Fires in compartments: the phenomenon of flashover

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Fires in compartments: the phenomenon of flashover

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It appears that fires in buildings are inevitable. All too often they lead to loss of life and large costs in repairing damage to a building's structure and contents. There is a clear need not only to detect a fire in its early stages of development but also to stop it from spreading to adjoining areas either by active preventive measures or by design. When applying mathematical models to improve our basic understanding it becomes clear that an in-depth knowledge of fire growth involves a range of interacting processes including combustion chemistry, heat transfer and fluid dynamics. The development of a fire within a room needs to take into account additional factors such as material properties, room configuration and ventilation. We introduce here aspects that describe the evolution of a fire within a single room, particularly focusing attention on the sudden life-threatening phenomenon of flashover which leads to full room involvement.

Keywords: flashover; compartment fires; zone models; nonlinear dynamics

1. Introduction

It is reported that the number of people killed each year in fires in the UK is decreasing, with 1994 the lowest for 30 years, but yet there were still 676 deaths, 475 of which were in their own homes (Home Office 1996). This amount is still an alarming number. However, many other countries have a worse record (Sekizawa 1994), and occasionally one reads of single incidents in which hundreds of people have lost their lives (e.g. the fire at Kadar Industrial Co. Ltd, Thailand, on 10 May 1993; Grant & Klem (1994)).

An accidental fire in a building will generally start at a single location within a room, or *compartment*. In the early stages, it will present a threat to the occupants of that particular room, but if allowed to grow unchecked, adjacent rooms and indeed the whole building will eventually be placed at risk.

The threat to the occupants may be minimized and the damage to the fabric and structure of the building reduced to an acceptable level by applying our increasing knowledge of fire science and the principles of fire safety engineering. To protect life, the fire safety engineer can adopt various measures, including the provision of early detection, a suitable alarm system and adequate means of escape (the reduction in deaths in the UK in the years to 1994 has been attributed to the fact that more households have installed smoke alarms (Home Office 1995)). Even so, through

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faulty equipment, poor maintenance, negligence or simply the unpredictable human behavioural response in the presence of a rapidly deteriorating situation, any fire presents significant risk. While attempts to prevent fire will reduce the risk, further major improvements can be achieved by undertaking measures that will maximize the time available for the occupants to escape to a place of safety. This alternative approach is to use our growing understanding of fire behaviour to introduce fire safety measures at the early stages of the overall design process. Such an approach requires a detailed knowledge of the processes that lead to life-threatening conditions; specifically, rapid changes in the state of the fire.

To achieve this goal, there has been a steady increase in the output of the fire research community, and a truly interdisciplinary approach to the subject has been developed. Fire science encompasses, on the one hand, investigations into the toxicity of fire products (Purser 1995) and how people behave when exposed to a fire threat (see Di Nenno *et al*. 1995) and, on the other, research into the mechanisms responsible for rapid fire development in the compartment of origin, namely the processes which account for 'flashover', the topic to which this paper is addressed.

The term flashover is used to describe the transition that can occur in a compartment fire when the fire spreads rapidly from the area of its original locus to the state of full room involvement. The transition is associated with:

(i) high levels of radiant heat flux within the compartment;

(ii) a rapid spread of flaming over extended flammable surfaces;

(iii) a rapid increase in the burning rate;

(iv) the onset of flaming in the hot layer of unburned and partly burned fuel vapours and particulate smoke under the ceiling; and

(v) flames emerging from openings.

Accordingly, the onset of flashover—the beginning of the transition—is an extremely dangerous stage of a fire. Untenable conditions will have been achieved within the compartment of origin some time before, but after flashover the fire can spread to adjacent spaces as flames emerge through open doors, generating a flow of hot toxic smoke to the rest of the building. In recent years, there have been a number of major fires of high life loss which have involved flashover, including the fires at the Summerland Leisure Centre (Isle of Man in 1973), the Stardust Discotheque (Dublin in 1981), both reviewed by Rasbash (1991), and the King's Cross Underground Station fire (London in 1987) described in Fennell (1988). Flashover also presents a serious threat to fire-fighters: despite their rigorous training, there are occasional tragic deaths (Anon. 1996).

Some of the above aspects of flashover can be seen physically in figures 1 and 2. Figure 1, showing a flashover transition in progress, was taken during the full-scale experimental study of the fire at the Stardust Discotheque Club fire, which was carried out by the UK Fire Research Station (Building Research Establishment 1982) as part of the technical investigation in support of the Public Inquiry. The high levels of radiant heat can be inferred by the emission of smoke from the, as yet, unignited seating, while the appearance of flames in the hot layer of gas just below the ceiling is a further indication that flashover is in progress. Figure 2 shows a sequence of four photographs taken of a small-scale experimental study of flashover in a compartment. The internal dimensions of the fire box were 0.4 m × 0.4 m × 0.4 m modelling a simple room with a single opening. Inside the box, a tray with dimensions $0.15\,\mathrm{m}^2$ was filled with polypropylene, which was ignited. The photographs are taken at intervals of 4:00, 4:30, 4:45 and 5:00 minutes after ignition and show a rapid transition that results in flames emerging from the box.

