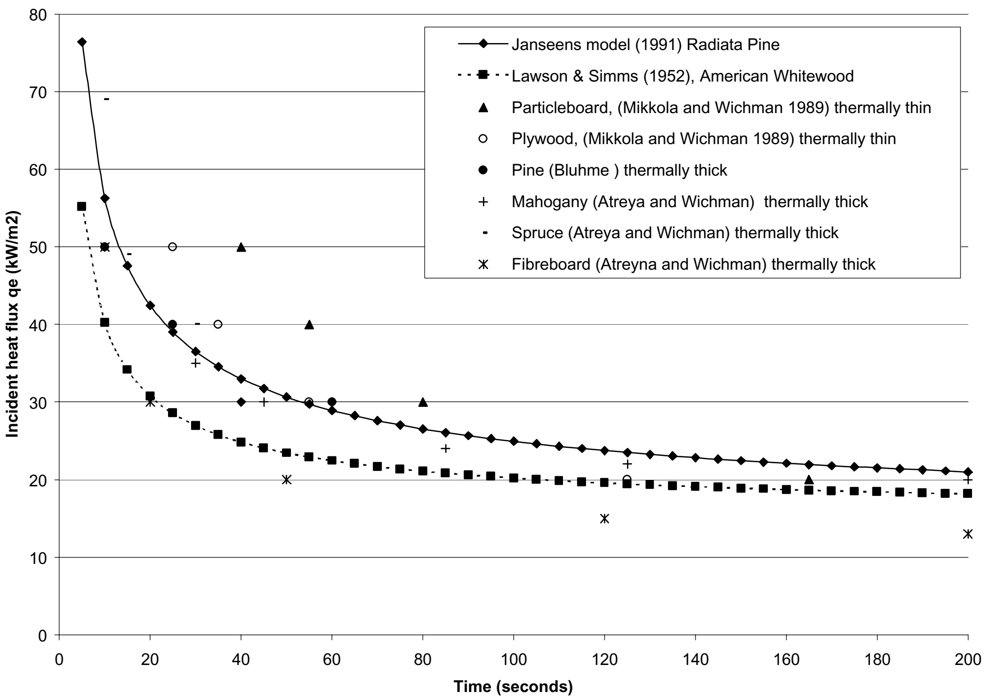

Figure 4.2 Comparison of t_{ig} for softwood materials, in the incident range 5-200 seconds

Figure 4.2 illustrates the results of the same models for exposure duration of between 5 and 200 seconds. This covers the range of data for which the models were developed, i.e. typically with fluxes of less than 80 kW/m^2. As can be seen from Figure 4.2, the incident flux for secondary ignition predicted by the models is similar for long exposures. Extension of the Janssens model has indicated that the critical heat flux for the material plotted is approximately 13.5kW/m^2. Similarly, the Lawson & Simms model gives a critical heat flux of 14.7kW/m^2. Both these values compare favourably with that adopted in the Building Regulations (Department of the Environment, 1992), UK, i.e. 12.5 kW/m^2.

Figure 4.2 shows that the Janssens model is a better fit to the data points plotted for the experiments presented by Mikkola & Wichman (1989), while the Lawson & Simms model is generally conservative with respect to the data.

Research undertaken by the Fire Research Station (Shipp, 1991) into the risk of fire spread between caravans resulted in some interesting findings. Materials such as the tyres of cars and other wood based products, all of which are likely to be found close to buildings, were found unlikely to ignite at irradiances below 15kW/m^2, and more generally 20kW/m^2, although wood may have done so at 12.6kW/m^2. Curtains exposed directly through an open window did not ignite at irradiances below 17kW/m^2. Results from the model developed by Wulff et al (1973), indicated similar values for curtain fabrics as the FRS study, i.e. polyester / cotton mixes, ranging from 15-20 kW/m^2.

It is proposed to use the model developed by Lawson & Simms (1952) to estimate secondary ignition. This choice is based upon the following considerations:

a) The Lawson & Simms model is generally conservative with respect to the data of Mikkola & Wichman (1989). For short duration exposures it is also conservative with respect to the data of Hymes et al (1996) for fabrics.

b) There is a lack of input data for more complicated models for building products, i.e. temperature at ignition (T_{ig}) and the Flux Time Product (FTP).

c) Current UK building regulations (Department of the Environment, 1992) refer to the Lawson & Simms ignition criterion in the estimation of fire separation distances between detached buildings, although this is for low incident heat flux, (less than 100kW/m^2), with long incident duration.

d) Lawson & Simms provide correlations for both piloted and spontaneous ignition.

It is noted that the Lawson & Simms (1952) correlation is the most empirical of the models considered. It is correlated for particular wood species and does not consider the thickness of the exposed material. In practice, the most easily ignited parts of the exterior of a building are softwood fixings and the most easily ignited parts of the interior are curtains. The Lawson & Simms model appears, from Figures 4.1 and 4.2, to be adequate for these materials. The thermal thickness of exposed material is not as important for short duration fire events, for which there is insufficient time for heat to be transferred away from the material. It is further noted that all of the models and data discussed in Sections 4.2.1 and 4.2.2 are for untreated or uncoated materials. However, as discussed by Janssens (1991a), most paints and varnishes under normal application have a negligible effect on the piloted ignition behaviour of wood.

4.3 Model definition

4.3.1 Event tree definition

The model takes the form of a simple event tree, as illustrated in Figure 4.3. The starting point of the event tree is the incident heat flux and exposure duration of the flash fire event. Ignition of the interior of the building due to a flash fire can occur by means of the following routes:

a) direct ignition of the interior by flame penetration;

b) ignition of the exterior of the building due to the incident, then fire spread from the exterior to the interior;

c) direct ignition of the interior by radiation through windows.

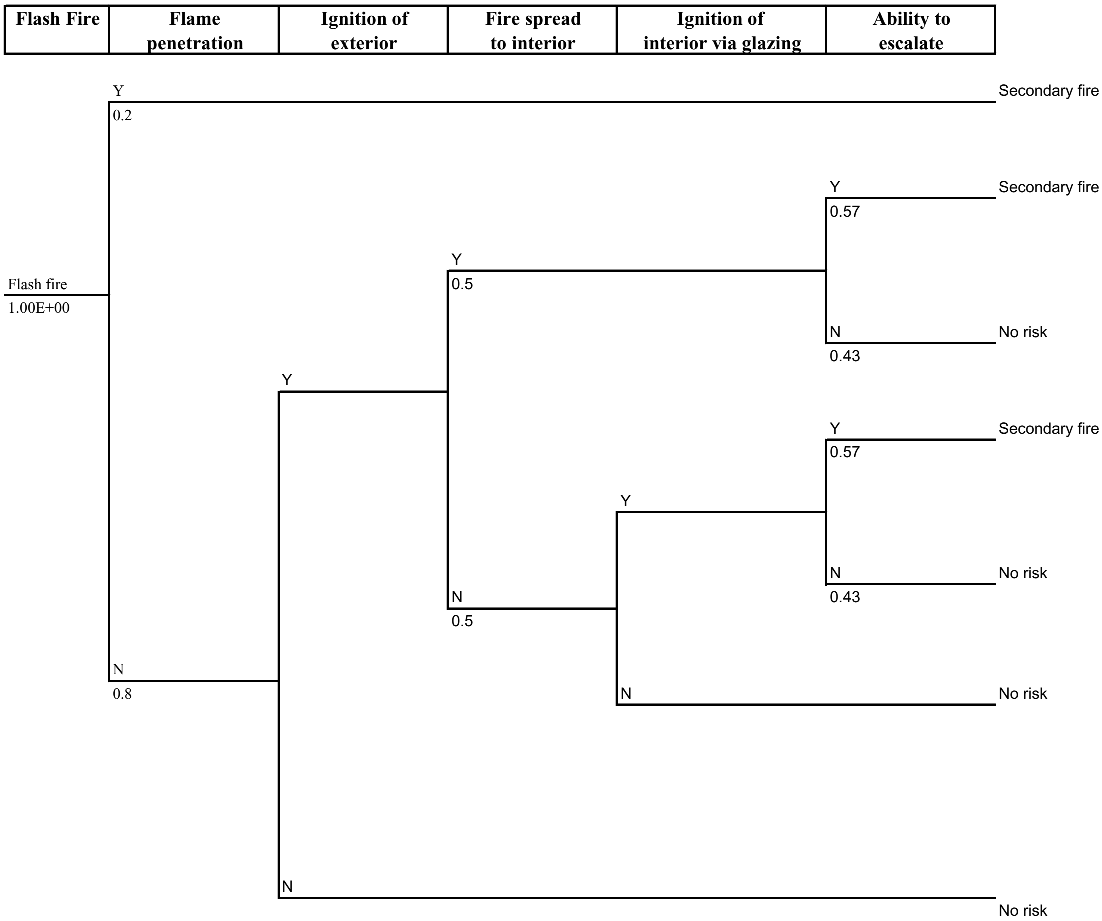

Figure 4.3 Event tree (dwellings) to estimate the probability that a secondary fire will develop

