EVALUATION OF FIRE SAFETY

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John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

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in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Evaluation of fire safety / D. Rasbash ... [*et al.*].
p. cm.
Includes bibliographical references and index.
ISBN 0-471-49382-1 (Cloth : alk. paper)
1. Fire protection engineering. 2. Fire prevention. I. Rasbash, D.
TH9145 .E94 2004
628.9′22–dc22
2003023868

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-471-49382-1

Typeset in 9.5/11.5pt Times by Laserwords Private Limited, Chennai, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry
in which at least two trees are planted for each one used for paper production.

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PREFACE

David Rasbash began publishing and teaching about the evaluation of fire safety in the 1970s. The accumulation of contributions to the subject over the succeeding years, by himself and others, reached a stage where a textbook was clearly needed, and David's colleagues managed to persuade him that he was the ideal person to prepare such a book. Having agreed, he planned the book's structure and enlisted 'Ram' Ramachandran, Baldev Kandola, and Jack Watts to contribute a number of the chapters. During the final stages of his illness, David could not complete the task and he was happy to accept the suggestion that Margaret Law might take over and bring the book to completion. Margaret has filled in the gaps in David's chapters and has consulted the other authors about any tricky parts in their work. She found the process to be tiring but completely fascinating.

An engineering approach to the evaluation of safety is not, of course, a new subject. However, what is new about this book is that it brings together data, information, and techniques that are particularly relevant to evaluating fire safety. The authors hope that not only students but also practising engineers will want to dip into its pages many times.

PART I STRUCTURE OF THE FIRE PROBLEM

1 THE PLACE OF FIRE SAFETY IN THE COMMUNITY

1.1 The nature of the fire hazard

The hazard of fire is the consequence of uncontrolled, exothermic chemical reactions, especially between organic materials and air. It is particularly associated with combustible materials and energy sources used by people in everyday life. Although fire threatens both life and property and its control occasions much expenditure, the hazard must be set against the benefit gained from these resources so that a balanced view can be obtained. Moreover, living standards are highly dependent on the use of buildings. The extra danger when fires occur in an enclosure, with the heat and smoke being trapped rather than moving relatively harmlessly upward, needs to be set against the intrinsic value of using buildings. It follows that one cannot, in general, eliminate fire hazard, although one can reduce it to an acceptably low level by suitable design procedures.

1.2 Interaction between fire hazard and other hazards

Fire takes its place alongside many other hazards in living. These include health hazards such as epidemics and sickness, industrial transportation and domestic accidents, as well as natural hazards such as earthquakes, floods, hurricanes, and so on. The fire hazard can of course be reduced by a severe restriction in the use of energy and combustible materials, but this could bring in its wake suffering and cost in excess of any alleviation of the fire problem. It could even give rise to conditions that prompt other hazards, particularly health hazards. There is a tendency for people who specialize in fire safety to look at the fire problem in isolation. One must be careful not to lose perspective in so doing, for example, with regard to the benefits that might ensue using a material or process that might incidentally impose an increased fire hazard.

This point is illustrated diagrammatically in Figure 1.1 (Rasbash, 1974). Risks are associated with the act of living. Some risks have to be taken, while others are taken voluntarily. Risks are taken to obtain a benefit, of which perhaps a notional measure might be denoted by A. Amongst the risks, there are those with fire, which may inflict a penalty of "detriment" of fire damage and hurt because of fire occurrence. These may be assigned a notional value of f_{d} ("d" for detriment). The fire danger requires a fire safety programme that inflicts a cost of f_{c} ("c" for cost). In the same way, other hazard scenarios inflict detriment h_{d}, and safety programme costs of h_{c}. The

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 ISBN: 0-471-49382-1

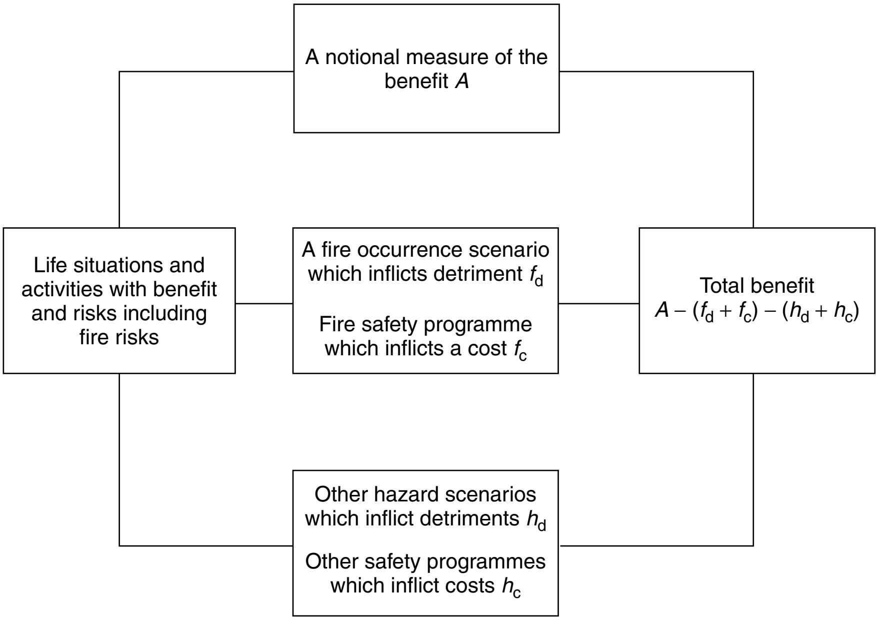

Figure 1.1. Fire safety in the community

object of any rational programme toward controlling fire safety should be to maximize the total benefit: $[A - (f_d + f_c) - (h_d + h_c)]$.

Two examples serve to illustrate this point. Insulation in houses saves energy and would thus increase A. Insulation, particularly on the inside surfaces of a room, is also known to increase the rate of fire spread even if the insulation is not combustible. The introduction of such insulation would therefore serve to increase f_d. Would $[A - f_d]$ be increased by the introduction of insulation? Many effective insulating materials are in themselves highly flammable. This tends to rule out their use on interior walls. It is normal in these circumstances to introduce a noncombustible layer on the inside wall with extra cost f_c. In this case, the relevant benefit is the change in value of $[A - (f_d + f_c)]$.

The provision of smoke stop doors is common in buildings, particularly in the United Kingdom. These of course occasion a certain cost that contributes to f_c. As long as they can be opened when necessary by people escaping a fire, such doors reduce the risk of death in the event of a fire and thus reduce f_d. But an extra cost that tends not to be brought into the equation is the inconvenience of having these doors scattered about buildings, particularly to those who have a physical handicap. There is a consequent reduction of the general benefit factor A, although in this case the reduction is difficult to quantify. This factor usually manifests itself by the doors being propped open much of the time, thus nullifying much of the reduction in f_d. Again, this can be overcome by having such doors held open and closed only following automatic detection of fire. This substantially increases the cost f_c.

1.3 Major fire hazard areas

Fires causing loss and damage can occur wherever human activity occurs. Perhaps the most frequent location for fires is within buildings. These include both domestic and nondomestic premises, and the latter can extend to a wide range of occupancy, such as factories of various kinds, buildings where there are special risks to the public, including places of public assembly and places where people sleep, such as hotels and hospitals. Industrial occupancies extend beyond buildings to include mines, process plant housed in the open, offshore installations, agricultural crops, and forestry. Finally, there is a whole range of facilities for road, rail, marine, and air transport even extending in recent times to satellites and space modules. For most of these hazard areas, a considerable and costly fire occurrence background has built up over the years and has given rise to extensive requirements for fire safety. In the world of fire insurance, specific hazard areas are often called "risks."

1.4 The total cost of fires

The total cost of a fire to a community may be represented by the sum ($f_d + f_c$) for all the fire risks in the community; this would include all buildings, plant, processes, means of transport, and so on. Many items contribute to the sum. With regard to f_d, the detriment produced by fires, we have, of course, the direct toll of life and injury and the actual financial losses caused by fire. There are indirect or consequential effects due to disruption of facilities, loss of trade, and employment. There is also public concern and anxiety, particularly following major disasters and the cost of any inconvenience caused. The cost of fire safety measures f_c includes costs aimed at preventing fires, controlling them when they occur, and mitigating their direct and indirect effects. They include the cost of services such as the fire brigade, fire insurance, and a substantial part of building control or other regulating procedures.

Information on the direct financial loss due to fires has been available in the United Kingdom since World War II. However, it was realized in the 1950s that this direct financial loss was only the tip of the iceberg since it is necessary to be concerned with the total cost of fire. An early exercise to deal with this matter was made by Fry (1964). He found that the direct fire loss in the United Kingdom when corrected for rising prices had remained relatively constant until 1957, although there were indications of an increase after that date. During the whole of the period covered, the direct financial fire loss represented about 0.2% of the gross national product. However, when some other costs of fire relevant to f_c were included, particularly incremental building costs and the costs of fire services and insurance, the total cost of fire to the nation was found to approach about 1% of the gross national product.

