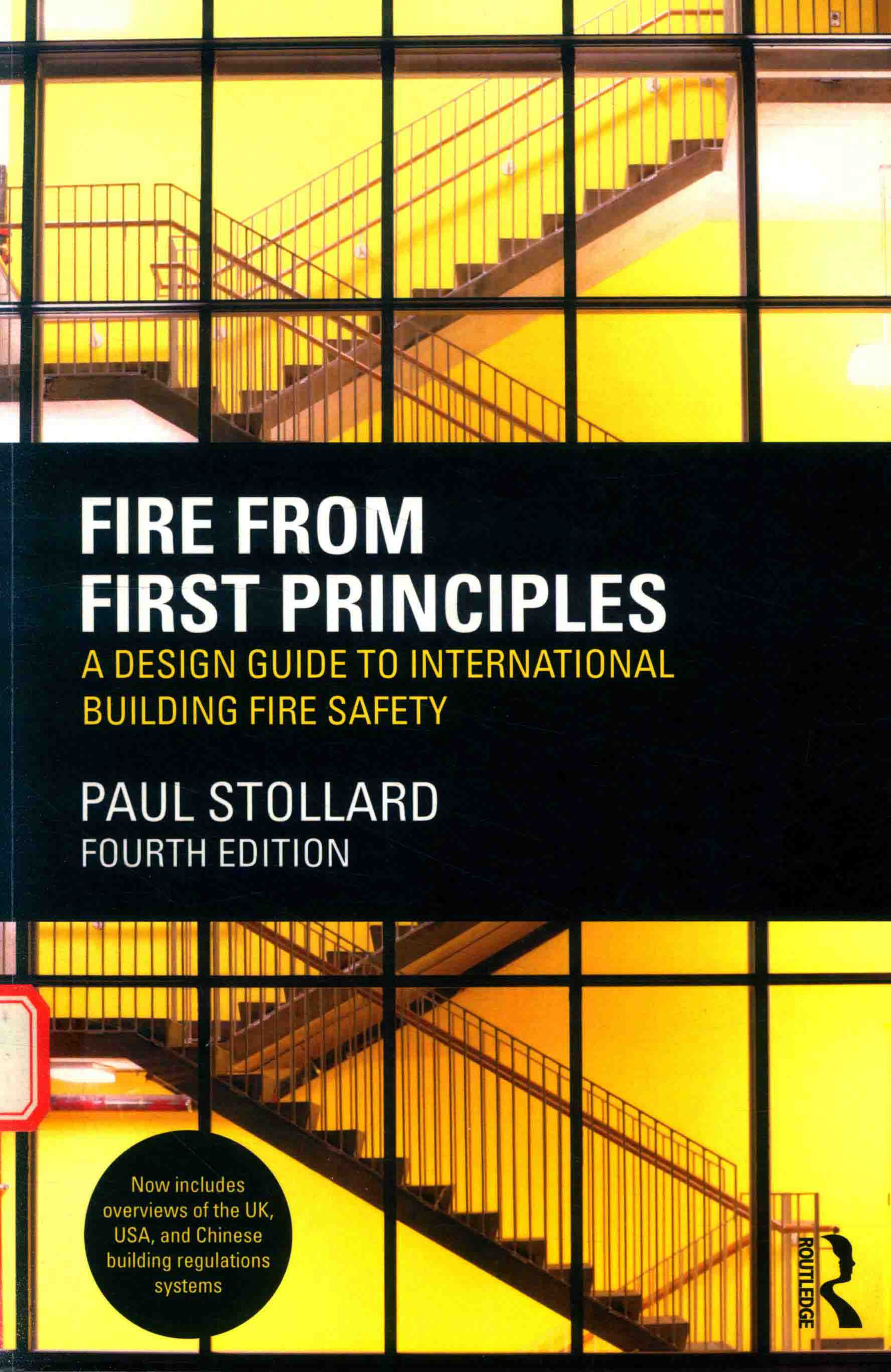

FIRE FROM FIRST PRINCIPLES

A DESIGN GUIDE TO INTERNATIONAL BUILDING FIRE SAFETY

PAUL STOLLARD

FOURTH EDITION

Now includes
overviews of the UK,
USA, and Chinese
building regulations
systems

ROUTLEDGE

Fire from First Principles

A design guide to international building fire safety
Fourth edition

Paul Stollard

with contributions from
Brian J. Meacham, W.K. Chow and X. Dong

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Fire from First Principles

Fire safety is a fundamental requirement of any building, and is of concern to several professions which contribute to the construction process. Following on from the success of the previous three editions, Paul Stollard has returned to update and expand this classic accessible introduction to the theoretical basis of fire-safety engineering and risk assessment.

Avoiding complex calculations and specifications, *Fire from First Principles* is written with architects, building control officers and other construction professionals without fire engineering backgrounds in mind. By tackling an overview of the factors which contribute to fire risk, and how building design can limit these, the reader will gain a fuller understanding of the science behind fire regulations, safe design, and construction solutions.

All regulations content is fully updated, and has been expanded to cover the United States and China as well as the United Kingdom. The book is ideal for students of architecture and construction subjects, as well as practitioners from all built environment fields learning about fire safety for the first time.

Paul Stollard is an architect and chartered fire engineer who has worked in this field for over 30 years. He is a former Director of Abrahams Stollard Ltd, and has been Chief Executive of the Scottish Buildings Standards Agency and Regional Director for Scotland and Northern England with the Health and Safety Executive. He received the 'Peter Stone Award', the highest individual award given annually by the Association of Building Engineers for his work on fire engineering and building standards.

Preface to the Fourth Edition

The three previous editions of this book were written jointly with John Abrahams, who sadly died in 2001. He was one of the first practical fire engineers in the British Isles, working hard to improve fire safety in many building types, most especially health buildings.