Table 4.3 outlines the assumptions made with regard to construction of the different building types. Note that the chosen materials are considered to be typical for the specified building types with regard to glazing and to provide worst-case ignition criteria in the case of interior and exterior materials. Further discussion of these assumptions is given in the following sections, which outline each event in detail. Typical results and a sensitivity analysis of the model are presented in Section 6.

	Building type	
	Dwelling	Office
Glazing (transmission value)	Single (0.82)	Double (0.62)
External material	Softwood	Refuse
Interior material	Softwood	Softwood

Table 4.3 Construction properties of the various building types

4.3.2 Flame penetration (Event 1)

Exterior fires can penetrate building envelopes via a number of pathways to become interior fires. One pathway is through open windows and doors. Another is through windows and other glazed openings that have been broken by fire induced stresses. This event is linked to the findings of Section 3

-, although the event tree only considers the contribution of flame penetration to ignition of interior materials and resultant secondary fires, rather than direct effects on occupants. As discussed in 3.1, the extent of flame penetration into a building cannot be determined using simple methods. However, it is reasonable to assume that some flash fire events will lead to secondary fires via this route. The probability of flame penetration leading to secondary fires has been assumed to be 0.2, noting that there is much uncertainty in the choice of this value, as there is in determining the direct effects of flame penetration on occupants. It is assumed that if ignition occurs due to flame penetration, then the resulting fire will always escalate.

4.3.3 Ignition of exterior (Event 2)

The output from a flash fire model, i.e. the duration of exposure to the incident and the incident heat flux, provides the input data used in the model for piloted ignition proposed by Lawson & Simms (1952), to determine whether the exterior of the building will ignite due to a flash fire. The model correlates the incident heat flux (q_e) required to cause ignition, with the critical heat flux (q_{cr}) of the material, and the incident duration (t_i). Thus ignition occurs if:

$$q_e > C_{ls}/t_i^n + q_{cr}$$

<u>Input</u>

- Heat flux intensity (q_e) and duration (t_i) from the flash fire model.
- Building type, either dwelling or office.

The choice of the building type will determine the type of external cladding, which in turn will determine the critical heat flux (q_{cr}) and value of C_{ls} for that material.

It is assumed that a dwelling may be clad in softwood, or that softwood joinery may be exposed, giving a critical heat flux, q_{cr}, of 14.7 kW/m^2, a value of C_{ls} equal to 118.4 kJ/m^{2}s$^{1/3}$ and an index n of 2/3 for piloted ignition. In the majority of cases, modern office buildings will not be clad in timber. The lowest critical heat flux for a material at the exterior of an office building is that for refuse (waste, rubbish), implying a critical heat flux, q_{cr}, of 15kW/m^2 (Shipp, 1991). Therefore, the same ignition model is assumed as for dwellings.

<u>Output</u>

- Conditional probability of ignition of exterior, i.e. whether exterior ignites or not. Thus p_1=1 for ignition and p_1 = 0, otherwise.

4.3.4 Fire spread to interior (Event 3)

Event 2 determines the probability of ignition of the exterior of the building due to an external fire. If ignition occurs to the exterior of the building, fire spread to the interior may occur by various means. For example, ignition of the soffit/fascia of a building may cause fire spread to the interior roof space and hence to the interior of the building. Another means of fire spread to the interior is the ignition of exterior doors or service penetrations on the external facade. Information on the probability of spread of fire from a burning part of the exterior of the building, i.e. exterior timber, roof covering etc., to the interior is limited. However, given the general position of exterior combustibles, i.e. at high level (soffit/fascia boards) in dwellings and not necessarily directly adjacent to office walls (rubbish/waste), there is no evidence to suggest that there is a high probability of fire spread to the interior of a building from a burning exterior item.

Since no information exists on the frequency of such an event, it is proposed that the probability of fire spread from the exterior to the interior, p_2, is assumed to be 0.50, which is considered to be conservative.

Output

- Conditional probability of fire spread to the interior, p_1=0.5.

4.3.5 Ignition of interior via glazing (Event 4)

As pointed out in Section 4.3.1, the issue of whether a window will lose its integrity in a fire situation, i.e. the cracked glass falls out, remains unresolved. At this stage it has been assumed that the integrity of the window will be maintained. The Lawson & Simms (1952) model is used to determine whether ignition of the interior occurs through windows, noting that the radiative flux must be reduced by the transmission factor, t_r, as defined in Section 3.3.

Input

- Heat flux intensity (q_e) and duration (t_e) from flash fire model
- Building type, either dwelling or office

Irrespective of the building type, it has been assumed that both dwellings and offices will contain timber products and fabrics. Since it is assumed that the glazing system maintains its integrity during a fire event, a pilot flame will be prevented from entering the building by the glazing system. Therefore piloted ignition cannot occur and the model parameters for spontaneous ignition are used. The critical heat flux (q_e) assumed for spontaneous ignition of softwood is 25.6 kW/m^2, with C_{ls} equal to 167.6 kJ/$m^2s^{1/5}$ and n equal to 4/5.

Output

- Conditional probability of ignition of interior, i.e. whether interior ignites or not. Thus p_4=1 for ignition and p_4 = 0, otherwise.

4.3.6 Fire escalation (Event 5)

Once ignition has occurred within the interior of the building, the ability of the fire to escalate is assessed. If the secondary fire does not escalate, there is limited risk to the occupants.

In order to determine the proportion of fires having the ability to escalate, reference was made to fire statistics published by the Home Office (1995). This table provided information on the percentage of fires in dwellings and other buildings that are confined to the item of ignition, for which cases it is assumed that the fire has not escalated. Therefore, it has been estimated that the probability that a fire, once started, will develop is 0.57 for dwellings, and 0.66 for other buildings.

Output

- Conditional probability of a escalated fire within the interior of the building. Thus p_5=0.57 for dwellings and p_5 = 0.66 for offices.

4.4 Model summary

The results of the above event tree analysis are input to the model described in Section 5, which then determines the likelihood of fatality for building occupants given that a secondary fire has occurred. The intermediate conditional probabilities for occurrence of a secondary fire can be summarised as follows:

Event description	Probability of secondary fire	
	Dwelling	Office
Flame penetration only	0.2	0.2
Heat load sufficient to ignite exterior, but not interior	0.43[1]	0.46[1]
Heat load sufficient to ignite exterior and interior	0.66[1]	0.73[1]

1. including flame penetration component

Table 4.4 Summary of probabilities of occurrence of secondary fires

5. PROPORTION OF OCCUPANTS ESCAPING FROM SECONDARY FIRES

5.1 Introduction

Once it has been determined whether the interior of the building will ignite during a flash fire event (see Section 4), the likelihood of fatality for building occupants can be estimated. This likelihood depends on the interrelationship between the following factors:

i) time for the occupants to evacuate that building, considering such factors as detection time, recognition time, response time and travel time;

ii) conditions to which the occupant is exposed within the building.

The information currently published on human behaviour in fires, and on how to calculate evacuation time, is acknowledged to be incomplete (BSI, 1997). In addition, the behaviour of people in building fires caused by an external event has not been sufficiently addressed and may be significantly different from the behaviour observed in building fires caused by an internal hazard. Therefore, for the purposes of this study, reasonable assumptions have been made where insufficient information is available.