2. The burning of combustible solids

When a combustible solid (or liquid) is heated sufficiently, it will produce flammable vapours which, once ignited, will react exothermically with oxygen as they mix with air, producing a diffusion flame which is the visible manifestation of the gas-phase combustion process. Some of the heat released in the flame is fed back to the burning surface, thus providing the energy required to maintain the flow of fuel vapours that sustains the flame. For condensed fuels, the rate of burning may be expressed as a mass flux ($\mathrm{kg\,m^{-2}\,s^{-1}}$):

$$\dot{m}'' = \frac{\dot{Q}''_{\mathrm{F}} - \dot{Q}''_{\mathrm{L}}}{L_{\mathrm{v}}}, \tag{2.1}$$

where $\dot{Q}''_{\mathrm{F}}$ is the heat transferred back to the fuel surface from the flame ($\mathrm{kW\,m^{-2}}$), thus corresponding to the heat flux to the fuel surface when a fire burns in an unconfined location, $\dot{Q}''_{\mathrm{L}}$ is a term expressing the heat losses as a heat flux from the surface ($\mathrm{kW\,m^{-2}}$), and L_{v} is the effective 'heat of vaporization' of the fuel ($\mathrm{kJ\,kg^{-1}}$). This scenario is illustrated in figure 3 (see Drysdale 1985). For a combustible liquid, the flow of fuel vapours corresponds to a simple change of state, and under conditions of steady burning the surface temperature will be close to the boiling point of the liquid. However, the generation of fuel vapours from the surface of a combustible solid requires chemical decomposition of the condensed material. Thus, L_{v} is generally much greater for solid combustibles than for liquids, and the burning rates will be significantly less (Tewarson & Pion 1976; Drysdale 1985). The numerator of equation (2.1) is the net heat flux entering the surface of the fuel. When the fire is relatively small (with a diameter less than *ca.* 1 m), $\dot{Q}''_{\mathrm{F}}$ is a function of $\dot{m}''$, and a positive feedback exists. This is a characteristic feature of 'fire' that distinguishes it from other forms of combustion, although it is self-regulating: the aphorism 'combustion without taps', attributed to B. R. Morton, is most appropriate.

In the open, the buoyancy-driven flows of the fire plume will carry most of the heat, and the combustion products, away from the vicinity of the burning surface. However, in a compartment, the fire plume interacts with the ceiling and walls, forming a layer of hot fire products under the ceiling. This has a significant effect on the way in which the fire develops. The act of confinement increases the proportion of heat which is transferred back to the combustible surfaces by radiation from the ceiling and upper walls as they are heated, and increasingly from the hot smoke which accumulates under the ceiling. The rate of burning is enhanced and equation (2.1) can be modified accordingly. Thus,

$$\dot{m}'' = \frac{\dot{Q}''_{\mathrm{F}} + \dot{Q}''_{\mathrm{E}} - \dot{Q}''_{\mathrm{L}}}{L_{\mathrm{v}}}, \tag{2.2}$$

where $\dot{Q}''_{\mathrm{E}}$ is the additional heat flux reaching the surface ($\mathrm{kW\,m^{-2}}$).

Figure 1. Full-scale reconstruction of the events leading to the fire at the Stardust Discotheque. (Photograph: courtesy of Building Research Establishment Ltd.)

It is argued that the rate of energy release in a fire is the most important single characteristic (Babrauskas & Peacock 1992). This is borne out by the fact that a number of key features of a fire correlate with the rate of heat release, for example, flame height (Heskestad 1995) and temperature in the fire plume (McCaffrey 1979) and ceiling jet (Alpert 1972). The rate of heat release (kW) is related to the rate of burning as follows:

$$\dot{Q}_{\mathrm{c}} = \chi A \dot{m}'' H, \tag{2.3}$$

where A is the surface area of the fuel (m^2), H is the heat of combustion of the fuel ($\mathrm{kJ\ kg}^{-1}$) and χ (< 1) is a factor that accounts for incomplete burning. Experimental techniques are now available for measuring the rate of heat (energy) release in fires, not only for single items of furniture such as armchairs, but also for full-scale room fires (Babrauskas 1992; Sundstrom 1995).

In an enclosure, the rate of burning will be enhanced as $\dot{Q}''_{\mathrm{E}}$ (from the upper parts of the enclosure) gradually increases. This effect will be minimal when the fire is small (i.e. when the heat output is of the order of 10 kW) and can be easily extinguished, but if it is left to develop, $\dot{Q}''_{\mathrm{E}}$ will gradually increase in significance, particularly if the ceiling is low and the fire can spread to involve further areas of combustible material. If there is limited fuel present, or if there is very poor ventilation, the fire may self-extinguish, but otherwise, if left unchecked, it may undergo a rapid transition from a localized fire to one in which all combustible surfaces in the room are burning. The fire is now fully developed, and it is during this phase that there will be thermal damage to the structure and flames will spread from the compartment of origin to the rest of the building, either externally through windows or internally