From our consultancy and teaching work in the 1980s, we had both come to realise that architects, and the statutory authorities, lacked a design-based guide to fire safety which would enable the underlying principles to be understood and incorporated at the earliest stages of an architectural project. Too many of the existing books simply expounded the legislation without real understanding, or over-complicated issues with too many detailed calculations. Therefore we wrote "Fire from First Principles" together. The first edition was published in 1991, and its preparation received financial support from "The Interbuild Fund". It was such a success that subsequent editions appeared in 1995 and 1999.

This new and completely updated edition is dedicated to John's memory.

Paul Stollard
Edinburgh
July 2013

Introduction

Fire can be useful, but it can also be deadly. It has always fascinated and frightened; and as the proverb states; "fire is a good servant and a bad master". Without fire, civilisation would be radically different, it might not even exist. However, the cost of fires which get out of control is high, and an average of seven to eight people die in fires in the United Kingdom every week.

There is a risk of fire in every building that is designed, and it is accepted that complete safety fire is an impossible goal. The fire risks inherent in different building types are normally only highlighted when a particularly serious and fatal fire attracts public attention, such as the fire in January 2013 at the Kiss nightclub in Brazil which led to the deaths of at least 241 people. Such major fires underline the importance of building design and remind architects of their responsibility to minimise the risks of fire in buildings.

However fire safety is not the only objective which an architect designing a new building has to fulfil. Aesthetic, functional, technological, economic, sustainability are also objectives which must also be satisfied, and there are many more. If the design is to be successful all these potentially conflicting objectives have to be integrated into a coherent whole during the design process. This is where the architect's role is critical and the extent to which the integration is seamless is a measure of the expertise, and hopefully genius, of the architect. This book tries to help that process of integration by outlining the fundamental principles of fire safety so that architects, building surveyors and others in the design team can work from first principles to ensure an integrated design where safety is imperceptibly achieved without detriment to any of the other objectives. Where fire safety measures detract from the appearance, functionally or cost of a building then the architect has failed.