5.2 Review of evacuation behaviour

5.2.1 General evacuation studies

The majority of published literature on the subject of evacuation behaviour is related to incidents for which the hazard is within the building and, therefore, for which the place of safety is deemed to be outside the building. The subject of this study is to establish the proportion of occupants who will escape from a secondary fire within a building, caused by a flash fire, i.e. for which the region outside the building may not necessarily be considered to be a place of safety. Therefore, the question of whether an occupant will attempt to escape from such an incident is unclear.

Incidents such as bushfires and fires caused by earthquakes are similar in some respects to secondary fires caused by a flash fire incident. However, to understand the information from these similar events, the differences that do exist must be highlighted:

a) In the case of bushfires, pre-warning is commonplace, e.g. from the weather conditions (hot, dry, low humidity, high wind speed), and warning by media and emergency services. Mechanisms of warning do not generally exist for flash fire events, and indeed are unlikely to be possible.

b) In the case of bushfires, the flame front is relatively slow moving. This is generally not the case in flash fire incidents.

c) A certain number of individuals may have experienced bushfires, or have knowledge of individuals who have experienced such events. This is not likely to be the case for flash fires.

d) Where earthquakes and bushfires are a realistic risk, occupants are educated in the actions to adopt in the case of such an event. This is generally not the case for flash fires.

e) In the case of earthquake events, fire is not the only hazard. This is in contrast to a flash fire event, were fire is the main hazard.

Research undertaken by Sanders (1998) highlighted the difference in human behaviour in office fires and in bushfires. In all fire instances in the experimental study (office buildings), people demonstrated a reluctance to fight the fire or remain in the area in a building fire emergency. In contrast, for bushfires 80% of the residents said that they remained with their property. By far the greatest reason for evacuating in the case of bushfires was being ordered to do so by police and emergency services.

A similar study into the experience of residents in a bushfire in Hobart, Tasmania in 1998 (Sanders, 1999), concluded that one of the determining factors in personal behaviour is household composition at the time of the bushfire. Personal safety, the safety of others and feeling able to defend the property were significant factors for all groups. From the small number of interviews with residents it appears that many of those who evacuated did so because they were concerned for vulnerable members of the household (babies, young children, elderly family members or pets) and because they provided the only means of transporting the others from the danger. Had they not been in that situation, the majority indicated that they would have remained with the house. For those who remained, the high confidence in their ability to defend the property and the perceived low level of threat to their own or others personal safety could be due to the presence of at least one other capable adult and the absence of vulnerable members of the household. The outcome of this research highlights how even just one factor, household composition, can make the prediction of evacuation behaviour highly complex.

A recent paper by Shepherd & Sime (1998) suggests that one of the key variables in the decision process of whether a building is to be evacuated due to an external hazard is 'place attachment' at an individual, social group, and community level (sometimes called 'home attachment'). Those with a strong place attachment are more likely to be reluctant to abandon their respective homes, because the home is somewhere to be protected and which affords protection. A home for most people is a psychological, social and physical shelter.

In the case of the Hanshin-Awaji Great Earthquake (Murosaki & Shao, 1998), 60% of respondents took evacuation measures of some kind. According to a similar investigation of action by citizens who live in regions susceptible to fire, conducted by the Japan Association for Fire Science and Engineering (1996), approximately 36% of people evacuated because their house started burning; and another 15% because of an approaching fire. In this investigation, the presence or anticipation of fire was a major cause of evacuation. Many casualties in Hanshin-Awaji were caused by overly optimistic individual judgements that the fire would not spread.

Sime (1998) suggests that '*in general it has been found that patterns of response are influenced to a considerable extent by the knowledge people have of a fire in its early stages, which is often ambiguous. People rarely respond with any great degree of urgency unless they are aware of the threat.....A bush or forest fire can present comparable conflicts to a flood between the decision to stay in or leave a home....Until there is a direct or obvious danger, many hazards are inherently ambiguous to all except those retrospectively assessing whether the course and timing of a disasters victim's actions are sensible'*.

Given the lack of relevant information or research into the effects of an external fire on the evacuation behaviour of occupants within a building, two incidents have been highlighted, which give some indication of the likely behaviour in similar incidents. These are discussed in the next section.

5.2.2 Specific case studies.

Fire at Lightfoot Street, Chester, Cheshire (Davis, 1998)

The purpose of studying this incident was to try to identify the behaviour of residents, since there are very few published incident reports which contain such information. The approach was to try to identify the time at which residents became aware of the incident and how they reacted initially. The incident involved a rapidly growing fire in a furniture depository, which was located only 18 metres from a residential street. The fire started at 1:30am, when all residents were asleep. A survey of the residents, and interviews with the fire brigade, highlighted that, during the initial stages, the vast majority of people evacuated. Five people out of fifty were still in their premises at 2:00am (30 minutes after the start of the incident) believing that it was safer, even though there was an extremely serious fire affecting the front of their building.

Meissner plant at Hickson and Welch Ltd, Castleford (Lees, 1995)

At about 1:20pm on 21st September, 1992 a jet flame erupted from a manway in the side of a batch still on the Meissner plant at Hickson and Welch Ltd at Castleford. The flame cut through the plant control/office building, killing two men instantly. Three other employees in these offices suffered severe burns from which two later died. The flame impinged on a four-storey office block, shattering windows and setting rooms on fire. The 63 people in this block managed to escape, except for one who was overcome by smoke in the toilet; she was rescued but later died from the effects of smoke inhalation.

The information available on the two incidents outlined above suggests that the majority of occupants will attempt to evacuate. However, for various reasons, a proportion of the occupants may choose not to evacuate a building fire caused by an external event. The evacuation behaviour in these situations is a complex issue, and limited research has been undertaken in this area. Possible reasons for not evacuating the building is that building occupants may perceive the interior of the building to be safer than the exterior, they may wish to undertake property protection, or they may not perceive the situation to be serious.

5.3 Modelling approach

The estimation of the proportion of fatalities within buildings, due to a secondary fire resulting from a flash fire, has been considered in two ways:

Method 1 involves the analysis of Fire Statistics in the UK and USA, to estimate indicative probabilities for people escaping from secondary fires.

Method 2 involves a study of the evacuation of two building types (office and dwelling). Deterministic procedures are used to quantify fire growth, fire spread, smoke movement and the consequences for the building and its occupants. Event tree analysis is then used to estimate the probability that the occupants will be fatalities.

5.4 Method 1 - Analysis of Fire Statistics

The following data, taken from the UK fire statistics (Home Office, 1995) and the National Fire Protection Association (NFPA, 1998), give some indication of fatalities and injuries in fires which are similar (in some respects) to a flash fire engulfing a building. For example, hostile or malicious fires in dwellings may produce a rapidly growing fire with little or no warning, thus being similar in at least one respect to a flash fire incident.

Home Office Fire Statistics, UK

	Dwellings	Other buildings
Total number of fires	58600	1741
Fatalities per fire	0.6%	0.1%
Non-fatal casualties per fire	13.6%	4.8%

Table 5.1 Percentage fatalities / injuries resulting from malicious fires, 1988-93

The results outlined in Table 5.1 are slightly lower than those outlined in a previous analysis (Rew et al, 1997), which gave 0.5% for malicious fires and approximately 1% for fires caused by bombs, petrol bombs or other incendiary devices. The reason for the difference is because the figures outlined in Table 5.1 refer to 5 years of fire statistics, where as the previous analysis only referred to the fire statistics for 1993.

US Fire Administration

Major cause	Total number of fires	Percentage of fires involving fatalities	Percentage of fires involving injuries
Incendiary or suspicious causes[1]	57900	1.1%	4.1%
Exposure (to other hostile fires)[2]	17500	0.2%	1.0%
Natural causes[3]	8800	0.1%	1.7%

1. Fires that were proven or believed to have been deliberately set.
2. Incidents that are caused by the spread of a hostile fire. The cause of ignition for the adjacent building is proximity to the hostile fire; or the form of heating is spreading from another hostile fire via direct flame or convection current; radiated heat; heat from flying brands, embers or sparks; conducted heat; or unclassified or unknown-type heat.
3. Incidents in which the ignition factor was lightning or the form of heating was a natural source (sun's heat, spontaneous ignition, chemical reaction, static discharge, or unclassified or unknown-type heat from a natural source).