In an analysis for 1976, Rasbash (1978) added estimates of costs of indirect loss, fatalities, injuries, and inconvenience to f_d and of fire prevention to f_c. This increased the total value of ($f_d + f_c$) relative to the gross national product by 50%. The fire precaution costs were about twice as great as the cost of losses and hurt. This points to the necessity of being sufficiently discerning in fire safety design to ensure that the increase in the cost f_c brings about a comparable reduction of the expected detriment f_d. The estimated detriment in the Rasbash analysis did not include the cost of public anxiety, which is a major factor following the occurrence of fire and explosion disasters.

Since about 1980, Wilmot has collected data that provide a continuous overview of costs of fire precautions and fire detriment for a number of countries. These are summarized in Section 6.7.4.

1.5 Prescriptive and functional approach to fire safety

In the past, and indeed for the most part in the present as well, the provision of fire safety has been through enactments that have been prescriptive. This may be regarded as the traditional approach to fire safety. More recently, as test methods for performance of items of fire defense have become available, the entirely prescriptive approach to fire safety has become modified, in requiring that items of fire defense fulfill a performance standard. Moreover, there has been a move in recent years from prescriptive to functional, that is, what is proposed can be shown to bring about sufficient safety from fire. This recognizes the multifaceted approach to fire safety and the demand for obtaining cost-effective fire safety. To achieve this it is necessary to specify not only the objective of the fire safety activity but also the degree of fire safety aimed for. There is a tendency for official legislation, at least in the United Kingdom, to be somewhat open ended in this matter. Thus, the Health and Safety legislation generally aims for the level of hazard to be "as low as reasonably practicable" (ALARP) while recognizing risk levels that are either negligible or intolerable. "Not reasonably practicable" may be defined as incurring costs in bringing about a reduction in risks that are seriously out of proportion to the benefits achieved by the reduction in risk (Royal Society, 1983). The relative value of f_c to f_d referred to in the previous section, would indicate that, at least for the United Kingdom as a whole, the level of fire safety reaches this standard. Building Regulations (England and Wales) now aim for some requirements to be for "appropriate levels of safety." Nevertheless, insofar as the requirements are functional rather than prescriptive, the detailed way in which these aims are accomplished is left to the designer.

The difference between the prescriptive and the functional approach is that in the latter it is necessary to quantify the elements of fire safety, particularly how much "fire" can be expected, how much "safety" is being installed, and at how much cost. This helps ensure that money is spent on safety where it is most needed and the least costly regime of precautions capable of providing sufficient safety is put in place. It also helps to give flexibility to designers and to demonstrate that solutions to fire safety for a given risk are equitable and fair. This aspect will assume increasing importance as harmonization is sought on fire safety design between countries with different traditional approaches to fire safety. It has been the practice in the past to follow fire and explosion disasters by lurches of requirements for fire defense. A quantitative fire safety design procedure for complex plant and building hazards would be a major step in avoiding disasters in the first place. Currently, there is a move toward the functional approach to fire safety in buildings by defining the constituent elements to be expected of fire control and fire safety needs in buildings of a given hazard type and setting up performance standards for each of these elements (Bukowski and Tanaka, 1991). It is visualized that these performance standards would not require special expertise for supervision by a control authority.

There is a tendency, particularly in the reports of public inquiries following disasters, for a detailed range of prescriptive measures to be laid down to ensure the disaster "never happens again." Much of this tends to become embodied in prescriptive requirements. However, this need not necessarily be the case. An example of a recommended scheme following a disaster, where the object was to give flexibility of design and management, is given in the Keane report into the inquiry into the Stardust disaster in Ireland (1982). This report indicated the way the hazard in public assembly buildings might be assessed and appropriate fire safety introduced to fit the hazard.

1.6 Purpose and outline of this book

The last few decades have seen the development of methodologies that will allow a designer to accomplish the change from a prescriptive approach to a functional approach to fire safety. It is the purpose of this book to provide a description of these methodologies. Part I deals with the structure of the fire problem and, in addition to this introductory chapter, contains in Chapter 2 a description of the fire safety system. This will outline the constituent and interdependent components of the system, particularly precautions for prevention, protection, and accommodation, concepts of fire safety design and management and the place of quantitative objectives in dealing with fire safety. The major input into fire safety are the lessons of disasters, lessons we continue to have to learn. Chapter 3 gives summaries of some recent fire and explosion disasters that have been studied in detail and those lessons that are currently being absorbed into fire safety requirements. A range of prescriptive requirements for fire safety has been inherited from the past and will be outlined in Chapter 4. An appreciation of these is an important part of the functional approach to fire safety since usually the levels of safety they represent form a basis against which functional approaches to fire safety can be judged. Part II will be devoted to the data that are available for a quantitative functional approach to fire safety. Although Chapter 5 will outline recent physical experimental data, particularly on fire behavior and control, Part II will deal mainly with data from statistical sources on various aspects of fire safety. Part III – Methods of measuring fire safety – will describe the methods currently being developed to pursue the functional approach, particularly methods to quantify fire safety and measure it against objectives. This will feature deterministic, probabilistic, and stochastic methods as well as the use of logic diagrams in fire safety evaluation. The book does not discuss economic aspects. Topics such as cost-benefit analysis, consequential losses, value of human life, decision analysis, and application of Utility Theory, all in relation to fire, are discussed elsewhere (Ramachandran, 1998).

1.7 Definitions

It is desirable to set down the meaning of a number of terms that will be used frequently in this book.

First the word "fire." Fires occur because sources of ignition come into contact with or develop within combustible materials. Most fires, of course, are wanted fires, since they are the most widespread way of making energy available for general use. As far as the context of this book is concerned, fires are mainly of interest where they extend beyond the point of origin to cause hurt, damage, expense, or nuisance. This would exclude wanted fires, unless they fall into the above category, and indeed those unwanted fires that do not extend beyond the point of origin to cause detriment in the above way. But the term is wider than those "fires that result in a call to the fire brigade," which is often taken as a definition of the term "fire."

The word "risk" has been defined as the potential for realization of unwanted negative consequences of an event or process (Rowe, 1977) or the chance of injury or harm (Cassell, 1974). Following this, "fire risk" may be stated as being the chance for injury or harm associated with the occurrence of fire, as defined above. It will be a major concern of this book to quantify the "chance" or "potential for realization" of the risk by characterizing the expected frequency of its occurrence against the severity of the consequences. The words "risk" and "hazard" are interchangeable in general usage. However, in recent years it has become accepted in the professional engineering world that the word "hazard" should cover descriptive definition of the dangerous situation and that the word "risk," a quantification or estimation of the hazard. Thus the nomenclature of the Institution of Chemical Engineers (Jones, 1992) defines "hazard" as

> "a physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these."

"Risk" is defined as

> "the likelihood of a specified undesired event occurring within a specified period or in specified circumstances. Risk may be either a frequency (the number of specified events occurring in unit time) or a probability (the probability of a specified event following a prior event) depending on the circumstances."

More briefly, a glossary of terms associated with fire (British Standard 4422, 1984) defines fire risk as the probability of a fire occurring and fire hazard as the consequences of the event if fire occurs. It will be noted that there is a lack of coincidence between these two pairs of definitions. The latter pair also masks the fact that a fire, if it occurs, can have a whole gamut of possible effects ranging from a call to the fire brigade without damage to the destruction of a city. In this book, the assessment and quantification of fire risk will usually be visualized as the product of the frequency (F) with which fire occurs with each product of the probabilities (p_i) relevant to specific harmful effects (Ha_i) that may follow.

$$\text{Fire risk} = F(p_1 Ha_1 \ldots p_i Ha_i \ldots p_n Ha_n) \tag{1.1}$$

Equation [1.1] embraces both the above pairs of definitions for n harmful effects under consideration. It may not be possible to sum these harmful effects directly for two reasons. Firstly, they may not be expressible in similar terms, for example, number of deaths, direct loss due to damage, and public anxiety. Secondly, the specified harmful effects may overlap, for example, the chances that area damaged may exceed $100\,\text{m}^2$ and $1000\,\text{m}^2$. Where the harmful effect is readily expressible as a mean value, particularly financial loss or areas damaged, then the fire risk can also be expressed as the product of frequency and the mean effect.

The above differentiation between hazard and risk will generally be followed in this book, but it will not be followed slavishly since, in the fire safety world, particularly the insurance world, there is an inherited tendency to use the words "risk" and "hazard" interchangeably and to use the word "risk" for a specific hazard area. The term "risk agent" is the name given to entities, particularly people, exposed to the risk.

The term "major hazard" has come into use to describe an activity, process, or a situation in which the consequences of an incident may be disastrous or catastrophic. The likelihood of such a disaster may be very small, although the public perception of the risk may be influenced by the catastrophic consequence. It is possibly as a counter to this that the professional engineering world has sought to discourage the use of the word "risk," particularly in this situation, except as a quantitative statement of likelihood.