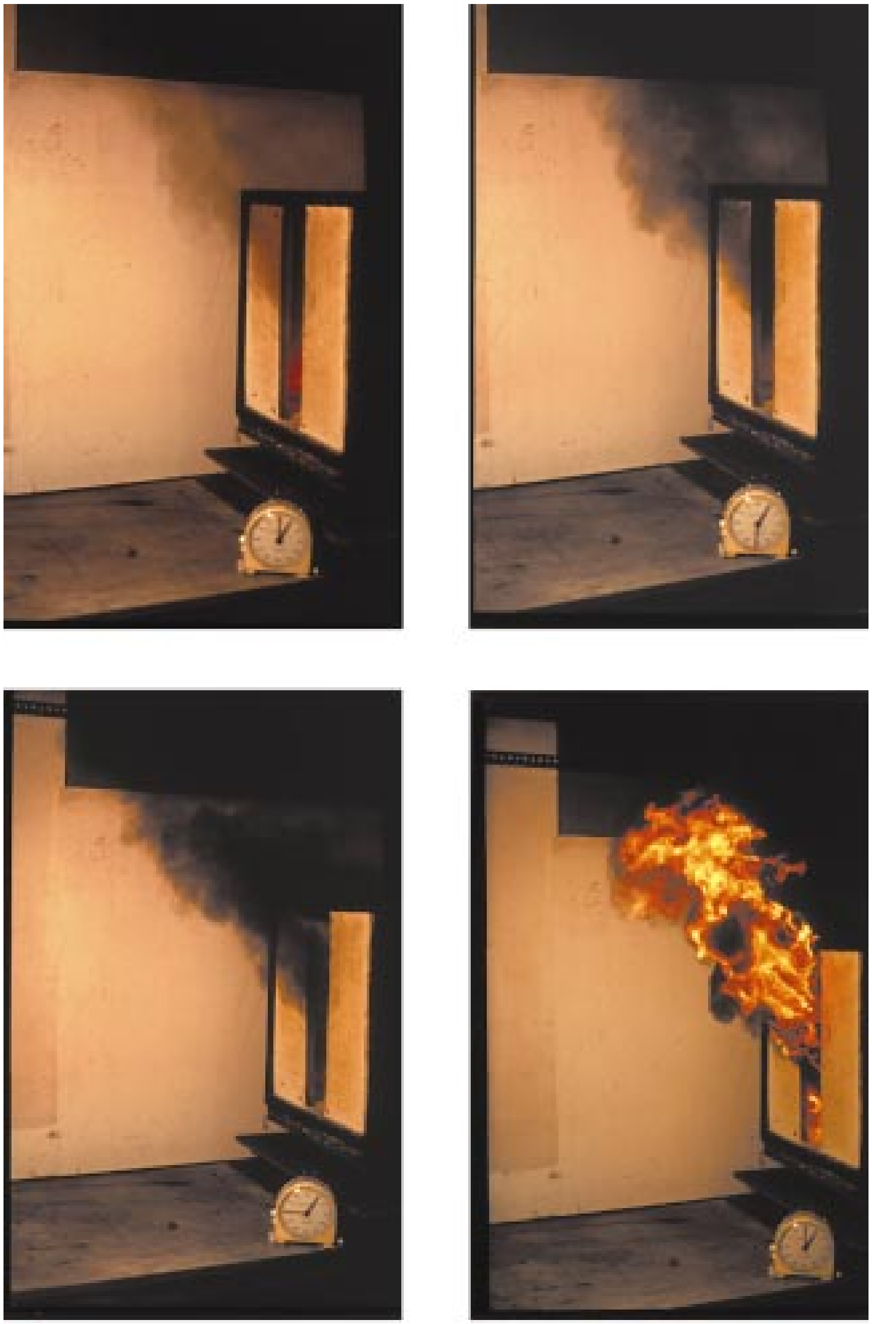

Figure 2. Demonstration of flashover in a small-scale compartment (internal dimensions, 0.4 m × 0.4 m × 0.4 m), with 120 g polypropylene in the form of 6 mm thick strips (100 mm × 10 mm) contained in a lightweight mild steel tray (0.2 m × 0.3 m, by 0.01 m deep). The ventilation opening was 0.1 m wide, 0.4 m high. Ignition was achieved by igniting 100 ml of methyl alcohol in the tray: (*a*) 4 min 00 s; (*b*) 4:30; (*c*) 4:45; (*d*) 5:00. Thereafter, the polypropylene burned out within 45 s.

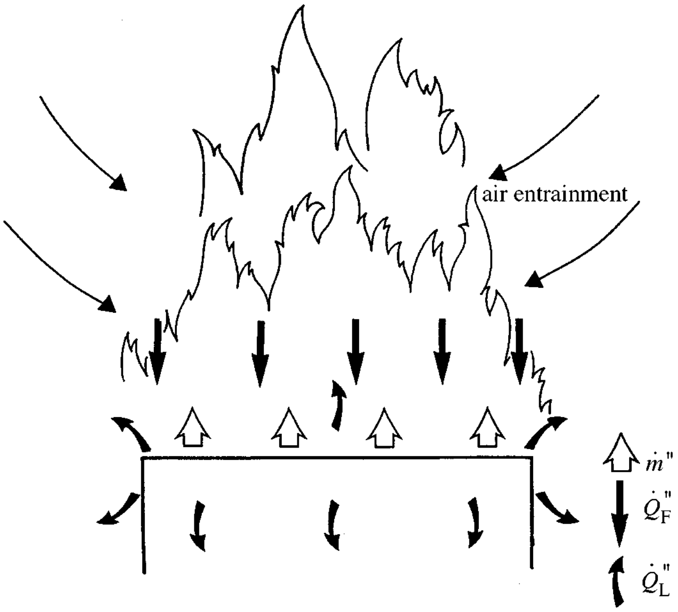

Figure 3. Diagram showing the essential features of the burning of condensed (solid–liquid) fuels (Drysdale 1985).

through open doors or other breaches in the compartment walls. Conditions will rapidly become untenable for the occupants in the remainder of the building. When this happens, the fire may reach a quasi-steady state, limited by the flow of air into the compartment through the openings. The fire is then said to be ventilation controlled: under these circumstances, the rate of supply of air is insufficient to meet the air requirements of the burning fuel, and unburnt vapours escape through the openings to burn vigorously when they encounter a supply of air. The rate of heat release inside the compartment is then dictated by the air inflow. If there is a large ventilation opening and a limited area of burning fuel surface, then the air supply rate may be more than adequate for the rate of burning. Under these conditions, flashover will not occur and the fire will remain ‘fuel controlled’.

The purpose of this paper is to discuss the circumstances and mechanisms that can lead to the flashover transition and examine how the conditions which determine the transition may be defined.