Table 5.2 Percentage fatalities / injuries from fires 1991-1995 caused by incendiary or suspicious causes, exposure (to other hostile fires) and fire resulting from natural causes

As can be seen from Tables 5.1 and 5.2, the average number of fatalities per fire is in most cases less than 1%. Note that this is not the same as the percentage of occupants who are fatalities given a fire, as some buildings may be unoccupied and some may have multiple occupants when the fire occurs. Assuming that the average number of occupants per dwelling per fire is of order 1-3 for dwellings, it seems reasonable to assume that the proportion of occupants who are fatalities per fire is broadly the same as the average number of fatalities per fire.

In general, the percentage fatalities estimated from the US Fire Administration data is higher than the estimates from the UK Fire Statistics. This difference may be as a result of the definition of the various fire causes.

The low fatality percentages derived from the incident data should be treated with caution, as many of the fires may have been attended by the fire service, who would also have conducted fire rescue. In the case of a flash fire incident, numerous secondary fires may result. The fire service would therefore be stretched between many dwellings, resulting in reduced effectiveness. Other differences that must be considered include the willingness of occupants to escape in the event of a flash fire incident, and the multiple ignition points caused by a flash fire.

5.5 Method 2 - evacuation assessment

Introduction

The assessment of evacuation involves the following:

a) estimating the available safe egress time (ASET), by considering the fire load, fire growth and geometry of the building;

b) estimating the required safe egress time (RSET), by taking into consideration the occupant and building characteristics.

If ASET < RSET, injuries and fatalities may occur. Based on the environmental conditions within the building caused by fire, and the time to evacuate the building space, both the thermal dose ($L_T = I^{4/3}t$) and toxic dose ($L_c = Ct$) are calculated (where I is the incident heat transfer, t is the exposure duration and C is the toxic concentration, predominantly of CO). The probability of fatalities within the building space are then calculated using probit functions. Probit (probability unit) functions make it possible to relate the intensity of some phenomenon such as heat radiation or toxic gas concentration to the degree of damage which can result from it.

Assumptions

The following is a list of the assumptions made in the deterministic analysis. The building types modelled are dwellings and office buildings.

Building layout	Dwelling Office	= Two-storey building with 6 rooms = Three-storey, open plan (BRE, 1996)
Maximum travel distance (based on buildings being constructed to current building regulations)	Dwelling Office	= 35 metres (DOE, 1992) = 45 metres (DOE, 1992)
Pre-movement time[1] (based on level of alertness and familiarity with enclosure)	Dwelling (day) Dwelling (night) Office	= 180 seconds (BSI, 1997) = 240 seconds (BSI, 1997) = 180 seconds (BSI, 1997)
Travel speed	Tenable conditions Smoke logged area	= 1.0 m/sec. (BSI, 1998) = 0.3 m/sec. (BSI, 1998)
Fire growth rate	Dwelling Office	= Medium rate of fire growth (BSI, 1997) = Medium rate of fire growth (BSI, 1997)
Carbon monoxide probit	$Pr = - 37.98 + 3.7 \ln (L_c)$ (TNO, 1989)	
Heat flux probit	$Pr = - 14.90 + 2.56 \ln (L_T)$ (TNO, 1989)	

1. The pre-movement time is made up of two components:
   i) recognition time, which is the period after an alarm or cue is evident but before occupants of a building begin to respond;
   ii) response time, which is the period after occupants recognise the alarm or cue and begin to respond to it, but before they begin to move directly to an exit.

Table 5.3 Modelling assumptions

The pre-movement times used in the deterministic analysis are based on guidance from DD240: Fire Safety Engineering in Buildings (BSI, 1997). It has been assumed that an external process fire event would provide the same warning level as a 'W2' system, i.e. non-directive (pre-recorded) voice systems and/or informative warning visual display.

Prior to the pre-movement component of the evacuation process, detection of the event must occur. The detection time component of the analysis is assumed to be zero as it is considered that the flash fire will be immediately obvious to the building occupants.

Fire modelling

The fire model used is FAST, developed by the National Institute of Standards and Technology (NIST) (Peacock et al, 1997). FAST is a zone model capable of predicting the environment in a multi-compartment structure subjected to fire. It calculates the time-evolving distribution of smoke and fire gases and the temperature throughout a building during a user-specified fire. It is assumed that the fire grows at a medium rate, as defined in DD240 (BSI, 1997).

Evacuation modelling

The evacuation model used in the analysis is a simple model which considers such time factors as detection time (t_{det}), recognition time (t_{rec}), response (t_{res}) time and travel (t_{trav}) time.

Evacuation time (t_{esc}) = $t_{det} + t_{rec} + t_{res} + t_{trav}$

Note that one simplification made to the modelling is the assumption that people in the room of origin of the fire will always be successful in evacuating. There may be circumstances for which this is non-conservative. However, for evacuation from secondary fires, most fatalities occur in rooms remote from the fire start and are predominantly due to the effects of smoke.

Event tree analysis

Figure 5.1 defines the event tree adopted to estimate the probability of a fatality occurring due to a secondary fire in a building caused by a flash fire. The data used in these event trees are presented in Table 5.4.

	Single point ignition[1]		Multi-point ignition[1]	
Event	Dwelling	Office	Dwelling	Office
Fire spread beyond[2] room of origin	0.19	0.21	1	1
Evacuation attempted[3]	0.90	0.98	0.90	0.98
Evacuation unsuccesful[4]	0.01 (awake) 0.25 (asleep)	0.01	0.01 (awake) 0.25 (asleep)	0.01

1. Single/Multi point ignition refer to the type of incident, i.e. if the building is completely engulfed by the incident, such as for a flash fire, multi-point ignition is assumed. Likewise, if the incident affects only one elevation of the building, single point ignition is assumed.
2. Fire spread beyond room of origin. If there are multiple points of ignition, it is assumed that all fires will spread beyond the room of origin, as all rooms will be affected. The probability of fire spread beyond room of origin for single point ignition is taken from the BSI document DD240 (BSI 1997).
3. The probability of evacuation relates to the fact that building occupants may not attempt to evacuate the building, as a result of a secondary fire caused by a flash fire. This is a complex issue, and limited research has been undertaken in this area. The probabilities used in the analysis are derived from information on two exterior fires. For dwellings (Davis, 1998), the fire incident was a large fire in a furniture warehouse in a heavily populated area, where 10% of the residents in the affected area did not attempt to evacuate their building. For office buildings (Lees, 1995), the fire incident was an industrial fire which directly affected an office building, where 2% of the office population did not evacuate.
4. Derived using the fire and evacuation modelling described above. It is assumed that building occupants who do not attempt to escape will become fatalities.

Table 5.4 Probability data used in the event tree analysis

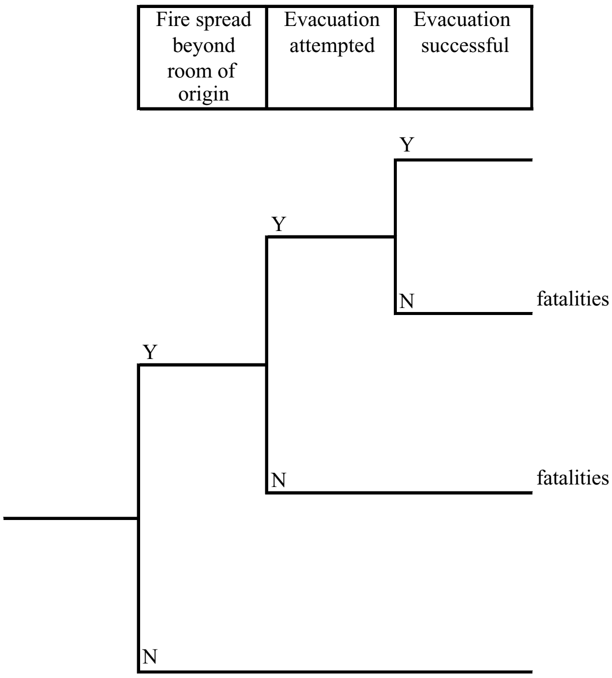

Figure 5.1 Event tree for secondary fire in dwellings or office buildings

<u>Results</u>

The results of the analysis are presented in Table 5.5 in terms of the proportion of occupants that are fatalities given a secondary fire. The values are conditional on secondary fires having started.