"Safety" is regarded in this book as the inverse, the complement or the antithesis of risk, that is, the lack of potential for unwanted negative consequences of an event, process, or activity. Assuming that air exists everywhere or cannot be rigorously excluded, there is a fire hazard and consequent risk wherever combustible material is present. There are thus very few situations indeed in which one can say that there is a complete absence of fire risk and that fire safety is complete. The quantification of safety will be approached through the quantification of fire risk associated with processes and activities. These may be said to be "fire safe" when a sufficiently low fire risk is associated with them. It should be noted that in this sense the word "safe" covers both a description of the harmful effects arising from the hazard and a quantification of freedom from these effects. For a given harmful effect Ha_1, and assuming that F is substantially less than one per year, which is generally the case for frequency of fires in buildings attended by the fire brigade (Chapter 7), the safety for this harmful effect may be expressed as

$$\text{Safety}(Ha_1) = 1 - Fp_1 \tag{1.2}$$

This is the probability in a year that the harmful effect by fire will not occur.

An alternative definition of safety is

$$\text{Safety}(Ha_1) = 1/Fp_1 \tag{1.3}$$

This is the expected time interval between fires that brings about the harmful effect.

In the fire safety world, one frequently comes across the terms "fire prevention," "fire protection," "fire safety design," and "fire safety management." There is as yet no general consensus on the meaning of these terms, particularly the first two of them. Thus, the term "fire protection" is often implied to cover all of the above terms. This is apparent in the activities of many organizations in this field known as Fire Protection Associations or Organizations. The term "fire prevention" is often used by Fire Services to cover all aspects of fire safety other than direct fire-fighting actions carried out by themselves. The British Standard Glossary of fire terms (British Standard 4422, 1984, Part 1) defines fire prevention as

"measures to prevent the outbreak of a fire and/or to limit its effects"

and fire protection as

"design features, systems, equipments, buildings or other structures to reduce dangers to persons and property by detecting, extinguishing or containing fires."

It will be noted that the second part of the definition of fire prevention overlaps heavily with the definition of fire protection. The IChemE nomenclature (loc.cit) defines fire prevention as

"measures taken to prevent outbreaks of fire at a given location."

and fire protection as

"design features, systems or equipment which are intended to reduce the damage from a fire at a given location."

Specific meanings for these terms as used in this book, which are in line with the IChemE nomenclature, will emerge in Chapter 2, which will introduce the concept of fire safety as a system. The term "fire safety" itself is comparatively recent. It is used to cover all aspects of safety from fire. It is finding increasingly widespread use in this sense, although it is sometimes limited to safety of life only.

"Fire Safety Engineering" is a relatively new term used to describe the discipline concerned with the design and management of Fire Safety for situations in which hazards exist. Traditionally, the terms "Fire Protection Engineering" in the United States and "Fire Engineering" in the United Kingdom have been used. The term "Fire Safety Engineering" was adopted by the author, who found after inquiries that it was less confusing to lay people than "Fire Engineering."

Symbols

A	A notional measure of benefit associated with risk situations
f_c	A fire safety programme that inflicts a cost
f_d	A fire occurrence scenario that inflicts a detriment
h_c	Safety programme other than fire, which inflict costs
h_d	Safety programme other than fire, which inflict detriments
F	Frequency with which fire occurs
p_1, p_i, p_n	Probabilities of specific harmful effects associated with fire
Ha_1, Ha_i, Ha_n	Harmful effects associated with fire

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2 THE FIRE SAFETY SYSTEM

2.1 Basic questions of fire safety

The efficient design of fire safety for a unit such as a building or a plant where there is a fire hazard depends on obtaining answers to three questions. First, how much is the fire hazard? The answer can generally be divided as follows:

1. The likelihood that a fire with unwanted effects will occur.
2. Given that such fires do occur, the ways in which they can develop and be controlled.
3. The potential for the harmful effects produced by these fires to cause detriment, particularly hurt to people and damage to property and processes.

The second question that arises is whether the level of fire safety from the fire hazard so evaluated is acceptable. The acceptability of the hazard will depend on how safe is "safe enough." If the safety level is not high enough, the third question is what further different safety measures need to be introduced. The acceptability of the measures will depend on their cost, the latter including both the financial cost and any deleterious effect they would have on the function of the unit concerned.

The fire safety system considers these questions as an integrated whole. Here, we follow Beard's (1986) definition of a system as an entity, conceptual or physical, which consists of interdependent parts. In the present context, the system is the concept of the fire safety of the whole unit concerned. The model of the fire safety system that will be put forward in this chapter follows the line of the above questions and is based primarily on a series of suggested steps in the evaluation and design of fire safety for specific hazard areas (Rasbash, 1977, 1980). There will also be reference to other systemic approaches to fire safety, particularly the General Services Agency (GSA) and the National Fire Protection Association (NFPA) systems approaches, and the risk management approaches in insurance and industry. However, the dimension of a fire safety system can extend beyond single-hazard areas to cover collections of buildings, ships, aircraft, plants, and so on and indeed whole cities and communities. In large measure, these will tend to be a summation of the fire safety systems of the individual units manifesting the fire hazard.

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 ISBN: 0-471-49382-1

2.2 Fire safety objectives

Many organizations are concerned with the assessment, preparation, and dissemination of requirements for fire safety. Their contribution will be summarized in some detail in Chapter 4. The activity of such organizations represents the traditional and generally accepted way of achieving fire safety. In their deliberations, the procedures they follow must necessarily be influenced at least by the fundamental questions posed in Section 2.1.

In the activities of the above organizations, fire safety objectives are, in general, stated in one of three ways:

(a) To protect life
(b) To protect property
(c) To ensure that a disaster, which has caused the fire safety activity, "must never happen again."

The first two of the above objectives are open to quantitative definition, although rarely explicitly stated. The third objective reflects the impact of major disasters, particularly those with multiple fatality, fire, and explosion, on fire safety requirements and legislation. In absolute terms, it is unachievable in that even if all the precautions recommended for fire safety are put in hand and managed faithfully, there would still remain a remote chance of a fire disaster of similar dimensions happening. This especially follows when it is recognized that all safety measures are subject to human and/or mechanical failure. However, the third objective does imply a major additional objective in its own right, in that the disaster has caused such shock, concern, and anxiety to the public to bring about a demand for this objective to be pursued. Society as a whole has become involved in such a major way that the third objective may be regarded as a manifestation of societal risk or concern.

There is, in addition, another major objective of fire safety that individuals need to bring into focus, and that is maintenance of function. Whatever harm the fire may do, it is necessary for people to carry on and awareness is needed of the circumstances in which the occurrence of a fire would make this very difficult. Jeopardy of the functioning of an organization may arise particularly as a result of the destruction of certain specific key assets in a fire. The objectives of fire safety may therefore be extended to five areas as indicated in Table 2.1.

Most fire deaths and hurt occur near the point of fire origin and result from fires in items such as clothing, furniture, and heating equipment. Objective 1 is therefore, for the most part, the province of consumer legislation and public education on fire safety matters. Objective 2 is usually the prime objective of requirements for public buildings and certain industrial processes. The requirements have been framed particularly in response to disasters that have highlighted major hazards to life, or to the anticipation of such disasters. Objective 3 is usually the province of the management of the enterprise concerned. Objective 4 is deeply embedded in fire safety legislation, although rarely stated overtly at the present time. It can occur where a fire on one person's property involves that of another and it is of particular importance where a fire can grow to involve a whole city or part of a city. This was a relatively frequent occurrence until a hundred or so years ago, but because of fire safety requirements built into city design, it is infrequent in

Table 2.1. Major objectives of fire safety

1. Life safety of individuals
2. Life safety where there is a major societal concern
3. Loss prevention of individual premises and assets
4. Loss prevention of premises and assets where there is a major societal concern
5. Maintenance of function

Table 2.2. Life safety objectives for fires in buildings

1. Protect life (and limb) of individual users or occupants from fires (and explosions) that result from activities for which they (or their immediate family) are responsible.
2. Protect life of individual users of the building from fire that results from activities of: (1) owner or manager of the premises, or provider of services to premises and (2) other users.
3. Protect life of building users from fire that arises from activities of people outside the building.
4. Protect nonusers of building from fire that occurs within the building.
5. Protect life of people called to deal with emergencies, especially firefighters.

Western society today. Objective 5 is normally covered by insurance, which allows for financial cover of assets that could be destroyed, although industrial and commercial organizations may need to take special steps to take into account this aspect of fire safety.