Legislation attempts to set minimum standards of safety with which architects must comply; but attempts to comply without understanding the logic behind the law will lead to either inadequate levels of safety or cumbersome compromises. The design team should never treat legislation as design guidance. Legislation is written for enforcement authorities to check the designs being produced are intrinsically and fundamentally safe, not for architects to use as the basis of the fire safety design.

Therefore this book does not start by describing the legislation, but instead works from first principles to establish a coherent understanding of building fire safety. The various tactics that the architect can use to ensure the safety of the occupants and the protection of the building are outlined as the basis for design. Working from first principles and considering fire safety throughout the design process, the architect will be able to achieve both safer buildings and ones where the fire precautions are less intrusive. Fire safety measures will be less obvious and more effective if designed in, rather than bolted on afterwards.

Although it is essential for architects to work from first principles, it is not necessary for them to become fire scientists. Therefore the principles are laid out as simply and clearly as possible; and to supplement these, a series of tables are included to offer approximate guidance on matters of fire escape and fire containment. These tables are intended particularly for student architects working at the sketch design stage, for whom it is far more important to gain a general idea of what is required, and why, than to understand the minutiae of codes and standards. The inclusion of these tables does not contradict the first principles approach of the book; rather they seek to provide rules-of-thumb which designers can use to check that they are heading in the right general direction.

There is little value in confusing with unnecessary information, even less in presenting a spurious degree of accuracy through complex calculation. An architect should not need to get involved in anything which requires calculation: if the building warrants this, then a fire safety consultant should probably be involved. Therefore there are no calculations or formulae within this book. Similarly there are no references included in the first seven chapters, for this is not an engineering textbook, nor a treatise on fire science.

Chapter 1 provides a brief introduction to the theory of fire safety and introduces the technical terms of fire science which the architect will come across from manufacturers and authorities. The main part of the book (Chapters 2–6) examines the fire tactics available to the architect to achieve fire safety: prevention, communication, escape, containment and extinguishment. These are considered as design parameters and are relevant throughout the design process. Consideration of these tactics will ensure that the building not only complies with the legislation, but more important, offers an acceptable level of safety. Chapter 7 considers the fire assessment of existing building, outlining the basic principles.

Chapter 8 brings together all the information which an architect working in the United Kingdom might need including an annotated and structured bibliography in which further reading in specific areas is identified and a review of the current legislation in the various constituent jurisdictions showing how this relates to the principles of fire safety. Chapters 9 and 10 describe the fire safety legislative and engineering position in other major jurisdictions (the United States, Hong Kong and mainland China). These have been contributed by experts from those particular countries and each is well supported by references to the relevant documents and background texts. The book concludes with a glossary of fire terms.

Although primarily intended for architects, this book can also serve as a useful basic text for the statutory authorities (fire service, building standards, health and safety etc). It is even more important that these groups can understand the first principles of fire on which the legislation is based if they are to be able to enforce it fairly and effectively. One of the common causes of problems between the design team and the authorities is poor communications and a lack of mutual understanding. The early editions have already shown the value of a common textbook, working from first principles, in resolving some of the confusion and it has been used on many such courses.

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Chapter 1

Theory

Invariably there is too little time in the design process for architects to become fully involved in the technicalities of the combustion process and it just is not necessary. Architects do not normally want, and they do not need, to become fire scientists. However, to ensure an acceptable standard of fire safety without allowing it to dominate the design, it is necessary to be aware of what happens in a fire. Architects need to know what their design objectives ought to be, and how these can be achieved. Therefore this chapter briefly sketches in the few essentials that the designer should know, and places them in the context of the design process. It should not be necessary for architects to become involved in calculations, formulae and chemical symbols, and all of these have been avoided here. The references in the final chapters provide boundless technical data, but if architects become involved in the fine detail of chemical reactions or the structure of flames, then they have gone beyond the stage where specialist advice is essential. This chapter, then, is for the "ordinary" architect, who does not have the time or inclination to become a fire safety specialist.