Building type	Percentage fatalities (single point ignition)	Percentage fatalities (multi-point ignition)
Dwelling (day)	2.1%	10.9%
Dwelling (night)	6.2%	32.5%
Office	0.6%	3.0%

Table 5.5 Summary results from consequence analysis

5.6 Model summary

The percentage fatalities from the event tree analysis are higher than those derived from the information extracted from the Fire Statistics in the UK and US. Possible reasons for this difference may be as follows:

a) The probability of occupants attempting to escape is based on limited data.

b) In the consequence analysis for secondary fires caused by flash fires, some of the occupant population will not attempt to evacuate and are therefore assumed to become fatalities.

c) Fire Brigade rescue is assumed to be less effective in the current context because of the probable high number of fires in close proximity resulting from a flash fire. The model conservatively assumes there is no benefit attached to attendance of the fire brigade.

To conclude, if secondary ignition occurs and the resultant fire grows at a medium rate, the probability of fatality in dwellings during the day is assumed to be as given in Table 5.5. Note that these results do not take into consideration the direct effects of a flash fire, i.e. the direct effect of flame penetration on occupants.

6. MODEL APPLICATION

6.1 Application within risk assessment studies

6.1.1 Steady-state fire (single point ignition)

For the steady-state case it is assumed that the event is a jet or pool fire, with radiation incident on one side of the exposed building. Event duration is assumed to be long (of around 30 minutes), with radiation levels assumed to be constant.

The results indicate that, at radiative fluxes of less than 14.7 kW/m^2, no ignition will occur for dwellings. Thus secondary fires will not be produced within the building and no fatalities will result. At incident radiative fluxes of between 14.7 and 31.2 kW/m^2 (i.e. 25.6 kW/m^2 divided by a transmission factor of 0.82 for single pane windows) secondary fires will result from ignition of the exterior of the building and fire spread to the interior will result in fatality of 0.6% of the occupants during the day. At incident heat fluxes greater than 31.2 kW/m^2, secondary fires will also result from ignition of the interior through windows and will result in fatality of 1.2% of the occupants during the day. These results are summarised in Table 6.1 below, together with results for dwellings at night and office buildings. Note that in all cases, the probability of secondary fires occurring due to flame penetration is set to zero.

	Dwelling			Office building	
	Heat flux level (kW/m^2)	% fatalities		Heat flux level (kW/m^2)	% fatalities
		Day	Night		
Ignition of exterior	14.7	0.6%	1.8%	15.0	0.2%
Ignition of interior	31.2	1.2%	3.5%	41.3	0.4%

Table 6.1 Proportion of fatalities for occupants of buildings subject to steady-state (single-point ignition) fires

In the case of such an event, i.e. a long duration event, fire brigade intervention and evacuation of buildings prior to ignition should be considered and may mean that the above values are pessimistic.

Evacuation analysis, as described in Section 5.5 suggests that the fire brigade intervention time would be required to be less than 1 minute from the time of ignition if the probability of fatality is to be reduced. Minimum standards of fire cover are recommended by the Home Office (BSI, 1997), in terms of number of pumping appliances and the time limits for their attendance, as a function of the risk category for the area in which the building is situated. For Category A risk, e.g. concentrations of high-risk industrial or commercial property, approximate time limits for attendance are less than 5 minutes. Thus for many scenarios, the fire brigade will be in attendance before secondary fires occur within buildings. However, their effectiveness in aiding escape from multiple building fires is uncertain and it is conservative to retain the values given in Table 6.1.

Evacuation prior to occurrence of secondary fires is possible, although a dwelling may be considered to be a safe location until ignition occurs. Thus, again it is conservative to retain the values given in Table 6.1.

6.1.2 Transient fire (multi-point ignition)

A flash fire which engulfs the building for a short duration has been assumed for the transient fire case. As discussed in Section 3.1.2, the thermal dose to an object within a flash fire, based on CFD analyses by Rew et al (1997), ranges from 3200 to 43,000 $(kW/m^2)^{4/3}s$, although the upper end of this range is considered pessimistic when compared with heat transfer measured within flash fire trials. A dose of 3200 $(kW/m^2)^{4/3}s$ equates to a heat flux of 150 kW/m^2 for a duration of approximately 4 seconds.

Comparison with the Lawson & Simms (1952) ignition criteria, as given in Section 4.3, shows that this flux and duration is sufficient to cause ignition of the exterior and interior of both dwellings and office buildings.

The results of the model described in Sections 4 and 5 indicate that, for a flash fire giving a thermal dose of 3200 $(kW/m^2)^{4/3}s$, the proportion of occupants who are fatalities as a result of secondary fires will be as given in Table 6.2 below. Note that, as discussed above, both exterior and interior ignition will occur. However, for comparison, the table also provides percentage fatalities for exterior ignition only. All values include the contribution of flame penetration to the development of secondary fires.

Thermal dose $(kW/m^2)^{4/3}s$	% fatalities		
	Dwelling		Office building
	Day	Night	
Exterior ignition only	4.7%	14.0%	1.4%
Interior and exterior ignition	7.2%	21.5%	2.2%

Table 6.2 Proportion of fatalities for occupants of buildings subject to steady-state (single-point ignition) fires

It can be seen from Table 6.2 that the fatality levels for secondary fires resulting from flash fires are significantly higher than those for remote pool or jet fires. The main reasons for such an increase are the occurrence of flame penetration and multi-point ignition, i.e. if a building is engulfed by a flash fire, ignition may occur throughout the building, thus increasing the probability of occupants becoming trapped in the building. Furthermore, due to the speed of the flash fire event, which is over in less than 15 seconds, fire brigade intervention is assumed to be ineffective.

6.1.3 Discussion

Sections 6.1.1 and 6.1.2 outline the application of the proposed model to both steady-state and transient fires. The probability of fatality for occupants within buildings ranges from 0.2% for office type buildings in a steady state fire, to approximately 21.5% for dwellings at night in a transient fire. The key feature of the results is the difference between whether a building is exposed on one elevation, i.e. pool fire (steady state), or whether the building is engulfed by a flash fire event (transient) which may result in multiple ignition points and direct flame penetration to the interior of the building.

As a result of the application of the model to typical scenarios, various weaknesses in the model have been identified, as follows:

a) The model does not take into account the severity of the event, i.e. if secondary ignition occurs, the probability of fatalities of occupants within the building is assumed to be constant irrespective of the intensity of the heat flux at that particular location.

b) For the case of steady state fires, the time to ignition has not been incorporated in the evacuation model. However, the case study outlined in Section 5.2.2 suggested that occupants may not attempt to evacuate up to 30 minutes after the start of the incident, even if their building is in direct danger.

c) Fire brigade intervention has not been directly included in the model. This has been discussed in some detail above, where it was concluded that, if fire brigade intervention is to have a significant effect on the probability of fatalities for a steady state fire, intervention times would have to be less than 1 minute from ignition, which is unlikely when multiple buildings are involved. Due to the speed of the transient fire, fire brigade intervention would be ineffective.

6.2 Sensitivity of risk calculations to model uncertainties

Tables 6.3 and 6.4 both illustrate the effect of varying model input parameters on the probability of fatalities within a building due to an external fire event. The base case in Table 6.3 relates to single point ignition of a dwelling during the day (except for event 8.2 which is at night). The external fire event affects only one elevation of the building, such as for a pool fire, and is severe enough to cause interior and exterior ignition. However, there is no flame penetration.

As can be seen from Table 6.3, the parameter for which probability of fatality is most sensitive to changes in the input value is Event 7. Event 7 refers to whether, in the event of an external fire, the occupants within the building will attempt to evacuate the building. The primary reason for the high sensitivity to this variable is that it is assumed that, if secondary ignition occurs and the fire escalates, then any remaining occupants within the building will be fatalities. The values assumed in the model have been derived from individual case studies (see Section 5.2), involving a similar fire event. As outlined in Section 5.2, the issue of whether occupants would remain within the building during an external fire event is highly complex, and information on such events is limited. However, it is believed that the assumed values of 0.1 for dwellings and 0.02 for office buildings are reasonable.