3. Dynamics of the compartment fire

Once an initial, or primary ignition has occurred then, provided no preventive measures are taken, a fire will develop through three major phases; growth, the fully developed fire and decay. This sequence is illustrated schematically in figure 4, in which the power of the fire is measured as the rate of heat release, $\dot{Q}_c$, in MW. The rapid increase in power linking the growth period with the fully developed fire is associated with flashover. The fully developed fire may exceed 10 MW, depending on the ventilation conditions, while the onset of rapid growth is marked by a heat output of the order of 0.5–1 MW, depending on the size of the compartment, the size of the openings to the outside and (to a lesser extent) on the thermal properties of

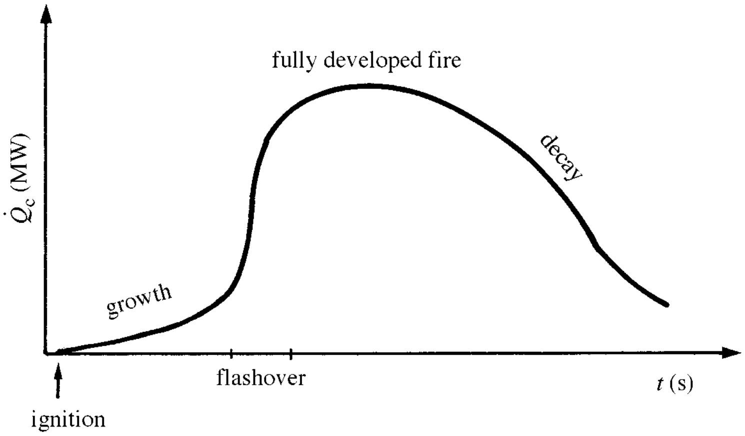

Figure 4. Schematic diagram of the time history of heat release for a typical compartment fire indicating the three main phases and the flashover transition.

its boundaries. In general, conditions in the original compartment become untenable long before the onset of rapid fire growth. Life safety is closely associated with the duration of the growth period, both for those in the room of origin, and for those elsewhere in the building. The greater the duration of the preflashover phase, the longer the period of time available for the occupants to escape to a place of safety.

Various strategies can be adopted to improve safety. Although strict control of ignition sources will reduce the risk of an outbreak of fire, this will have no effect on the course of a fire should ignition occur. A strategy that leads either to the prevention of flashover or to a significant delay is needed; this in turn requires a detailed understanding of the fire processes associated with flashover.

In the early stages after ignition, while the fire is relatively small (e.g. less than 50 kW), it behaves as in the open, spreading slowly over contiguous surfaces at a rate which will be determined by the physical and chemical properties of the fuel (the furniture, etc., in the case of a room fire) and by its configuration and orientation. The flames and hot products will rise vertically as a plume and be deflected by the ceiling to form a ceiling jet whose horizontal travel will be arrested when it reaches the walls (Alpert 1975; Drysdale 1985; Beyler 1986; Zukoski 1995; G. Heskestad, this issue). Thereafter, the hot smoke and gases will accumulate as a steadily deepening layer through which the fire plume will penetrate. The temperature of the layer will be determined by a number of factors, including the rate of heat release from the fire and the vertical height through which cool air from the lower part of the room is entrained into the fire plume. As the fire grows in size and the hot smoke layer descends, not only will the temperature of the layer increase, but the upper part of the flame will be burning in an environment increasingly deficient of oxygen and rich in partly burnt fuel vapours, and soot (Beyler 1985; Zukoski *et al*. 1988). The consequence is that the layer will radiate strongly and the lower portion of the compartment will be exposed to rapidly increasing levels of radiant heat. This has two major effects: it will increase the rate of burning of surfaces already burning ($\dot{Q}''_{\mathrm{E}}$ increases, see equation (2.2)) and it will enhance the rate of flame spread over contiguous surfaces (see, for example, Quintiere 1981; Hasemi *et al*. 1991), thus increasing the burning area. As the radiant flux from the upper parts of the enclosure ($\dot{Q}''_{\mathrm{E}}$) is strongly temperature dependent, the rate of burning will increase rapidly: given the right circumstances, the fire can undergo a rapid transition and become 'fully developed' when all exposed combustible surfaces are involved (see § 5).

Theoretical considerations and experimental observations indicate that 'flashover' is associated with the attainment of certain conditions in the compartment of origin. Specifically, it has been argued in Thomas (1980) and shown by McCaffrey *et al.* (1981) that flashover requires that a critical rate of heat release be achieved within the compartment. The diagnostics associated with flashover have been reported variously as a radiant flux of 20 kW m^{-2} at floor level (Waterman 1968) (effectively, the end of the growth period), a temperature of 600 °C under the ceiling (Hagglund *et al.* 1974; Fang 1975) (indicating that there are flames under the ceiling and marking the onset of the flashover transition), and the establishment of *continuous* flaming from the ventilation openings (Hagglund *et al.* 1974). The latter indicates that the flashover transition has occurred and that the fire has become ventilation controlled, i.e. insufficient air is entering the compartment to burn all the fuel vapours *in situ*. Thomas *et al.* (1980) have summarized the principal contributory mechanisms that are known to participate in the process; namely

(i) an increase in the rate of burning per unit surface area of the fuel;

(ii) enhanced flame spread over exposed surfaces; and

(iii) burning of the smoke layer under the ceiling leading to spontaneous ignition of combustible items remote from the seat of the fire.

All of the above aspects can be accommodated within the hypothesis that flashover represents a rapidly increasing rate of heat release resulting from an instability caused when the rate of heat release within the compartment exceeds the rate at which heat can be lost. This corresponds to the basis of thermal explosion theory (Semenov 1928). The character of the fire changes as it moves to a new state, corresponding to the fully developed ventilation-controlled fire.

From the point of view of life safety, the processes that lead to flashover are of greater importance than the transition itself—thus any process which is capable of reducing the time to achieve this critical rate of heat release must be identified. In effect, this means that it is necessary to predict the evolution of heat-release rate as a result of the growth of the fire area within the compartment. We are still some way from being able to carry out such a calculation, except for very specific situations, such as flame spread over wall linings (Karlsson 1994). However, it is now possible to measure the rate of heat release from items of furniture (such as armchairs) and simple assemblies of combustible materials using the 'furniture calorimeter' which relies on dynamic oxygen depletion measurements in the fire products to determine the rate of heat release (Babrauskas 1992). If the critical rate of heat release capable of giving rise to flashover in a particular compartment was known, then materials and assemblies could be selected on the basis that they could not (singly or together) give rise to the conditions for flashover.