1.1 Fire science

This first section is intended to provide an outline of the key stages in ignition and fire growth and to outline the products of combustion. Some of the most common technical terms are explained, so that the designer will be able to follow manufactures' literature and to discuss their designs with the legislative authorities. A full glossary of fire terms is included at the end of the book, as is an index. Terms in the glossary are highlighted in bold on their first use in the text.

1.1.1 Ignition

Combustion is a series of very rapid chemical reactions between a fuel and oxygen (usually from the air), releasing heat and light. For combustion to occur, oxygen, heat and a fuel source must all be present and the removal of any one of these will terminate the reaction. These three ingredients of **fire** are so essential that they are referred to as **the triangle of fire**. Removal of any of the three (heat, fuel or oxygen) will terminate the reaction and put out the fire.

Flames are the visible manifestation of this reaction between a gaseous fuel and oxygen. If the fuel is already a gas and already mixed with oxygen, then this is described as a **pre-mixed flame**; if the fuel is a solid or liquid and the mixing occurs only during combustion as the fuel gives off flammable vapours, then the flames are described as **diffusion flames**. The gasification of a solid or liquid fuel occurs as it is heated and chemically degrades to produce flammable volatiles. Simply heating a suitable fuel does not necessarily lead to combustion, this only occurs when the vapours given off by the fuel ignite, or are ignited.

The temperature to which a fuel has to be heated for the gases given off to flash when an **ignition source** is applied is known as the fuel's **flash point**, while the temperature to which a fuel is heated for vapours given off by the fuel to sustain ignition is described as the **fire point**. If these vapours will ignite spontaneously without the application of an external flame, then it is said to have reached its **spontaneous ignition temperature**.

Therefore it is not the fuel itself which burns, but the vapours given off as the fuel is heated. Once **ignition** has begun and the vapours are ignited, these flames will in turn further heat the fuel and increase the rate of production of flammable vapours. For the flames to exist at the surface of the fuel, the combustion process must be self-sustaining and capable of supplying the necessary energy to maintain the flow of flammable vapours from the fuel.

In diffusion flames the rate of burning is determined by the rate of mixing of the fuel and oxygen and this is normally controlled by the degree of ventilation, the amount of fuel and the configuration of the room – all factors which the architect can influence. However, no such restrictions exist with pre-mixed flames and therefore the rate of burning can be very much faster. A common example of a pre-mixed flame is the laboratory Bunsen burner. A pre-mixture of fuel and oxygen in a confined space will lead to an explosion risk. Although a gaseous fuel can be mixed in different proportions with air, not all such mixtures are flammable, and it is possible to establish upper and lower **limits of flammability** outside of which flame cannot travel through the mixture.

Throughout this section it is intended to refer to recent fire statistics, showing the practical applications in buildings of the theoretical issues of fire ignition, growth and products. In 20011/12 there were a total of 272,000 fires attended by public fire services in Great Britain; however less than 30 percent of these fires occurred in occupied buildings. In very general terms, these figures are very encouraging as they show the continuing downward trend in the number of fires and consequential injuries, which has been the case for a significant number of years.

It is occupied buildings which are obviously of concern to the architect. In 2011/12 there were 312 fatalities in occupied buildings, with the number of other injuries over 10,000. It is important to distinguish between dwellings and other occupied buildings. Over 60 percent of fires in occupied buildings occurred in dwellings, but they accounted for around 90 percent of the deaths and non-fatal injuries (Table 1.1).