Carelessness on the part of one party causing hurt to another is also a factor in 1 and 2 above. In multiple fatality disasters, many of those killed and hurt are likely to be completely innocent parties. However, fires that involve one or two deaths rarely become matters of major concern, unless a number of incidents of a similar type come before the public. Nevertheless, according to the degree of responsibility of those who may suffer the hurt, different levels of fire safety might be called for. With this in mind, it has been suggested that Objective 1 in Table 2.1 could be extended for fire hazards in buildings, as indicated in Table 2.2 (Rasbash, 1980).

The majority of fire deaths in buildings are in the ambit of Item 1 in Table 2.2. Typically, the fire and the exposed are in the same dwelling or even in the same room. Ignition of clothing due to carelessness, of beds or armchairs due to smoking and misuse of heating and electrical appliances are major causes in this item. In Items 2 and 3, smoke and toxic gas from a fire often move to surround individuals concerned and hinder their escape. Explosions also cause collapses that kill people away from the explosion source. In Item 4, fire spreads into a building from an outside ignition source or another burning building. An explosion, as a consequence of a leak into the building from outside, also comes into this category. Item 5 covers the spread of fire from the building to other buildings or to collapse of buildings onto people outside due to fire or explosion. With regard to Item 6, firemen can protect themselves against normal smoke hazards but are endangered by sudden increases in the flame size, by collapse of the building without warning or by the release of exceptionally toxic fumes.

It is important when attempting to obtain a rational approach to fire safety not only to recognize the relevant objectives that are being pursued but also to give them quantitative definition. It is reasonable to do this in financial terms for Objectives 3 and 4 in Table 2.1, and in so doing, to pursue a further possible objective of optimizing total fire safety costs to obtain a minimum value of $(f_d + f_c)$ (Section 1.2 and 2.10). This is more difficult for Objectives 1 and 2. Having defined the extent and frequency of hurt that one might be prepared to tolerate, it is possible to approach the optimization of fire safety procedures by looking for a minimum cost and inconvenience for measures specified to bring about the desired degree of safety.

2.3 Steps in fire safety design

Given a specific fire hazard area, for example a specified dwelling, factory, ship, or railway tunnel, the process of designing fire safety has been broken down into a number of steps (Rasbash, 1977, 1980), which, with some minor modifications, have been reproduced in Table 2.3. The steps logically follow each other in the sequence indicated. These steps may all be regarded as

Table 2.3. Steps in the evaluation of fire safety

1.	Define the fire hazard area.
1a.	Identify people, property, and processes at risk from fire and explosion incidents within the fire hazard area.
2.	Define the fire safety objectives.
3.	Assess materials that can burn.
4.	Assess sources of ignition.
5.	Assess the conditions of fire spread that would lead to an established fire.
6.	Assess agents that cause fire (i.e. that bring 3, 4, 5 together).
7.	Estimate the probability of fires being caused.
8.	Assess the means available of limiting fire, (1) active means (2) passive means.
9.	Estimate the courses of fire behavior.
10.	Assess the harmful agents produced by fires and their capacity to harm people and property
11.	Estimate the production and range of action of harmful agents produced by fires.
12.	Assess methods of protection against the harmful agents.
13.	Estimate the direct detriment to people and property that may be caused by fires.
14.	Assess available methods of protecting people and processes from the indirect effects caused by direct detriment.
15.	Estimate indirect detriment.
16.	Judge whether estimated direct and indirect detriment comply with fire safety objectives. If Step 16 shows that the objectives of fire safety are not met, then carry out the following steps.
17.	Postulate changes in the fire safety situation, for example in the precautions taken.
18.	Estimate the effect of changes on achievement of fire safety objectives.
19.	Define an acceptable method of achieving objectives, taking into account cost and convenience.
20.	Formulate and express fire safety requirements.

component parts of a fire safety system for the hazard area concerned. They interconnect in the manner shown in Figure 2.1, which may be regarded as a diagram of the fire safety system. It will be seen that the steps concerned are mainly squares representing data acquisition steps or circles representing data processing steps. Except for Step 1, each data acquisition step feeds into at least one data processing step.

Steps 1, 1a, and 2 in Table 2.3 are introductory steps and provide basic information concerning the risk. It is necessary to first define the type of hazard area and the occupancy as described in Section 1.3. This action will give access to relevant legislation literature and fire codes based on previous experience with the type of hazard area concerned (Chapter 4) and to comparative information available in many statistical compilations on fire safety (Chapter 6). Guided by such information and for a given specific hazard area, this step leads to Step 1a, which identifies who and what may be hurt by fire or explosion within the area. This includes the numbers, the nature, and likely location of people both inside and outside the specific hazard area that could be exposed to the effects of an incident within the area and the material items such as stock, equipment, plant and buildings that could be put at risk. In recent years, there has also been concern on the way a fire can damage the environment, particularly by pollution of air caused by smoke from the fire and ground contamination by toxic materials in run-off fire-fighting water. Beyond this, there are processes necessary for maintenance of functions that may be affected if people are hurt or items are damaged or destroyed. These processes include manufacture, servicing, and business processes associated with the enterprise as a whole. Steps 1 and 1a are therefore essential information gathering steps of the sort of fire and explosion experience that may be expected and what may be endangered by such experience.

The definition of objectives as required by Step 2 would, if put forward in quantitative terms, differentiate the systemic approach to fire safety from the traditional, empirical approach of

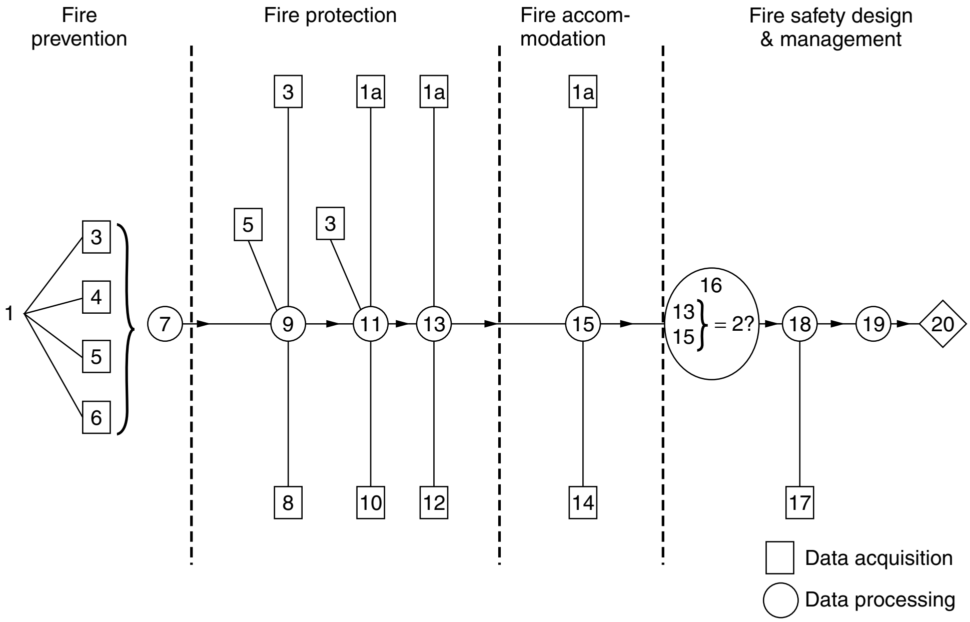

Figure 2.1. Steps in the evaluation of fire safety (see Table 2.3 for description of the steps)

regulatory authorities. The objective could also be an optimum financial balance of cost of precautions and residual risk or a minimum cost necessary to achieve a safety level that may not be expressed in financial terms. The steps from 3 to 16 seek to quantify the hazard to allow comparison with objectives. Data in the acquisition steps (Figure 2.1) are obtained from a detailed study of the specific hazard area concerned. In general, people and property are involved in direct detriment caused by fire and it is estimated in detail by the time Step 13 is reached. Insofar as air or water pollution may cause environmental damage, this should be included in direct detriment. Processes become involved in indirect detriment, in consequential loss and interruption losses, and people who need to recover from direct detriment. These should be accounted for by the time Step 15 is reached. The societal concern associated with Objectives 2 and 3 in Table 2.2 may also be regarded as coming into this category, the process disturbed being the smooth running of society as a whole. If Step 16 shows that the fire safety of the hazard area does not meet the objectives, then it is necessary to carry out the fire safety design process implied in Steps 17 to 19 to ensure that it does.

Finally Step 20, “formulate and express requirements,” may be regarded as a fire safety management step and it is an integral part of the fire safety management process, which requires that fire safety measures be applied in practice and kept under constant review (Section 4.8.5).