Event no.	Event		Dwelling		
			Assumed value	Test value	% change
1	Flame penetration	Variable Pr fatalities	N/A	N/A	N/A
2	Ignition of exterior	Variable Pr fatalities	From ignition model	-	-
3	Fire spread to interior	Variable Pr fatalities	0.5 0.0059	0.8 0.0094	60% 60%
4	Ignition of interior	Variable Pr fatalities	From ignition model	-	-
5	Ability to escalate	Variable Pr fatalities	0.57 0.0059	0.8 0.0083	40% 40%
6	Fire spread beyond room of origin	Variable Pr fatalities	0.19 0.0059	0.40 0.0124	110% 110%
7	Evacuation	Variable Pr fatalities	0.9 0.0059	0.75 0.0139	20% 135%
8.1	Fatalities (awake)	Variable Pr fatalities	0.01 0.0059	0.1 0.0103	1000% 75%
8.2	Fatalities (asleep)	Variable Pr fatalities	0.25 0.0176	0.4 0.0249	60% 41%

Table 6.3 Results of sensitivity analysis for a dwelling (single point ignition)

Table 6.4 refers to multi-point ignition of a dwelling, i.e. a flash fire engulfs the building, such that all elevations of the building are exposed to incident heat flux. For the sensitivity analysis, it is assumed that interior ignition does not occur, except via flame penetration. As for single point ignition, the parameter with the highest sensitivity is Event 7, i.e. evacuation.

Tables 6.3 and 6.4 do not consider the sensitivity of probability of fatality to criteria for exterior or interior ignition. This is because the model incorporates ignition as a step function, i.e. if the fire event meets the ignition criterion then there is a probability of 1 that ignition occurs. The weakness in using such an approach is that the probability of fatality due to secondary fires may, for some scenarios, be highly sensitive to whether the fire event just meets or just misses the ignition criteria. In reality, as the scatter of the ignition data in Figure 4.2 suggests, ignition is a highly uncertain process and a given heat load may be sufficient to ignite one building but not another. The uncertainty in choice of ignition model has been discussed in Section 4.2.3, and is evident from the difference in model results and scatter of data in Figure 4.2.

Event no.	Event		Dwelling		
			Assumed value	Test value	% change
1	Flame penetration	Variable Pr fatalities	0.2 0.0467	0.5 0.0700	150% 49%
2	Ignition of exterior	Variable Pr fatalities	From ignition model	-	-
3	Fire spread to interior	Variable Pr fatalities	0.5 0.0467	0.8 0.0616	60% 32%
4	Ignition of interior	Variable Pr fatalities	From ignition model	-	-
5	Ability to escalate	Variable Pr fatalities	0.57 0.0467	0.8 0.0567	40% 21%
6	Fire spread beyond room of origin	Variable Pr fatalities	1 0.0467	0.9 0.0420	11% 11%
7	Evacuation	Variable Pr fatalities	0.9 0.0467	0.75 0.1102	20% 135%
8.1	Fatalities (awake)	Variable Pr fatalities	0.01 0.0467	0.1 0.0813	1000% 74%
8.2	Fatalities (asleep)	Variable Pr fatalities	0.25 0.1391	0.4 0.1969	60% 42%

Table 6.4 Results of sensitivity analysis for a dwelling (multi-point ignition)

7. CONCLUSIONS

7.1 Direct effects of flash fires on building occupants

The first step in assessing the risk to building occupants of being enveloped in a flammable gas cloud is to consider whether gas ingress to the building has occurred. If the concentration within the building (i.e. within a room or part of a room) is greater than the lower flammable limit at ignition then an internal explosion will occur. As discussed in Section 3.2, simple models are available for assessing gas build-up within buildings and, if an explosion occurs, it is reasonable to assume that 100% of occupants are fatalities.

If there is insufficient time for internal gas build-up to occur then external blast effects may be significant in terms of breakage of windows and allowing flame penetration. As discussed in Section 3.1.1, breakage of typical windows is unlikely for low flame speed flash fire events (around 10m/s) which, as shown in the Maplin Sands trials (Blackmore et al, 1982), produce overpressures of less than 1 mbar. However, an increase to flame speeds of 40m/s, say due to the presence of sparse obstructions within the gas cloud or energetic release scenarios, may produce overpressures of order 20 mbar. Although such events would not be classified as a vapour cloud explosion, such overpressures are still capable of causing failure of windows and allowing flame penetration.

Another means of flame penetration is via windows broken by thermal effects. Comparison of estimated heat loads typical of flash fire events with data on window breakage due to thermal radiation (Mowrer,1997), suggests that some or all windows of a building engulfed in a flash fire will fail. However, this conclusion is sensitive to the prediction of heat transfer inside a flash fire. A model for heat transfer within flash fires (Rew et al, 1997) is to be validated in an on-going collaborative project (CERC, 1999).

Even if windows are not broken by blast or thermal effects, flame penetration may occur through open windows or doors. There are no simple models available which can be used to predict the extent of flame penetration into a building and the effect of flame penetration on building occupants. If occupants are adjacent to the window surface then it would be reasonable to assume 100% fatality. Away from the window, the prediction of fatality is highly uncertain. Flame penetration may also lead to secondary fires.

If no flame penetration occurs to a building then transfer of radiation through windows may be significant, but only if people are located adjacent to the window surface. For a typical flash fire scenario, at distances of more than 0.7m from a single glazed window, the thermal dose drops to below the Dangerous Dose level for an average population (equivalent to that which gives 1% probability of fatality). The effect of radiation transmission through windows on occupants is not likely to be significant, unless it can be shown that flame penetration does not occur.

7.2 Initiation and effect of secondary fires on building occupants

A model for the prediction of the effects of external fires on building occupants has been defined. The model comprises two sub-models: an ignition model and an evacuation model.

From a comparison of various ignition models, the model developed by Lawson & Simms (1952) was found to provide reasonable predictions of the ignition of building materials, and was in a form that is easily applied to the problem of building ignition. Furthermore, it considers both piloted and spontaneous ignition.

Review of literature with reference to the ignition characteristics of typical buildings has indicated that wood has the lowest critical heat flux (q_{cr}) of most building materials, even including most soft fabrics. The reason for the slightly higher critical heat flux of soft fabrics is primarily due to the thermally thin nature of such fabrics, i.e. increased heat loss to the unexposed face of the materials when exposed to an incident heat flux (q_e). Therefore, it has been assumed that all building types, i.e. dwellings and office buildings, will contain some wood products. The critical heat flux (piloted ignition) for wood has been assumed to be 14.7 kW/m^2 and that for spontaneous ignition is 25.6 kW/m^2 (Lawson & Simms, 1952). Piloted ignition has been assumed for ignition of the exterior of buildings, since for flash fires flame impingement will occur and for other fires, incandescent particles or burning brands will provide the pilot source. Spontaneous ignition has been assumed for ignition of building interiors, unless flame penetration occurs.

Prior to the development of the evacuation model, a review of evacuation behaviour of people within buildings exposed to an external fire event was undertaken. The majority of research into evacuation behaviour from buildings has been concerned with situations in which the fire is within the building. Due to the lack of relevant information on the evacuation behaviour due to an external threat, various case studies were used as guidance. Analysis of statistics for related fire events, e.g. exposure to malicious and other hostile fires in the UK and USA, has also been undertaken.

The key finding of this study is the increased probability of fatalities of building occupants due to multi-point ignition events, as compared to that for single point ignition. Multi-point ignition refers to events which engulf the complete building, i.e. flash fires, where secondary ignition of all rooms and flame penetration is possible, whereas single point ignition refers to events such as pool fires, where only one elevation of the building is exposed to the incident flux.