4. Modelling fire growth in a building

In principle, the general solution method for determining fire growth is to consider the conservation of mass, energy, momentum and chemical species. Two types of model are available for developing mathematical models of compartment fire growth, namely field models and zone models.

(*a*) *Field models*

The compartment (together with any wider 'domain of interest') is divided into many small control volumes (typically tens of thousands). For each volume the mathematical treatment is to consider the local conservation of energy, mass, momentum and species, taking into account any initial boundary conditions and adopting a suitable turbulence model. This leads to a model based on partial differential equations (PDEs) involving the Navier–Stokes equations which can only be solved numerically using codes of computational fluid dynamics (CFD). There are a number of general CFD codes available, such as PHOENICS and FLOW3-D (now referred to as CFX), but JASMINE (based on PHOENICS) and SOFIE have been developed specifically for fire problems (Cox 1995). The complete solution of this model may take considerable time to compute and minor changes to the initial set-up may require a full rerunning of the solution routine. However, on the positive side the solutions will be fully three dimensional and time dependent, which at the outset do not assume a particular form of the temperature–flow field. This topic is addressed by Cox (this issue).

(*b*) *Zone models*

The compartment is divided into a small number of control volumes, or zones, in each of which the conditions are assumed to be uniform (Quintiere 1989). The earliest zone models were developed for domestic-sized rooms at Harvard University by Emmons and co-workers in the 1970s (Emmons 1978). The simplest ones for a preflashover fire incorporate only two zones, a homogeneous hot gas layer whose depth increases with time as the fire develops, and a cooler lower layer. These have been used with some success to examine the main features of the developing fire (see, for example, Thomas *et al*. 1980; Bishop *et al*. 1993; Graham *et al*. 1995) and the principles used to extend the model to multiple compartments (see, for example, Jones 1985).

In the single-compartment case, consideration of the conservation of the various properties within the zones produces a model which is based on ordinary differential equations (ODEs). Using semi-empirical relationships and employing a number of assumptions to simplify the model, the derivation becomes very specific and restricted to a particular problem. On the other hand, because the model is a set of ODEs its numerical solution is relatively quick, cheaply achieved and easily repeated.

A convenient four-zone model consists of the upper layer (hot gases and smoke), the lower layer (consisting of clean air), the fuel bed, and the fire plume (which penetrates the upper layer). With time, the smoke layer descends, the height through which air is entrained into the fire plume progressively reduces, and the temperature of the upper layer increases. Eventually, the depth of the hot gas layer will have increased until the smoke is able to flow out of the room through an opening (a window or door), and fresh air will enter at low level to take its place. The rate of heat release of the fire is enhanced by the increasing downward radiation ($\dot{Q}''_{\mathrm{E}}$), and the flame height will increase accordingly. Heskestad (1981, 1995) has shown that the height of the visible flame (l) increases as

$$l = 0.23\dot{Q}_{\mathrm{c}}^{2/5} - 1.02D, \tag{4.1}$$

where $\dot{Q}_{\mathrm{c}}$ is the rate of heat release (see equation (2.3)) and D is the effective fire diameter. As the fire grows, the flame will become tall enough to penetrate the descending smoke layer and eventually impinge on the ceiling. The upper portion of the flame now entrains vitiated gases from the smoke layer, affecting the combustion efficiency and leading to higher yields of partly unburned species, including carbon monoxide and particulate matter (i.e. soot) (Beyler 1985; Zukoski *et al*. 1988). The combined effect of increasing temperature and emissivity of the smoke layer (the latter responding to the increase in thickness and soot concentration as burning progresses) conspires to produce rapidly increasing levels of radiant heat flux at low level. This may be said to mark the onset of the flashover transition.

5. Flashover

There is still some debate in the academic and technical literature regarding the precise definition of the term ‘flashover’. It is argued here that there are several factors that contribute to the process, none of which provide a unique definition. Indeed, it is likely that under different circumstances, different factors may be dominant, but the net effect is the same; the fire undergoes a transformation from being relatively localized to one in which all combustible surfaces are burning—the fully developed fire. A number of other terms appear from time to time, particularly in the Fire Service literature. These include *flameover* and *rollover*, as well as *flashback* and *backdraught*. The first pair are sometimes used by fire-fighters, but they appear to be variants of the ‘flashover transition’, as defined above. ‘Flashback’ has different connotations, normally in the context of a premixed flame propagating back into the tube of a burner when it becomes unstable at low exit velocities (Lewis & von Elbe 1987). It has also been used to refer to the remote ignition of an escape of flammable gas, which then ‘flashes back’ to the source of the leak (also known as a ‘flash fire’). Backdraught on the other hand, is associated with poorly ventilated compartment fires which have created a vitiated atmosphere that is ‘rich’ in unburnt and partly burned fuel vapours. A supply of fresh air, entering as a gravity current when a window breaks or a door is opened, allows the fire to flare up, and the hot fuel-rich oxygen-poor gases burn vigorously as they mix with the incoming air (Fleischmann *et al*. 1994). This produces an effect which resembles a weak confined explosion (Croft 1980), expelling fuel-rich gases which will burn externally as they meet a fresh supply of air. This is a well-known hazard which can cause serious, sometimes fatal, injuries to fire-fighters (Bukowski 1995, 1996) and almost inevitably will be followed by a fully developed fire. In this sense it is a flashover transition of a particular type.

However, flashover need not be associated with compartments with limited ventilation. On the contrary, a sequence of events, which conforms remarkably closely to figure 4 (but involving much higher rates of burning), occurred in the UK at the Bradford City Football Stadium in May of 1985 (Popplewell 1986). The main stand was an open wooden structure, 90 m long and 15 m wide, which had an undivided double pitch roof running its entire length. The front and both ends of the stand were completely open. The fire is believed to have been started by discarded smokers’ material falling on to rubbish which had accumulated in a continuous void under the wooden floor of the rear section of the stand. When it was discovered, the fire was already spreading rapidly and soon burned through the floor to give a fire of considerable magnitude involving the seating area. Within five minutes of discovery, the entire stand was ablaze—a sequence which is consistent with the above definition of flashover as a transition between a localized and the fully developed fire.