The fire safety system as illustrated in Figure 2.1 has the potential of becoming highly complex. It will tend to be characterized over a period of time as the relevant data are acquired. However, it is possible to regard the clusters of factors as leading to separate data processing points in Figure 2.1, that is, to Steps 7, 9, 11, 13, 16, 18, and 19 as subsystems. One could also regard certain continuous groups of processing points as, for example, $7 + 9$ or 9, $11 + 13$ as enlarged subsystems. These subsystems, which are listed in Table 2.4, may be associated with specific limited fire safety objectives. Names are suggested for these subsystems, some of which have been featured in Figure 2.1. It is necessary to feed information into such subsystems appropriate to the data input leading to it. Thus, information on the probability and location of the occurrence

Table 2.4. Fire safety subsystems

Subsystem designation	Data processing steps (see Figure 2.1)	Area of application	Processed data input needed or assumed	Suggested name for subsystem
(i)	7	Occurrence of fire, fire prevention methods	–	Fire occurrence or fire prevention
(ii)	9	Fire growth, fire size, fire extinction	Fire occurrence	Fire development or fire control
(iii)	7 + 9	Total amount of fire	–	Amount of fire
(iv)	11	Amount of harmful effects	Amount of fire	Harmful effects
(v)	13	Direct detriment. Safety from harmful effects	Amount of harmful effects	Direct detriment
(vi)	11 + 13	Direct detriment. Safety from harmful effects	Amount of fire	Main safety
(vii)	9 + 11 + 13	Direct impact of fire. Fire protection methods	Fire occurrence	Fire impact or fire protection
(viii)	7 + 9 + 11 + 13	Total direct cost of fire	–	Total direct cost
(ix)	16	Consequential detriment	Direct detriment	Consequential detriment or fire accommodation
(x)	7 + 9 + 11 + 13 + 16	Total cost of fire	–	Total cost of fire
(xi)	18 + 19	Designing acceptable fire safety	Present situation + change + objectives	Fire safety design

of established fire associated with Step 7 would need to be fed into a subsystem based on 9 + 11 + 13 in which the objective is to estimate direct damage to assets or hurt to people. It is usually in dealing with one of these subsystems or even part of a subsystem that much of the quantitative approach to fire safety has been pursued up to the present time. Section 2.5 will consider these subsystems in some detail. However, before this, it is necessary to outline sources of fire safety data available for the system.

2.4 Sources of fire safety data

The main source of information on fire safety is accounts of fire and particularly fire and explosion disasters that have occurred in the past. Over the course of history, the lessons that have been learnt from past fire disasters have been assimilated in requirements and legislation and into accepted fire safety design. Thus, extensive city fires that are so much a feature of the history of fire are very rare nowadays in Western society because of basic steps in fire safety. These include fire separation of buildings either by party walls or space across streets, noncombustible exteriors to buildings, and organization of fire brigades. Fire disasters in theaters, which occurred particularly toward the end of the nineteenth century, have been countered by the statutory introduction of fire safety measures such as separation of the stage area from the auditorium by the safety curtain and protected means of escape from the auditorium. Also disasters that occurred because of the rapid spread of fire through combustible linings, draperies, and furnishings in a public place, as in the Coconut Grove disaster, have been countered by control of the performance in fire of such items. However, learning from fire disasters is a continuous process and is still a major input into the improvement of fire safety. For this reason, Chapter 3, which gives accounts of some recent fire and explosion disasters, has been introduced as an indication of where we stand currently on this matter. Fire in high-rise buildings, leisure and transport facilities, and industrial processes handling flammable fluids and dangerous substances feature in this summary.

The bulk of recent fire experience in many countries is encapsulated in the form of fire statistics. These provide a major input of data into the fire safety system and into the processes of fire safety design and management. Data based on fire statistics can be fed into specific parts of the system, particularly as lead information into the various subsystems. Statistical information will be considered in detail in Part II of the book.

The third major branch of fire safety information is provided by experimental observation and scientific interpretation of fire processes and methods of countering fire. The present generation has seen a major increase of data in this area, such that it is possible now to describe in quantitative terms major areas of ignition, fire and harmful agent development and control that previously had not been possible. A broad survey of such information as it exists at present will also be given in Part II (Chapter 5). This information also extends to the behavior of people in fire situations.

Throughout Table 2.3, the term *identify and quantify* has been used in association with data acquisition steps. It is of course essential to identify a specific need for data before those data can be quantified. The identification process is aided greatly by experience of past fires together with a detailed examination of the hazard situation. However, the process of quantification still leaves many gaps. In many of the areas where quantification is called for, there is a dearth of objective data. This lack may not only cover intrinsic properties that are measurable but also ways of making use of these properties to predict what needs to be estimated. This is particularly so in the case of the development of fire and the spread of harmful effects. Even where statistical and experimental data are available, doubts can arise as to the relevance of such data to a real hazard. It is inevitable that engineers under such conditions, particularly when working under time constraints, will supplement objective data with subjective data based on their own and other people's judgments. The quality of such data inevitably depends on the experience of the people involved. Indeed, in certain approaches to quantitative fire safety evaluation for recognizable types of hazard, the experience and judgment of a group of people may be deliberately and systematically harnessed to provide necessary quantitative data.

2.5 Subsystems

2.5.1 FIRE OCCURRENCE AND FIRE PREVENTION

Steps 3 to 7, in Subsystem (i), is associated with the prediction of the tendency of fires to start, that is, the expected frequency of fire (F in equation 1.1). The position of this subsystem has been indicated in Figure 2.1. Traditional knowledge of fire ordains that fire will occur when three constituent factors are brought together, namely, combustible materials, heat, and air. Bearing in mind that air is always present unless it is deliberately made absent, it does not need special consideration in the present context. However, two further items are necessary for fire, particularly when it is defined as in Section 1.7. First is the ability of a combustion zone to spread from the point of ignition sufficiently to form what may be called an *established fire* or a fire that can be specifically recognized as following a definition, for example, causing damage or a call to the fire brigade. Second is the agent or agents that bring the conditions for an established fire together. Steps 3 and 4 respectively identify and quantify the materials that can burn and the sources of ignition, and embrace the first two essential components of fire. These are invariably highlighted in methods of risk assessment. Much statistical information has been published, and even more unpublished information exists, tabulating these factors for different occupancies. However, it is desirable in exercises that seek to quantify safety that these steps should go further than the normal pinpointing of materials that can burn and potential sources of ignition. They should include the quantity of heat required to produce fire conditions, the heat that can be produced by the fire itself, that is, the fire load, and indeed, in certain instances, the properties of the reaction itself. The latter is implicitly present in data such as flammability limits, fundamental burning velocity, and conditions for ignition and extinction. The power and the potential for ignition of different sources also need to be classified. Some further detail on these matters is given in Chapter 5. Step 5 covers the ability of the combustion zone to spread from the point of ignition, and is the factor that probably most controls whether there is or is not a fire.

In most hazard areas, extensive amounts of combustible material are present as well as many potential sources of ignition and even many conditions that will allow fire to spread and perhaps even spread rapidly. Yet, fire is a very rare condition, since a causative agent is needed to bring these constituents of fire physically together and induce fire. This is covered by Step 6. The most important of these causative agents are

1. human beings,
2. failure of mechanical and electrical and other forces under human control,
3. natural forces.

They may operate either by introducing an ignition source, for example, smoking materials to where there is flammable material, or vice versa, for example, spillage of flammable liquid near an electrical source, or removing a barrier between ignition source and fuel, for example, fire guard. Human failure includes deliberate, careless, or unintentional introduction of combustible materials to sources of ignition and vice versa. In addition, mistakes made in design, manufacture, and operation of machinery or plant could have the same effect. The natural forces under Step 3 are mainly gravity and wind, although lightning, earthquakes, and tremors are also candidates. Some information on these items is available in certain national statistics. However, in carrying out Step 6, direct experience within a hazard area and knowledge of management attitudes count a great deal.

Information on Steps 3, 4, 5, and 6 is basically what is needed to estimate likelihood of fire occurrence. For most risks, it is difficult to carry this out quantitatively as an exercise in its own right, chiefly because of the widespread use of combustible materials of different kinds, the availability of sources of ignition, and the absence of quantified information on human behavior referred to under Step 6. However, it is possible to make a shortcut to this point by taking figures on the frequency of fire occurrence from statistical information covering a class of similar hazard area. A statistical figure may be adjusted taking into account information in Steps 3 to 6, which suggests a departure, either beneficial or otherwise, from those average conditions for which statistics may be assumed to apply. Experience here of many hazard areas is a useful background in making such a judgment. The precautions taken to prevent fires in the hazard area play a major part in the management of fire safety. They include items such as management, education, and training of staff and other risk agents, housekeeping, design, and maintenance of power and plant equipment, record keeping and follow-up of hazardous occurrences. These may be classified as *fire prevention* measures and the extent to which they are in operation would be relevant to establishing the probability of fires occurring in a given hazard area.

2.5.2 FIRE DEVELOPMENT AND FIRE CONTROL

Subsystem (ii) covers the evaluation of the ability of fires to grow and be controlled. Steps 3 and 5, as well as being input into the fire occurrence subsystem, are major inputs into this system as well in governing what may burn and how rapidly combustible material may become involved. The quantification of rapidity of fire spread is a major objective of fire safety science. Given the existence of combustible materials, some of the common factors that may give rapid fire spread are considered in Chapter 5. The factors particularly depend on the geometry of the combustible materials in relation to the environment and the potential ignition sources. Situations that may give rise to disastrously rapid and extensive fire spread are described in Chapter 5.