Typical case studies have been applied to the model, and the results in terms of the probability of fatalities for building occupants are given in Tables 6.1 and 6.2. For a steady-state fire remote from the building (single-point ignition), producing sufficient radiation to cause ignition of the interior as well as the exterior, the probabilities of fatality range from 0.4% for a office building to 3.5% for a dwelling at night. For flash fire events (multi-point ignition), the corresponding probabilities for office buildings and dwellings are 2.2% and 21.5%, respectively. These probabilities can be compared with the value of 5% suggested for dwellings in an earlier report (Rew et al, 1997). However, since this figure did not differentiate between single and multi-point ignition, it is considered that the new figures are broadly consistent. Note that the above probabilities of fatality relate to the effects of secondary fires only and do not include the direct effects of flame penetration on occupants.

7.3 Key uncertainties

The key uncertainties in the modelling of the effects of flash fires on building occupants are identified below:

1. The likelihood of flame penetration during a flash fire event, and the effects of flame penetration on building occupants is highly uncertain, but is expected to be a significant contribution to the risk associated with flash fire events. The likelihood of flame penetration is dependent on whether blast or thermal effects cause failure of windows. The thermal effects of flash fires on windows may be partially resolved through use of internal heat transfer data resulting from an on-going collaborative project (CERC, 1999). The weak blast effects of flash fires on windows and the extent of flame penetration to a building could be assessed using more detailed CFD analysis. However, it is noted that no experimental data has been identified to validate such an analysis.

2. There is some uncertainty in the response of building materials to short duration, high intensity events (i.e. flash fires). Most research for ignition relates to longer exposure duration, and there are still significant differences between ignition models. The uncertainty in use of such ignition models for short duration exposures could be reduced by testing of representative building materials.

3. Various assumptions need to be made when modelling the effects of secondary fires on building occupants, and the sensitivity of risk to these assumptions is tested in Section 6. The main conclusion was that the assumption to which risk is most sensitive is the proportion of occupants who remain within the building. This proportion is clearly related to the proportion of occupants who will not attempt to evacuate the building during an external fire event. Further analysis of the issue of evacuation behaviour may be extremely difficult due to the complex nature of the issue, the limited research in this particular area, and the relative infrequency of the type of fire under consideration.

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APPENDIX A

IGNITION OF BUILDING MATERIALS

This appendix provides a review of the modelling of ignition of typical building materials, and in particular wood. It makes use of recent reviews on the subject by Janssens (1991a) and Mikkola & Wichman (1989).

A critical radiant heat flux (q_{cr}) is sometimes quoted as the limiting criterion for pilot ignition, although this criterion will be sensitive to changes in heat loss from the surface, to the thickness of the material and hence to the orientation and geometry of that surface. Lawson & Simms (1952) obtained an estimate of the limiting flux for vertical samples of wood by extrapolating a plot of q_e versus $q_e/t_{ig}^{1/2}$ to $t_{ig} = \infty$, where t_{ig} is the time to ignition under a radiant heat flux q_e. For this study, oven dry samples of seven wood species, ranging in density between 240 and 720 kg/m^3, were exposed to the heat of a radiant gas panel. The pilot was a small flame 12.7mm long located 12.7mm from the exposed surface at the top of the sample. Irradiance was varied between 7.5 and 75 kW/m^2. In order to correlate the data, thermal properties were assumed constant and assumptions were made regarding heat losses from the surface. A critical surface temperature was taken as the criterion for piloted ignition, while the samples were assumed to behave as a semi-infinite solid. By correlating their ignition data in this way, Lawson & Simms obtained a fairly constant value for q_{cr} of approximately 14.7 kW/m^2, irrespective of species. Lawson & Simms expected ignition time to be a function of the difference between incident irradiance (q_e) and the critical irradiance of ignition (q_{cr}). Thus log t_{ig} (ignition time) was plotted against $\log(q_e - q_{cr})$, and it was found that for piloted ignition:

$$(q_e - q_{cr})(t_{ig}^{2/3}) = C_{ls}$$

where C_{ls} is a wood species-dependant constant, and is correlated against the thermal conductivity (k), density (ρ) and specific heat capacity (c) of the wood species.

From these and other data, a minimum flux for piloted ignition of wood was deduced as approximately 12.5 kW/m^2 (for African mahogany). This figure was incorporated in the UK Building Regulations (Department of the Environment, 1992). The minimum flux for softwood was found to be 14.7 kW/m^2 (for American whitewood). Note that Lawson & Simms provided criterion for spontaneous ignition of wood as well for piloted ignition.

As part of a larger project, Buschman (1961) undertook a series of experiments which were very similar to the original tests of Lawson & Simms (1952). Oven dry timber samples of six wood products ranging in density from 160 to 1100 kg/m^3 were exposed to the heat of a radiant gas panel, and irradiance was varied between 14 and 37 kW/m^2. The data was correlated using a similar relationship to that of Lawson & Simms (1952):

$$(q_e - q_{cr})(t_{ig}^{n}) = C_b$$

where C_b is a constant. Best fit values for n, q_{cr} and C_b for all six species were correlated with thermal conductivity (k), density (ρ) and specific heat capacity (c), to give the following relationships:

$$q_{cr} = 17.73 - 2.09x10^{-5} k\rho c$$

$$n = 0.975 - 0.069x10^{-5} k\rho c$$

with kρc in SI units (J^2 m^{-4} K^{-2} s).

$$C = k\rho c\left(165x10^{-4} - 1.8x10^{-4}\sqrt{k\rho c}\right)^2$$

The thermal properties used by Lawson & Simms (1952) and Buschman (1961) were evaluated at ambient temperature. However, the values of k and c for wood products are strongly dependent on temperature.

At the end of the 1960s and in the early 1970s, much piloted ignition data was generated at the University of Oklahoma. Koohyar et al (1968) designed an ignition cabinet to expose wood samples to irradiance from benzene pool burners. Oven-dry samples of 5 wood species (densities between 381 and 770 kg/m^3) were tested at irradiance levels between 11.5 and 36 kW/m^2. Koohyar et al first attempted to correlate the data following the approach of Lawson & Simms (1952), by plotting the energy modulus versus the cooling modulus, but with little success. According to Koohyar, this was due to the fact that the heat transfer coefficient (h) was not constant in his experiments. To resolve this problem, further analysis led to the use of two non-dimensional groups, the Fourier modulus and the Irradiance modulus:

$$\text{Fourier modulus} = \frac{kt_{ig}}{\rho c L^2}$$

$$\text{Irradiance modulus} = \frac{\omega q_e L}{k(T_{ig} - T_\infty)}$$

where: ω = fraction of incident irradiance to net heat flux into the solid

L = thickness of the slab (m)

T_{ig} = temperature at ignition (K)

T_∞ = free stream (ambient temperature, K)

k = thermal conductivity (kW/m K)

c = specific heat capacity (kJ/kg K)

Wesson et al (1971) tested oven-dry specimens of thirteen wood species (densities between 70 and 1020 kg/m^3) in Koohyar's ignition cabinet. Benzene flames and tungsten filament lamps were used as heat sources, providing irradiance levels between 11.5 and 145 kW/m^2.

Tewarson & Pion (1976) found q_{cr} as the intercept with the abscissa of a linear fit in a graph of $1/t_{ig}$ versus q_e for data on a number of plastics obtained in the Factory Mutual small scale combustibility apparatus. No physical justification was given other than that $q_e \rightarrow q_{cr}$ for $t_{ig} \rightarrow \infty$ (or $1/t_{ig} \rightarrow 0$). Tewarson & Pion concluded, on the basis of a steady state heat balance at the material surface, that t_{ig} should be correlated against $1/q_e$ when heat gains from the source flame (exothermic reactions at the material surface, etc.) approximately cancel heat losses from the surface (conduction into the material, re-radiation, etc.).