In the same way we can identify a flashover transition as having occurred at the King's Cross Underground Station fire (18 November 1987) (Fennell 1988; Moodie 1992). The fire was discovered at 19.30 under a wooden escalator. By the time the Fire Brigade was in attendance approximately eight minutes later, it was still perceived as a 'small' fire, yet at 19.45 it suddenly erupted, spreading rapidly up the escalator to engulf the Booking Hall in flames, fatally trapping those who were still present. This too is consistent with the above definition of flashover, although the mechanism was different from those discussed above. At the Public Inquiry, it was concluded that the so-called *trench effect* had been responsible for the extreme rapidity (Drysdale *et al*. 1992; Moodie & Jagger 1992). It would seem possible to be able to identify a spectrum of 'flashover' events with the well-ventilated Bradford Stadium fire at one extreme and the backdraught phenomenon at the other, with the King's Cross fire occupying an intermediary position.

In view of its importance, it is surprising that there is no established definition of the term flashover, although it is widely used in the scientific and technical literature, as well as in the popular press. The origin of the term is unclear, although it was first used (in a different context) to describe electrical breakdown of cable insulation due to excessive voltage, resulting in the formation of an electric arc (see, for instance, Morris 1992). There is no strict analogy between the two usages beyond the fact that they describe a process which leads to a new 'quasi-steady' state of high-energy dissipation. However, this is not the reason why the term was adopted to describe a fire process: its use appears to have evolved over the last few decades as an appropriate descriptor for a complex sequence of events, without implying or inferring a particular mechanism. If it is accepted that flashover can be broadly defined as the period of rapid fire growth preceding the fully developed fire, then it is clear that the mechanisms that lead to this transition have to be examined. Only then can a proper scientific understanding be developed which will allow practical objectives to be attained, specifically, the development of engineering methods by which flashover may be prevented, or at least delayed, thus improving life safety, particularly in large complex buildings. Not only would this benefit the building occupants and fire service personnel, but it would also reduce the fire losses.

The hazard of flashover in building fires was recognized in the UK in the 1930s, after which standard tests were developed to identify those wall-lining materials that were capable of contributing to the process in the early stages of fire. The 'Surface Spread of Flame Test' and the 'Fire Propagation Test' were developed to this end (British Standards Institute 1987, 1989). However, they were related to the flashover process only through empirical relationships between performance in the tests and the results of full-scale tests with the relevant materials. Moreover, the tests were not designed to give quantitative data which could be used to assess flashover potential, or predict 'time to flashover'.

The 'indicators' of flashover ($20\,\mathrm{kW\,m^{-2}}$ at floor level, $600\,^{\circ}\mathrm{C}$ at ceiling level, and continuous flaming out of ventilation openings) do not inform us of the mechanisms by which flashover is achieved. They derive from observations of flashover in experimental studies of compartment fires. Thus, Waterman (1968) concluded that a critical heat flux of 20 kW m^{-2} was a 'conservative' value to indicate the start of the flashover process from observations of the ignition of paper targets on the floor of experimental fire compartments. This figure has been adopted in a number of computer models as defining the moment at which the flashover process begins. Similarly, a temperature of 600 °C under the ceiling 'at flashover' was observed by Hagglund *et al.* (1974) to precede and accompany the appearance of flames from the ventilation openings (see also Lee 1982).

The three principal mechanisms introduced in § 3 as contributing to the flashover transition are in fact interdependent, and in many cases it is not possible to distinguish which process dominates. The first two ((i) and (ii)) are responsible for the increasing rate of heat release, while the third requires the fire to have grown sufficiently for the flames to reach the ceiling. It is only after this has occurred that the smoke layer will burn, although the mechanism by which this occurs is still uncertain. Beyler (1986) carried out a series of experiments in which he was able to measure the 'stoichiometry' of the combustion process by measuring the rate of entrainment of air into the diffusion flame below the hot smoke layer and comparing it with the rate of supply of fuel vapours. He found that when the fuel–air ratio exceeded 1.7, the layer became unstable and tended to burn. Similar results have been reported by Zukoski *et al.* (1988). It seems likely that this behaviour is associated with the flashover transition as the burning of the smoke layer must invariably be associated with the emergence of flame from openings. It will also lead to a dramatic increase in the radiant flux within the compartment, causing spontaneous ignition of items which are not already burning. This behaviour is to be seen in a number of videos of full-scale fire reconstructions carried out by the Building Research Establishment (1982, 1989).

(*a*) *Critical fire size*

There is good evidence to suggest that flashover can only occur in a given space if the fire has been allowed to grow to a critical fire size. This was first noted by Waterman (1968), who expressed the fire size in terms of a rate of mass loss ($\dot{m}$) for tests carried out in small-scale compartments. No attempt was made to relate this to the size of compartment, or the ventilation area, but Hagglund *et al.* (1974) noted a dependence of the critical burning rate on $A\sqrt{H}$, the 'ventilation factor' first identified by Kawagoe (1958). The theoretical foundations of the argument were first formulated in terms of the rate of heat release by Thomas *et al.* (1980), using a simple zone model. An earlier, but similar model (Quintiere *et al.* 1978) was adopted by McCaffrey *et al.* (1981) to correlate data from over 100 experimental fires which had not reached the fully developed stage (i.e. had not 'gone to flashover'). They used multiple linear regression analysis to obtain a correlation between the temperature excess under the ceiling (ΔT) and the dimensionless groups

$$X_1 = \frac{\dot{Q}_\mathrm{c}}{g^{1/2}(c_p\rho_0)T_0A_\mathrm{w}H^{1/2}}, \tag{5.1}$$

$$X_2 = \frac{h_kA_\mathrm{T}}{g^{1/2}(c_p\rho_0)A_\mathrm{w}H^{1/2}}, \tag{5.2}$$