Step 8 is a survey of the installed fire protection methods, which may be divided into (1) active methods and (2) passive methods. Active methods include the means of detection, control, and extinction of fire, the availability and effectiveness of the fire brigade, and the extent to which people on the premises have been trained to recognize and cope with fires. Passive methods include the control of the fire-spread conditions that might cause a small fire to become a big one and the means of compartmentation, segregation, and separation against fire within the hazard area. The passive methods are therefore complementary to the fire spread factors included in Step 5. In all situations in which protective requirements play a part, the reliability of the measures taken, and therefore their maintenance, is an essential component of the information needed. With addition of information available in earlier steps, particularly Steps 3 and 5, it is theoretically possible to estimate the courses that fires can take when initiated in various ways, and in various parts of the hazard. This is covered in Step 9. There is a large chance element depending on, for example, the availability and manifestation of various mechanisms of fire spread, the spatial distribution of items to which fires can spread, factors that control burning rate as well as fire spread such as extraneous wind conditions, the time and extent of window shatter, and the probability and effectiveness of functioning of active and passive fire safety measures. A probabilistic distribution of the fire sizes and size/time histories can be more meaningful than an average or maximum fire size, and approaches to this are being developed, which will be described in Part III.

The specific courses of fires through a specified fuel arrangement within the hazard area are often referred to as *fire scenarios* (Chapter 5). These fire scenarios may even postulate the heat output of a fire as a function of time within the hazard area. A statistical approach is also now available for providing the mean and variance of expected growth rates for specific types of hazard areas (Chapter 7).

2.5.3 HARMFUL EFFECTS

Step 1a has served to identify what is at risk. Steps 10 and 11 and Subsystem (iv) define and quantify the amount of the relevant harmful effects that may be associated with the fires defined by Subsystem (ii), particularly specific fire scenarios designated as representing fire development within this subsystem. The major harmful effect to property produced by a fire is heat, but under some conditions, particularly explosions, pressure effects and missiles may become the dominant causes of harm. All these can influence plant or buildings. Where people are concerned, smoke and toxic products also present a dominant hazard. Occasionally, the corrosive nature of the combustion products may cause harm to property. There has also been concern when carbon fiber products are involved in fire that the fibers released may harm electronic equipment (Fiskel and Rosenfield, 1982). Radioactive materials and toxic materials, particularly in industrial plants, although not created by fire, may be dispersed by a fire or explosion. Heat pressure and missiles produced by a fire or explosion may also give rise to the formation or release of other harmful effects, for example, the collapse of a building produces falling masonry, the breaking of a tank may release toxic, corrosive, or flammable materials. This may allow fire to be started in other areas.

For each item or person at risk, and for each kind of harmful effect, there is a critical value of the effect above which harm may be done and a relationship between the value of the effect and the amount of harm done. For heat, smoke, and toxic products, the time of exposure is an important aspect of these damage relationships. Within this subsystem, these critical values are defined and the possible range of distance and time at which they may operate.

2.5.4 DIRECT DETRIMENT

Having defined the potential damaging power of the harmful effects in Subsystem (iv), the actual damage and hurt will depend on the protective methods available to protect the risk agents from these harmful effects. These include methods of escape, smoke control installations, the assistance of emergency services, explosion relief, blast walls, and salvage methods during fire-fighting operations. Fire resistance and distance of separation are major factors in protecting risk agents from heat and in this respect, some of the factors in Step 8(2) are relevant. Dispersion mechanisms for heat, smoke, and toxic products would include buoyancy forces from the fire itself, wind, and imposed air currents. However, these dispersing agencies may also be the means of dispersing dangerous substances such as radioactive and highly toxic materials over a wide area and causing extensive environmental damage. The protective methods may involve the sheltering of the risk agent while in the hazard area. Such data provide the major input into estimating the direct detriment that may be caused by fire covered in Subsystem (v). In practice, it is often difficult to separate the potential of manifestation of harmful effects from the extent to which they may actually bring about damage and it is therefore usually convenient to combine data processing Steps 11 and 13 into one subsystem, namely, Subsystem (vi). This has been called *main safety* subsystem. Given postulated or calculated fire scenarios, this subsystem covers the amount of direct hurt or damage these scenarios can bring about. Subsystem (vii), which also includes the development of fire, has been labeled as the fire protection subsystem since it includes consideration of all direct fire protection methods as distinct from fire prevention methods. Its position is indicated in Figure 2.1. Within this subsystem, values of $p_i\ Ha_i$ (equation 1.1) are estimated insofar as they cover direct detriment.

As far as the occupancy type is concerned, the estimation of direct detriment at this stage would allow a check across to available statistics. Information on damage to people and property by fire, particularly people, is well documented in routine fire reports. If the intention of the exercise is to proceed only with further steps in the analysis, one could feed in details of expectation at this point obtained basically from available statistics but modified according to the information received from previous steps.

2.5.5 CONSEQUENTIAL EFFECTS AND FIRE ACCOMMODATION

Subsystem (ix) deals with the consequential effects that may stem from direct detriment (see also Figure 2.1). The process of dealing with these effects has been called *accommodation* of fire as distinct from prevention and protection against fire described earlier. However, the word does not meet universal approval because of an implication of tolerance and "contingency planning" has been suggested. In industry and commerce, plant, equipment, stocks or data vulnerable to fire may be essential components of processes or operations. Damage to a single small item may affect the condition of a whole process and may even go beyond the hazard area under consideration. Such losses cover indirect business interruption or consequential losses. There is very limited statistical information available on this aspect of risk. It varies in detail from one hazard area to another, and can in general be ascertained only by direct observation and inquiry. As far as people are concerned, death and injury will generally give rise to compensation demands and hospitalization services. There could, in addition, be trauma that may be long lasting, as well as societal concern referred to earlier.

A great deal of detriment and hurt following direct loss and hurt is usually covered by insurance, which is thus a planned accommodation to the loss. Moreover, in addition to the protection methods outlined in the earlier steps to protect risk agents from the direct effects of fire, specific facilities may be available to protect processes threatened by the consequential effects. These may take the shape of duplication of sensitive items, the dispersion of facilities, or of contingency plans for dealing with an emergency (Woolhead, 1976). Taking account of these should allow the expectation of direct detriment estimated in Step 13 to be extended to cover the extra risk agents concerned with indirect detriment giving the total expectation of detriment. An assessment of total expectation of loss taking into account all data processing Steps from 7 to 16 is contained in Subsystem (x) that is entitled *Total Cost of Fire*. The objective of this subsystem is to obtain a total cost of fire risk as covered in equation [1.1] for both direct and indirect harmful effect.

2.5.6 FIRE SAFETY DESIGN AND MANAGEMENT

If the safety estimated for risk agents does not come up to the required standard, changes that could improve matters might be postulated. This may be regarded as the fire safety design process and is covered in Subsystem (xi) (see also Figure 2.1). This would address changes to particular factors that occur in earlier steps and cover fire prevention and protection methods, fire fighting, and contingency plans. A possible change might be to move certain items away from the hazard area, which would modify Step 1a. Alternatively, it might be decided to modify objectives in Step 2. The costs and effectiveness of the changes considered would be major inputs into this subsystem and its objective would be the definition of an acceptable fire safety design.

The steps in Table 2.3 were put forward originally as a method of assessing the safety for a hazard area that was already in existence. For a postulated new building or facility with its accompanying fire hazards, it is very desirable that fire safety design is incorporated early in the design process and certainly well before the building or facility is completed or even seeking legislative approval. The earlier steps, particularly 3 to 13, would cover this initial design process and would tend to be assimilated with later steps 17 to 19. However, these later steps would accommodate later changes called for by interested bodies or a changing environment.

2.6 Contribution of fire safety engineering

The processing of data for the steps in Table 2.3 relevant to a real situation requires a substantial understanding of fire safety engineering. Indeed, the methodology of obtaining the content of these steps for hazard areas of different kinds may be taken as encompassing the bulk of the subject. Many of the steps imply specialization in their own right and even clusters of specialization. If the objectives of the system of precautions are stated in probabilistic terms, it is necessary to feed in data that contain probabilistic expressions of the phenomena concerned. This might occur in any of the data steps.

Malhotra (1991) has put forward a list of fire safety measures that need to be considered by a fire safety engineer when designing fire safety for a building.

1. Fire prevention
2. Fire detection/alarm

3. Fire growth/control
4. Means of escape
5. Smoke control
6. Structural stability
7. Fire-spread control
8. Fire extinction
9. Fire fighting
10. Fire safety management.