Table 1.1 Fire statistics, Great Britain 2011/12

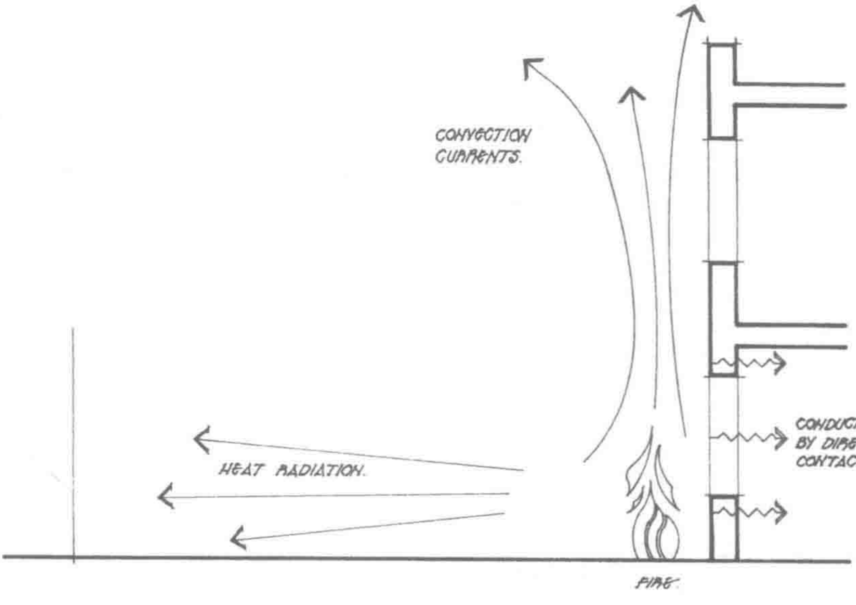
	Fires	*Fatal injuries*	*Non-fatal injuries*
Dwellings	44,000	287	8,900
Non-dwellings	27,000	25	1,200
All occupied buildings	71,000	312	10,100
Outdoor fires	193,000		
Chimneys	8,000		
Total	272,000		

Source: Department for Communities and Local Government, *Fire Statistics, Great Britain 2011 to 2012*, derived from tables 1.1, 2.1 and section 3.1.

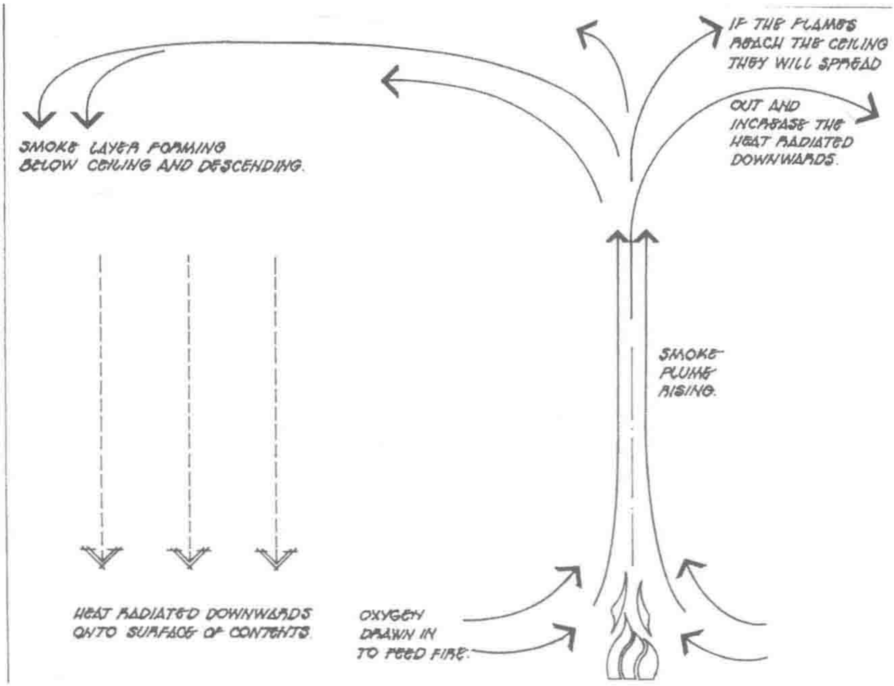
1.1.2 Fire growth

The three basic mechanisms of heat transfer are conduction, convection and radiation; and all three are common in building fires. **Conduction** is the mode of heat transfer within solids, and although it occurs in liquids and gases, it is normally masked by convection. **Convection** involves the movement of the medium and therefore is restricted to liquids and gases. **Radiation** is a form of heat transfer which does require an intervening medium between the source and the receiver (Figure 1.1).