Magnusson & Sundstrom (1985) suggested an inverse correlation procedure, i.e. a technique to derive an apparent kρc from piloted ignition data. The drawback of their procedure is that surface temperature must be measured, generally a very difficult task. Quintiere & Harkleload (1984) developed a more practical procedure for the Lateral Ignition and Flame Spread Test (LIFT), developed by the National Institute of Standards and Technology (NIST). This procedure is now standardised by ASTM (1990). The LIFT is primarily a flame spread apparatus, but, as the heat flux is fairly uniform over the first 100-150mm near the hot end of the specimen, it can also be used for ignition tests. In that case, 155mm x 155mm samples are exposed in the vertical orientation to the heat of a radiant gas panel (280mm x 483mm). A premixed acetylene pilot is located in the boundary layer above the sample. The first step in Quintere's procedure consists of running ignition tests starting at an irradiance level near the maximum for the apparatus (65-70 kW/m^2). Time to ignition is obtained at q_e levels in descending order at intervals of 5-10kW/m^2, preferably with some replicates. When ignition time becomes sufficiently long, data are obtained at smaller intervals (1.5-2 kW/m^2). At a certain level of q_e, ignition will no longer occur within the (arbitrary) maximum test duration of 20 minutes. A value of q_e slightly above this level is considered to be the critical heat flux q_{cr}. When ignition occurs at $q_e = q_{cr}$, t_{ig} is very long such that conditions are approximately steady.

Mikkola & Wichman (1989) developed two forms of a thermal ignition model in the following ways:

a) exact solution via Laplace transforms of the linearized problem with constant k and c for thermally thick and thermally thin samples;

b) approximate integral solution of the problem with non-linear heat losses for thermally thick, thermally thin and thermally intermediate specimens.

A thermally thick specimen in this context is one having its physical thickness always greater than its conduction thickness (i.e. the depth of conduction within the material at t_{ig}) at the time to ignition, while a thermally thin sample has its physical thickness less than the conduction thickness at ignition.

Both of the above approaches resulted in the same recommendation, i.e. to correlate $(1/t_{ig})^n$ with q_e where n = 0.5 for thermally thick materials, n = 1 for thermally thin ones and n =2/3 for intermediate thicknesses. The authors also gave some guidance to estimate the thermal thickness from physical thickness for wood products; thermally thick samples are over 15-20mm, thermally thin ones are thinner than 1-2mm, while n = 2/3 corresponds to a thickness of around 5mm.

Correlations have been proposed by Janssens (1991b) that relate the time-to-ignition t_{ig} to the magnitude of incident flux q_e impacting on combustible material. Piloted ignition data obtained in the Cone Calorimeter and LIFT were correlated according to:

$$q_e = q_{cr}\left[1 + 0.73\left(\frac{k\rho c}{h_{ig}{}^2 t_{ig}}\right)^{0.547}\right]$$

where h_{ig} = heat transfer coefficient at ignition (W/m^2 K).

Critical irradiance, q_{cr}, was found as the intercept with the abscissa of the straight-line fit through the data in a graph of $(1/t_{ig})^{0.547}$ versus irradiance, q_e. An apparent kρc was obtained from the slope of the line, noting that this kρc value was not equal to that at ambient temperature. For thermally intermediate materials, it was suggested that the experiments should be aimed at short ignition times or high irradiance levels i.e. where the material still behaves as a thermally thick solid.

Smith & Satija (1981) used data from a bench-scale rate of heat release apparatus ASTM E906 (ASTM 1989) for input into a mathematical model simulating a developing fire in a corner/wall scenario. In order to correlate ignition data obtained in the calorimeter, Smith suggested the following equation:

$$FTP = (q_e - SFE)^m t_{ig}$$

where FTP = flux-time product (a characteristic of the material)

SPF = self-propagating flux (kW/m^2)

m = empirical constant ≥ 1

In Smith's calorimeter, vertical samples are exposed to the heat of an electric radiant panel. Ignition is triggered with a small premixed H_2 pilot impinging on the surface at the bottom of the specimen.

From the correlation produced by Smith & Satija (1983), the Flux-Time Product (FTP) concept emerged with the potential for a simple method to predict the time-to-ignition of materials subjected to an external flux.

Toal et al (1989) tested six uncoated and four coated wood products in the ISO 5657 Ignitability test. Using an approach analogous to that of Smith & Satija (1981), they correlated the data according to the following power law:

$$(q_e - q_{cr})^m t_{ig} = FTP^m$$

For all materials tested except one, the value of m was found to be close to 1.5. This is in agreement with Lawson & Simms (1952) correlation for piloted ignition, where n =1/m = 2/3.

The correlations outlined above originate, it is assumed, from thermo-physical analysis of the pyrolysis of a combustible material before the lower limits of flammability are reached. They all include, in one form or another, assumptions regarding the prevailing boundary conditions that exist at ignition. It follows that, at the present time, there is no complete analytical solution which characterises this ignition process (Silcock & Shields, 1995). Common to all of the above correlations is the inclusion of a critical heat flux, q_{cr}, which is a theoretical lower limit for the incident heat flux necessary to create the conditions for ignition.

Shields & Silcock (1995) used dimensional analysis to determine which dimensionless groups are relevant to the piloted ignition process. A protocol for the analysis of ignition data for combustible material, based on the FTP, was proposed.

$$q_e = q_{cr} + \frac{FTP_n^p}{t_{ig}^p}$$

This equation is that of a straight line, when q_e is plotted against $1/t_{ig}^p$, and, provided an appropriate value of p is selected, the resulting straight line will yield q_{cr} which is the intercept of the straight line onto the q axis. The slope of the straight line will give FTP_n^p which can be modified to yield FTP_n. They concluded that this methodology is the most suitable method by which to analyse and predict data associated with the ignition of combustible materials.

The interior of most buildings will contain fabric of varying types and quantities, such as curtain fabrics. Most textile fibres are flammable in air unless they have been modified during fibre production or during processing to render them fire retardant. The majority of textile fabrics for major end-use applications are of relatively low mass/area and behave as thermally thin fabrics. Consideration of both the ignition of textile fabrics and the subsequent flame spread are of primary importance and there are many factors which influence both ignition and flame spread.

The main processes occurring in the ignition of fabrics are:

a) heat transfer from the ignition source to the fabric,

b) thermal decomposition of the fibrous polymer,

c) diffusion and convection of the products of thermal decomposition, and

d) kinetic reactions involving decomposition products and oxygen from the environment.

A scale of limiting oxygen index (LOI) can represent the relative flammabilities of various fabrics. An LOI of around 20 indicates that the material will burn readily in ordinary air, an LOI of 25 that it will not. The most common textile fabrics, i.e. nylon, polyester and cotton have a LOI of approximately 20. Woollen fabrics generally exhibit the greatest ignition resistance whilst cotton has the least resistance.

Wulff et al (1973) reported times to ignition of 20 fabrics for various incident fluxes. A semi-empirical relationship between ignition / melting time and radiative heat flux for a particular group of fabrics has been derived:

$$[N_{Fo}]_{i,m} = \frac{-1}{N_{Bi}} \ln\left[1 - \frac{N_{Bi}}{[q * rad\}}\right] + a[q * rad]^b \left[1 - \frac{N_{Bi}}{[q * rad]}\right]^{-1}$$

where $[N_{Fo}]_{i,m}$ is the non-dimensional destruction time of the fabric (that is, time to ignition or melting) and is given by:

$$[N_{Fo}]_{i,m} = \frac{(k/l)t_{i,m}}{\rho lc}$$

where (k/l) = average thermal conductance (W m^{-2} K^{-1})

$t_{i,m}$ = ignition / melting time (s)

ρl = mass / unit area (kg m^{-2})

c = average specific heat (J $kg^{-1}K^{-1}$)

N_{Bi} is the Biot Number which is defined as the ratio of the average convective heat transfer coefficient of the fabric to the average thermal conductance of the fabric, and which is obtained experimentally.

The non-dimensional radiative heat flux [q* rad] is given by:

$$[q*rad] = \frac{\alpha q_e}{(k/l)(T_{i,m} - T_o)}$$

where α = absorptance of charred fabric

q_e = incident heat flux (W m^{-2})

$T_{i,m}$= mean ignition / melting temperature (K)

T_o = ambient temperature (assume 298 K)

The constants a and b are specific to a particular fabric group and have experimentally derived values. By substituting the relevant values for a specific fabric and by applying the particular fabric type constants, a and b, an estimate of the ignition or melting time for any incident heat flux can be obtained. Typical results for various fabrics are shown in Table 4.2 of the main text.

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