Fire prevention is the broad objective of Subsystem (i) and fire safety management follows the fire safety design process in Subsystem (xi) in formulating the requirements of the design process and monitoring and auditing their application (Chapter 4). There are other measures that require quantification in the growth of fire or methods of protection against the harmful effects of fire (Steps 8 and 12 of Table 2.3). Thus, measures 2, 3, 6, 7, 8, and 9 above would generally be considered in Step 8 and measures 2, 4, and 6 in Step 12. Fire detection and alarm plays a major part in both Step 8 and Step 12: in the former by setting in train active measures of fire defense and in the latter by warning people of danger and expediting their escape. Moreover, insofar as fire occurrence is recognized by Step 5 as going beyond an incipient fire to one that is in line with some form of definition of fire (Section 1.7), then fire detection and alarm may also be regarded as contributing to the fire prevention subsystem. Insofar as the specified measures can influence stages in the fire safety system, as estimated by Steps 9, 11, and 13 in Table 2.3, they may be regarded as subsystems of the subsystem involving these stages.

2.7 Approaches to quantitative evaluation of fire safety

It will be apparent from the above comments on the fire safety system that even within a part of the system a wide range of factors may be present, which can influence the objectives of this system or even the partial objectives of a subsystem. This is illustrated in a study of fire safety effectiveness statements (Watts *et al*. 1979) that was addressed particularly to life safety in buildings. Watts lists 66 variables that affect life safety. Of these, 10 described the occupants (Data Step 1), 17 the features of the building (Data Steps 5, 8) 11 the means of egress (Data Step 12), 12 the means of detection, alarm, and extinguishment (Data Step 8), 9 the means of smoke control (Data Step 12), and 6 the properties of the potential fuel (Data Steps 3, 5, 8). In Watt's approach, one can thus recognize an integration of factors occurring within the broader range of disciplines given by Malhotra above. All but four of the 66 variables could be regarded as occurring in the fire protection subsystem, the four exceptions being in the fire occurrence subsystem.

It is necessary for any quantitative approach to the evaluation of fire safety to not only recognize the relevant factors but also quantify and order them in such a manner as to allow their contributions to fire harm and fire safety to be assessed. In general, there are two quite different ways of doing this, which may be respectively termed as *point schemes* and *mathematical models*.

With point schemes following the identification of the relevant factors, a methodology is developed for assessing their importance in achieving or hindering the stated objective, particularly safety of life or property or its converse risk to life or property. The methodology usually involves the systematic harnessing of knowledge and experience of a group of relevant experts. The main object is to develop a system of points according to recognizable levels of the variables involved, which could be processed in a simple manner to give the necessary level of safety or risk. In its application, no detailed knowledge of the way, and in which part of the system the factors contribute to fire safety, is assumed. It is however necessary to calibrate point schemes against an acceptable standard, usually buildings or processes that are regarded as sufficiently safe. Point schemes are also referred to as risk or safety rating schemes, index systems, and numerical grading. With mathematical models, the processes contributing to the safety objectives are directly modeled, particularly through the involvement of quantitative data in one or more of the data processing steps listed in Figure 2.1.

Mathematical models are basically of three kinds; deterministic, probabilistic, and stochastic (Kanury, 1987). However, there is a great deal of overlap between these different types of models. Deterministic models rest on the assumption that the behavior of the factor involved known quantitative relationships with time and space. Elements of fire safety relating particularly to the spread and growth of fire, the formation and movement of harmful agents, and the movement of people have been modeled in this way. Answers to objectives are provided in the form of a "yea" or "nay" because of the assumed certainty of knowledge of the processes. However, the data input into individual factors of a deterministic model can be cast into a statistical form if the likely nature of this input is known to vary. Thus, items such as response to fire brigade, wind direction, and expected fuel load in given premises over time would be expected to manifest variability. Moreover, a basically deterministic model can be applied to a wide range of similar units, for example, retail premises or office buildings in which perhaps a basic fire growth model is served with data representing a wide range of premises. Probabilistic models take into account the contribution of a number of factors by ordering the factors in a logical way, assessing their likelihood of coming into play. The performance of the system as a whole is then estimated by compounding the probabilities. The answers are provided in the form of probability of achieving objectives.

There are difficulties in probabilistic models in dealing with elapse of time. Stochastic models may be regarded as intermediate between deterministic and probabilistic models and apply particularly when random elements involving time and movement are associated with deterministic processes. These models are useful in characterizing the movement of hazardous conditions, for example, flammable vapors, fire, or smoke through time and space. They may also find use in modeling movement of people as they seek to gain access to a safe place.

Mathematical models have found their major use so far within Subsystems (ii), (iii), and (v) (Table 2.4), particularly those aspects that deal with the growth of fire, the emission and movement of smoke, and the movement of people and their egress to a safe area. The elapsed time following onset of fire plays a fundamental part in these processes and the focus of the calculations is to estimate if the people will have enough time to escape before their way of escape becomes blocked. The time (T_f) taken for dangerous conditions due to fire and smoke to spread through a building following the onset of an established fire will depend primarily on the position of the fire and the geometry and fire safety properties of the building. The time taken for a successful egress by people will depend on the time they receive a warning of fire (T_p), the time they respond to warning (T_a), the time it takes to achieve relative safety (T_{rs}), and the time to safe egress in the open air (T_s).T_p is dependent on the fire detection system in place but T_a, T_{rs}, and T_s are highly dependent on the nature of the people at risk. The total of these times needs to be less than the elapsed time, T_f, from ignition for the fire to develop untenable environmental conditions. Marchant (1980) has reviewed components of an escape route system that influence these times and has classified the importance of these components on a scale of 1 to 5, 1 being the most important influence. Factors that need to be taken into account in developing models of safe egress during a fire are given in Table 2.5.

The use of logic trees plays a major part in setting up mathematical models of fire safety. Indeed, Figure 2.1 itself may be regarded as a simple form of logic tree in that it illustrates how specific items of data feed into various points to control safety. The most widely used logic trees

Table 2.5. Selected variables influencing life safety and egress

Variables that describe the occupants

1. Physiological/psychological condition
2. Sociological orientation
3. Previous training
4. Familiarity of the building
5. Egress leadership
6. Alertness
7. Irrational actions/behavior
8. Occupant load
9. Density in corridors/exit ways
10. Ratio of immobile to mobile occupants

Variables that describe the features of the building

11. Height of building
12. Construction class of building
13. Fire resistance of structural members
14. Compartmentation
15. Fire resistance of exit way enclosure
16. Fire resistance of vertical shafts
17. Fire resistance of separation of hazardous areas
18. Protection of openings in fire resistant enclosures
19. Heat actuated automatic closing devices
20. Exposure protection
21. Exterior fire spread
22. Windows
23. Electrical system
24. Mechanical system
25. Elevators
26. Centrally located watch desk
27. Ignition prevention measures

Variables that describe the means of egress

28. Exit way dimensions
29. Egress capacity
30. Remoteness/independence of exit ways
31. Dead end exit ways
32. Lighted exit ways
33. Obvious/identified exit ways
34. Operation of exit way doors
35. Vertical exit way design
36. Heliport on roof
37. Exterior fire escape
38. Balconies
39. Rescue by Fire Department

Variables that describe the means of detection, alarm, and extinction

40. Automatic detection system
41. Manual alarm system
42. Distinctive audible alarms
43. Public address system

Table 2.5 (*continued*)

44.	Emergency control system
45.	Automatic notification of the Fire Department
46.	Automatic extinguishing system
47.	Standpipe system
48.	Portable fire extinguishers
49.	Systems maintenance
50.	Suppression by the Fire Department
51.	Suppression by the in-house fire brigade
Variables describing the means of smoke control	
52.	Structural smoke control
53.	Pressurization of adjacent compartment
54.	Manual HVAC shutdown
55.	Separate shaft for exhaust
56.	Exit ways used as return air plenum
57.	Automatic shaft vents
58.	Compartmented stairway
59.	Opening protection for smoke partitions
60.	Smoke-actuated automatic closing devices
Variables that describe the properties of the potential fuel	
61.	Probability of ignition
62.	Energy load
63.	Rate of energy release
64.	Duration of the fire
65.	Toxicity of the combustion products
66.	Light attenuation by the combustion products

are event trees and fault trees. With event trees, the outcome of a critical event is mapped. Thus, a critical event may be the occurrence of an "established fire" and the tree follows an input of factors as exemplified in Subsystems (ii) to (ix). Another common critical event is the occurrence of a leak of flammable fluid in a process industry. The event tree would follow the history of this leak until it encounters an ignition source and produces a fire or explosion. A fault tree specifies a certain fault and moves backward from the immediate causes of the fault to elemental causes that are responsible for it. Thus, the occurrence of fire itself may be regarded as a fault and Subsystem (i) is a first step to setting up a fault tree that aims at predicting the likelihood of a fire occurring. On the other hand, the occurrence of a major fire disaster itself may be recognized as a fault and the contributing factors leading to that disaster can be identified and quantified by using a fault tree, or as a possible outcome in an event tree. In recent years, there has been an average of less than one major fire disaster per annum (more than 10 people killed) in buildings in the United Kingdom, even though there are about 100,000 fires per annum to which the fire brigade is called, and possibly ten times as many to which the fire brigade is not called. A common factor in many fire disasters in buildings is the sudden change in the fire situation from a small unthreatening fire to a frightening extensive fire. It is important to recognize properties of the building and contents and possible defects in management that may bring this about. Taking cognizance of this in the fire safety design process has at least as important an effect in reducing the likelihood of fire disaster as efforts addressed to reduce the frequency of fires. This matter will be dealt with in Chapters 3 and 5.