where g is the gravitational constant, c_p is the specific heat of the gas at constant pressure (kJ kg^{-1} K^{-1}), ρ_0 is the density of ambient air (kg m^{-3}), T_0 is the ambient temperature and the relevant dimensions of the compartment are encapsulated in A_{T}, A_{w} and H. Thus,

$$\frac{\Delta T}{T_0} = C X_1^N X_2^M, \tag{5.3}$$

where C is a constant and the exponents N and M are derived from the regression analysis. Taking $\Delta T = 500\,\mathrm{K}$ as a conservative temperature excess to mark the onset of flashover, and the appropriate values for the other variables, they deduced

$$\dot{Q}''_{\mathrm{FO}} = 610(h_k A_{\mathrm{T}} A_{\mathrm{w}} H^{1/2})^{1/2}, \tag{5.4}$$

where $\dot{Q}''_{\mathrm{FO}}$ is the rate of heat release considered to mark the onset of flashover. For this estimate, the thermal properties of the boundaries are incorporated into h_k, an effective heat transfer coefficient which depends on the thermal conductivity of the walls, etc. This formula has not been adequately tested out with the range of data on which it is based, but it provides some experimental verification for the concept of a critical rate of heat release for the flashover transition to commence. Other correlations have been considered (see, for example, Babrauskas 1980) though these are not soundly based on experimental data (see also Walton & Thomas 1995). It should be noted that if the fire is against a wall, or in a corner, there is experimental evidence to indicate that flashover will occur at a lower rate of heat release than if the fire was in the centre of the room (Lee 1982).

The concept of a critical fire size is also compatible with the model of thermal instability in which the rate of heat release within the compartment exceeds the rate of heat loss (cf. Semenov 1928). Mathematically this can be expressed in simple terms by comparing the rate of production of energy within the compartment, $\dot{Q}_{\mathrm{c}}$ (kW), with the rate of heat loss, $\dot{L}$ (kW). The rate of production of energy is given by

$$\dot{Q}_{\mathrm{c}} = \chi \dot{m}_{\mathrm{f}} \Delta H_{\mathrm{c}}, \tag{5.5}$$

where $\dot{m}_{\mathrm{f}}$ is the rate of pyrolysis of the fuel ($\mathrm{kg\,s^{-1}}$) and ΔH_{c} is the effective heat of the combustion of the fuel ($\mathrm{kJ\,kg^{-1}}$). The rate of heat loss takes into account heat losses through the walls, $\dot{Q}_{\mathrm{w}}$ (kW), and the convective losses as hot fire products flow out of the compartment through any openings, which in turn are replaced by fresh air. This can be expressed as

$$\dot{L} = \dot{Q}_{\mathrm{w}} + c_p[\dot{m}_{\mathrm{a}} + \dot{m}_{\mathrm{f}}](T - T_0), \tag{5.6}$$

where, $\dot{m}_{\mathrm{a}}$ is the rate of air inflow to the compartment and T_0 and T are the ambient temperature and the temperature of the upper layer, respectively. Using equation (2.1), the rate of heat production is governed by

$$\dot{m}_{\mathrm{f}} = \left(\frac{\dot{Q}''_{\mathrm{F}} + \dot{Q}''_{\mathrm{E}} - \dot{Q}''_{\mathrm{L}}}{L_{\mathrm{v}}} \right) A, \tag{5.7}$$

where A is the area (m^2) of the burning surfaces. As in the classic Semenov model for thermal instability, a temperature is reached for which the rate of heat release exceeds the rate at which heat can be lost, i.e. $\dot{Q}_{\mathrm{c}} = \dot{L}$, and a new high-temperature steady state is achieved (as shown in figure 5). In this case the rate of heat production will continue to rise as the fire spreads (as A increases) and the upper layer temperature rises (due to an increase in $\dot{Q}''_{\mathrm{E}}$). In principle a critical fire size can be identified which cannot give a low-temperature intersection of the Semenov diagram (figure 5).

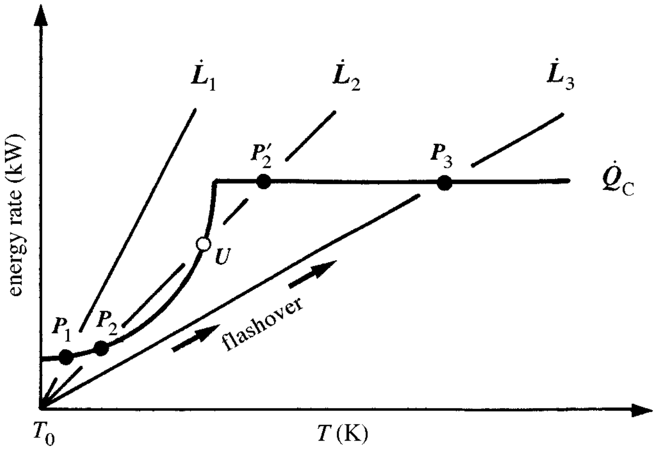

Figure 5. Variation of the energy gain rate and three energy loss rates versus temperature. The intersection of the two curves (at P_1, etc.) correspond to steady-state conditions.

Using a model which draws upon the work of Thomas *et al.* (1980), Hasemi (1981), Emmons (1978, 1983) and others, an approach to the problem of flashover based on a nonlinear dynamical systems perspective was formulated by Bishop *et al.* (1993; see also Holborn *et al.* (1993) together with the results found in Graham *et al.* (1995)). Consideration of the energy balance in the hot gas layer yields an equation for the rate of increase in temperature, T (K), of the hot gas layer:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\dot{Q}_\mathrm{c} - \dot{L}}{c_p m_\mathrm{L}}, \tag{5.8}$$

where m_L is the mass and c_p the specific heat of the gas in the upper layer. Additionally, a further equation was used to define the area of the burning surface (A), and thereby approximate the rate of growth in terms of the fire radius R (assumed to be circular):

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \dot{V} f(R), \tag{5.9}$$

in which $f(R)$ is a bounding function of the fire radius. Here, $\dot{V}$ is the flame spread rate which can be taken as a constant, a function of the air flow into the compartment, or the radiation flux from the gas layer.