Fires within enclosures behave differently and with different rates of burning from those in the open. It is important to understand the stages in the development of an enclosed fire as they will be the most common (Figure 1.2). The presence of a "ceiling" over the fire has the immediate effect of increasing



1.1
Forms of heat transfer

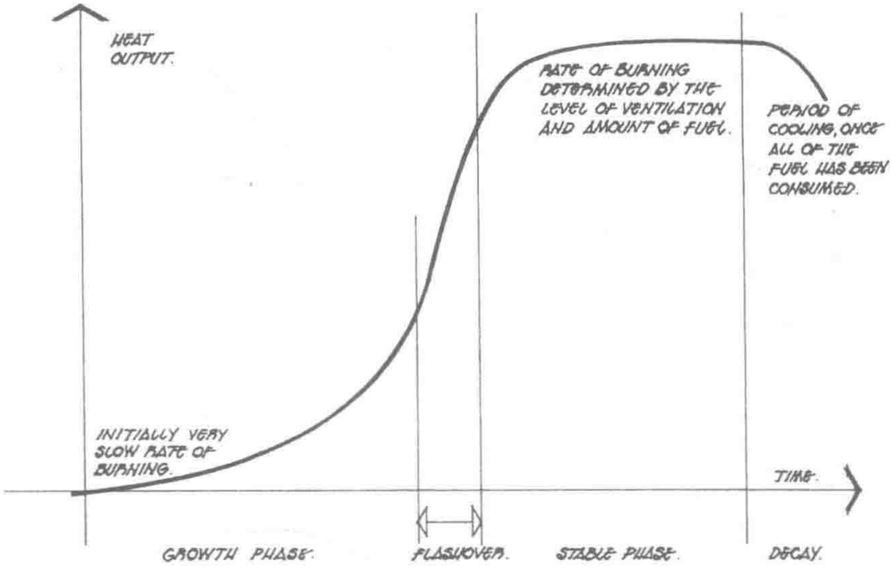


1.2
Standard compartment fire

the radiant heat returned to the fuel, and the presence of the walls will increase this effect, provided there is sufficient ventilation. With sufficient fuel and ventilation, an enclosed fire will pass through a series of stages after ignition: a period of growth, one of stability and then a period of cooling. The plotting of temperature against time from ignition will give a **fire growth curve**, and as these will vary to reflect the conditions of the fire, they are extremely useful to fire scientists considering the consequences of changing the conditions.

The growth period lasts from the moment of ignition to the time when all combustibles materials within the enclosure are alight (Figure 1.3). At first, the vapours given off by the fuel will be burning near the surface from which they are generated; the ventilation is normally more than enough to supply oxygen for this, and the rate of burning is controlled by the surface area of the fuel. The duration of the growth period depends on many factors, but a critical moment is reached when the flames reach the ceiling. As they spread out under the ceiling, the surface area greatly increases. Consequently, the radiant heat transfer back to the surface of the fuel is dramatically increased. This will probably occur (in a domestic sized room with typical furnishings) when the temperature at the ceiling has reached approximately 550°C. The remaining combustible materials will now rapidly reach their fire points and ignite within 3–4 seconds. This sudden transition is known as **flashover** and represents the start of the stable phase of the fire.