The development of the fire is then considered to be made up of a 'fast' variable—representing the temperature of the gas—and a slow variable—in the form of the fire radius. In this way the fire is assumed to be close to its quasi-steady-state equilibrium for any given fire radius.

Initially, the rate of energy gain rises rapidly due to the feedback of heat via radiation from the hot gas layer while the fire is fuel controlled. At some point the flow of incoming air will be insufficient to match this growth and the fire will switch to one which is ventilation controlled. This nonlinear feature checks the increase, effectively capping the rate of heat release (see figure 5). Meanwhile, the rate of energy loss, given by equation (5.6), is approximately linear. We show in figure 5 three such loss rate curves which might correspond to fires of different radii. The intersection of the two curves, i.e. $\dot{Q}_\mathrm{c} = \dot{L}$, determines the steady-state solutions of equation (5.8).

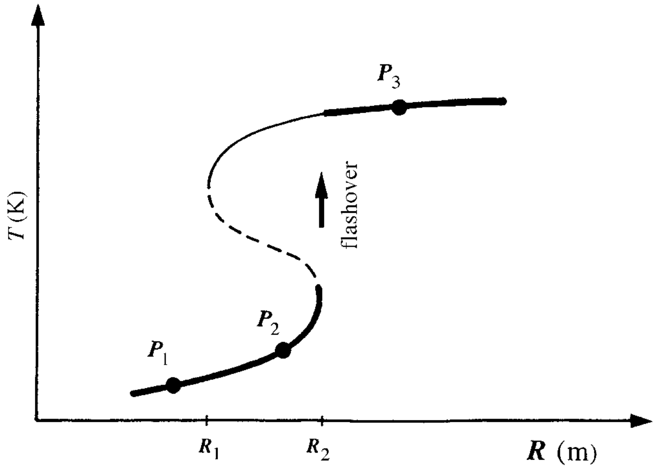

Figure 6. Variation of temperature of the hot gas layer versus fire radius.

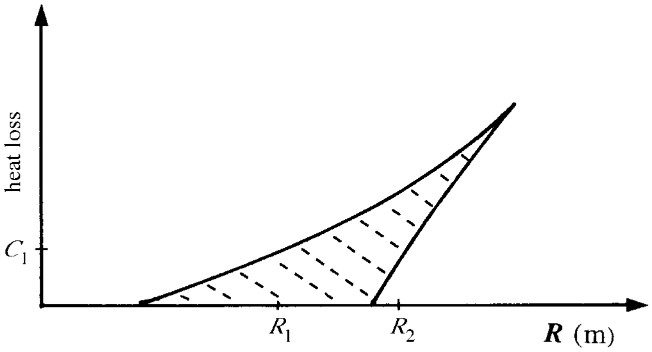

Figure 7. Schematic diagram of a variable representing the compartment characteristics (e.g. heat loss) versus fire radius. The hatched area is the zone in which flashover can occur.

As the fire grows the loss and gain rate curves slowly move relative to one another so that initially steady-state conditions corresponding to the points P_1 then P_2 on figure 5 lead to a low-temperature fire (note that for the loss curve alternative steady states can theoretically exist at P_2' and U, but these are not attained for a fire increasing in size. The point U is unstable, while an additional factor would be required to cause the fire to jump to P_2'). In principle, the critical fire size can be identified, which leads to the high temperature state at P_3 (schematically illustrated in figure 6), with the transition from a low- to a high-temperature fire associated with flashover.

Mathematically the nature of the fire can be investigated by evaluating the eigenvalues of the linearized system with flashover deemed to have occurred when an eigenvalue of the linear system becomes positive. In terms of the gain and loss rate curves, the flashover occurs when the two curves have only one intersection; when the steady state at U (on figure 5) coalesces with P_2 in an event dynamically termed a saddle-node or fold bifurcation (Thompson & Stewart 1986).

The main advantage of this latter model is that since it is based on a simple system of ODEs then it may be repeatedly investigated for a variation of the many integrated parameters that are incorporated into the various coefficients (e.g. the size of the openings, or the thermal properties of the walls). Indeed, codes may be written that follow the fold bifurcation which allow us to essentially bound those parameter values which lead to flashover. Thus the region in parameter space where flashover might occur can be noted. For instance if we consider the fire growth of figure 6 to be for a particular room with given controlling parameters (e.g. thermal qualities of the walls characterized by a heat loss parameter C_1), then theoretically flashover can occur between R_1 and R_2. If we now vary this additional heat loss parameter then we can identify the region in this control parameter space in which flashover may occur (figure 7 schematically illustrates such a diagram with the shaded region corresponding to those values that lead to flashover). While others have sought the critical time to flashover (see Graham *et al*. 1995), the aim of this approach is not to establish detailed quantitative behaviour of the fire but rather to establish under which conditions flashover would occur. The concept would be to incorporate such a model within an integrated design process so that fire safety can be considered at the primary phase of building design rather than after a disaster.

6. Conclusions

The phenomenon of flashover is an extremely dangerous event which all too often leads to tragic consequences. We have highlighted here the need to clarify the various mechanisms that can result in a fire undergoing a flashover transition. Our ultimate goal is to improve our understanding of the fundamental principles underlying the event. If the models and techniques are simple enough, then information provided about whether or not flashover can take place in a given compartment can be used during an iterative design process so that engineers and designers can create buildings which have a lower risk of flashover. We emphasize that if a model can be constructed that allows the circumstances required for flashover to be identified, then the designer, in association with the fire safety engineer, can ensure that for a given space, flashover cannot occur—provided that the design parameters are not exceeded.

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