If there is inadequate ventilation available to the fire during the growth period, then the fire may fail to flashover due to oxygen starvation. The fire may



1.3
Standard fire growth curve

die out completely, or it may continue to smoulder; and such a smouldering fire can be extremely hazardous as the enclosure fills with flammable vapours. If this is then mixed with a new supply of oxygen (e.g. by a door being opened), it may ignite with an eruption of flame, this effect being known as backdraught. This can be highly dangerous for firefighters attempting to enter rooms to search for survivors, and they have to ensure sealed or semi-sealed spaces are provided with some ventilation at high level before attempting entry.

During the stable phase of an enclosed fire the flaming is no longer localised, but occurs throughout the enclosure. The volatiles are mixing with the incoming air, and the rate of burning will be determined by the level of ventilation and the amount of fuel present. It is this stage of the fire which is of the greatest significance to the architect because maximum temperatures will be attained. The fire resistance of the elements will have to take into account both the maximum temperatures which will be reached and the length of time for which they are likely to be sustained. The final cooling period sees the decay of the fire, once all available fuel has been consumed.

Combustion can only occur if oxygen is present; many extinguishing agents operate by limiting the amount of oxygen available to the fire (e.g. carbon dioxide, foam, sand). The most common extinguishing agent, water, works by cooling the materials involved in the reaction. Without heat the reaction cannot start and if the materials are suddenly cooled the reaction will cease. The third method of extinguishing a fire is by interrupting the reaction itself, and dry powder does this by slowing down the reaction until it ceases to be self-sustaining.

Looking at the statistics for fires in occupied buildings, it can be seen that between 33 and 43 percent are confined to the first material ignited and only 9 to 13 percent extend beyond the room of origin, with the greater fire spread occurring in the occupied building other than dwellings. Over 90 percent of fires in dwellings do not extend beyond the room where they start. These figures are based on the spread of fire damage, and may not fully take account of smoke spread in advance of the fire (Table 1.2).

The major products of combustion are heat, light and smoke. The smoke consists of chemicals produced by the oxidisation of the fuel. They are included with fine particles of burnt and unburnt fuel, drawn into (entrained in) a buoyant plume of heated air. Mixed with this there may be toxic gases produced by combustion. Light is unlikely to be a danger, but the other two products, heat and smoke, are both particularly dangerous and must be designed against.

1.1.3 Heat

Smoke damage to a building can be severe, but it rarely causes total collapse; however, extreme heat can completely destroy a building. Steel will have lost two-thirds of its strength by the time it has been heated to around 600°C, a by no means uncommon temperature in a domestic fire. Concrete is a more resistant material; but as reinforced concrete depends on steel for its tensile strength, there needs to be sufficient insulation of the steel to prevent it reaching its critical temperature. Timber, of course, burns, but is a very good structural material as burning occurs at a fairly constant rate and so structural timbers can be oversized to provide a known measure of fire resistance. Bricks provide one of the best fire-resistant materials as they have already been kiln-fired at high temperature during manufacture. The design of structural elements to resist heat is the responsibility of the architect and will be considered in more detail in the discussion of containment (Chapter 5).

The amount of heat produced in a fire is often regarded as a measure of the severity of the fire. An understanding of the factors which determine the level of heat production will enable an estimate to be made of the potential of the fire to destroy property, both where the fire started and in adjoining areas. In a compartment fire the rate of burning has been identified as being dependent upon the fuel and ventilation available. Therefore, it is these same factors which determine the heat which will be produced.

Table 1.2 Fire spread statistics, United Kingdom 1992 (percentages)

	Percentages of fires in dwellings	*Percentages of fires in other occupied buildings*
Confined to first material ignited	43	33
Confined to room of origin	48	54
Confined to building or origin	8	8
Spread beyond building of origin	1	5

Source: Home Office, *Fire Statistics: United Kingdom*, 1992 (1994), derived from table 56.
(Note: this data is not included in the more recent statistics for Great Britain.)