Other logic trees known as *success trees* and *decision trees* are also in use. These aim at predicting success of objectives and modeling the outcome of decisions in the fire safety design process. The above methods for the quantification of fire safety will be developed in Part III of the book.

2.8 Other systems approaches

The GSA systems approach to fire safety was developed in the early 1970s by Nelson and may be regarded as the earliest systems approach to fire safety. It covered particularly Subsystem (ii), the fire development subsystem in Table 2.4 as applied to specific federal buildings in the United States. Given the occurrence of an "established fire," it sought to model and estimate the probability of fire spread from the compartment of origin of a fire to the whole floor containing the compartment and thence to the entire building. This was then compared with preset objectives limiting probabilities of fire spread throughout the building. Later modifications of this approach (Nelson, 1977) extended to cover Subsystem (iv) harmful effects, particularly insofar as they affect life safety and maintenance of function (Subsystem (ix)). The GSA system will be covered in detail in Part III, Chapter 16.

The NFPA has developed a systems approach to fire safety based on a logic tree of the success-tree kind, in that the aim of the approach is success in achieving fire safety objectives (NFPA, 1980). This tree, which forms the basis of a number of models of fire safety developed in the United States, will be dealt with in greater detail in Chapter 16. However, at this stage, the parallels between the NFPA system and the systemic approach developed above need to be pointed out. Thus, success in achieving objectives is stated to be obtained in one of two ways: (1) prevent fire ignitions (2) manage fire impact. The first of these is aligned with Subsystem (i), that is, fire occurrence and prevention in Table 2.4. The second may be aligned with Subsystem (vii), fire impact and fire protection. However, there are differences in approach in the structure of the two branches of the NFPA tree. Thus, "prevent fire ignition" is achieved by (1) control heat energy source, or (2) control heat energy transfer, or (3) control fuel response. There is no specific mention of a fire-spread characteristic as postulated in Step 5, although this may be presumed to be present in the factor "control fuel response." There is also no specific mention of the agents that bring the components of fire together as in Step 6, although there is substantial cover of agents that contribute to "control heat energy source." Since the agent that brings the other fire occurrence factors together is often highlighted as "the cause of fire," this perhaps is a limitation of the NFPA tree. The fire safety system represented in Figure 2.1 does not have a specific step dealing with heat energy transfer. However, Step 3 is presumed to include the knowledge of heat transfer necessary to ignite materials and Step 4 is presumed to include the heat transfer that ignition sources are capable of providing.

On the "manage fire impact" fire, the contributing factors are stated to be "manage fire" and "manage exposed." These are covered in Subsystem (ii) (fire development) and Subsystem (vi) (main safety) in Table 2.4 respectively. "Managing exposed" is stated to be achieved by either limiting the amount exposed or safeguarding the exposed and the latter by "defending in place" or by "moving the exposed." Defending while moving is a necessary requirement of "move exposed" and this is provided in the NFPA system by a factor called *provide protected path* as a necessary part of "move exposed." All these are factors that would be part of the data of Subsystem (vi) to be considered either during the initial fire safety assessment or part of the safety design process in Subsystem (xi).

A feature of the NFPA system is the manner in which "prevent ignition," "manage fire" and "manage exposed" are postulated as alternatives to achieving success in fire safety. In practice, it is very rarely possible to rely completely on any one of these, and fire safety design almost

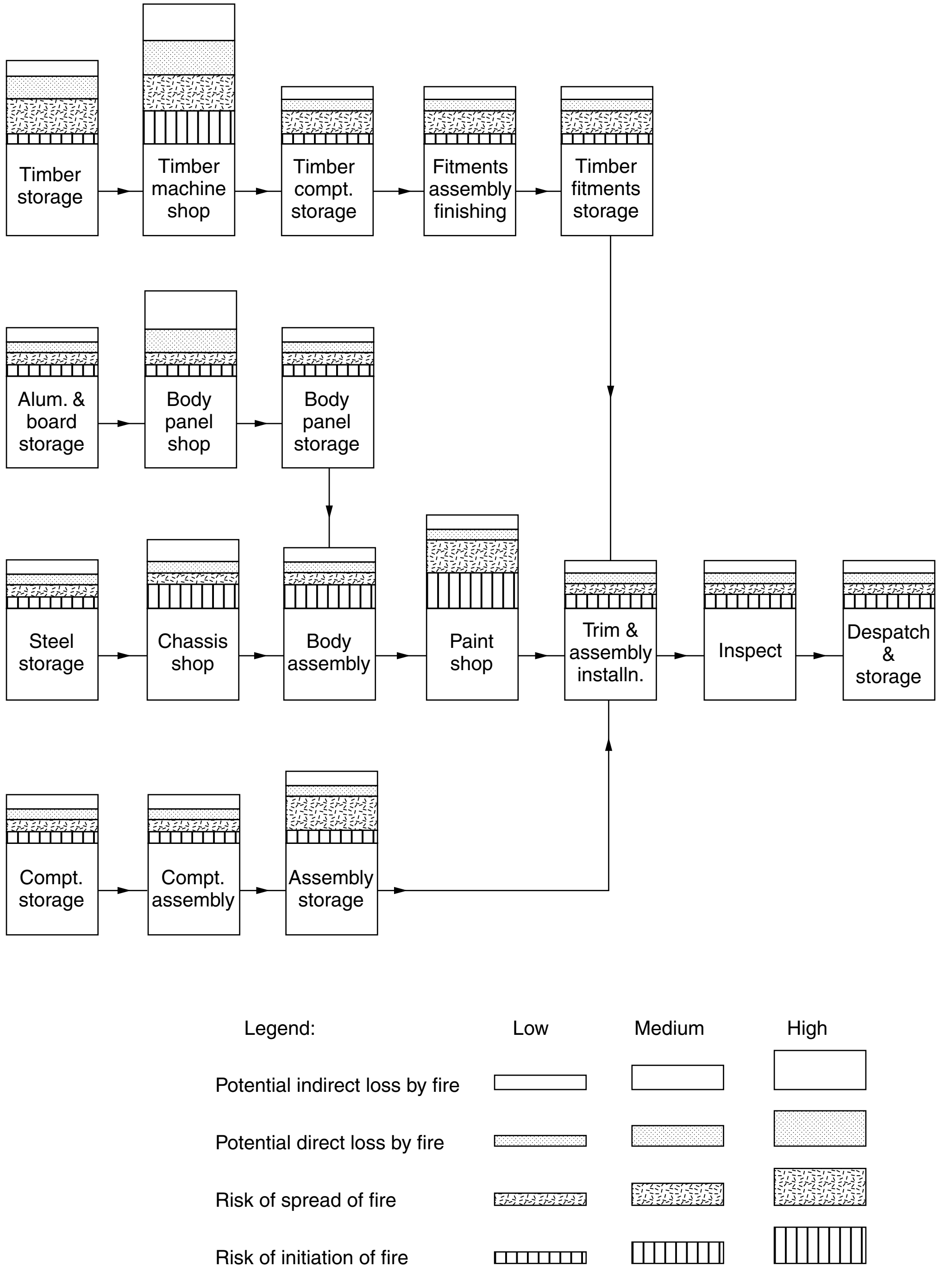

Figure 2.2. Example of representation of integrated fire hazard for industrial premises

invariably depends on an amalgam of all three. The NFPA system does not extend to cover consequential effects of fire and the range of precautions needed to cover these effects. However, the tree is very useful as a detailed indicator of components of fire prevention and fire protection that contribute to fire safety, and where they play their part in the system.

Another early systems approach to fire safety is covered by a document entitled "Management Strategy for Fire," produced by the UK Fire Protection Association. This was focused particularly on industrial premises where there was concern for potential indirect loss from fire, that is, where the "maintenance function" objective was important. The operations for a factory were divided into units and each unit was examined with a view to identifying four components of hazard, risk of initiation of fire (Subsystem (i)), a rudimentary method of quantifying them was made by judging whether the hazard component was low, medium, or high. This would then lead to an overall view of the total fire hazard that could be represented diagrammatically in a manner exemplified in Figure 2.2. Thus, the four components of hazard followed in the sequence given imply a similarity of approach with the systems outlined in Section 2.3 above.

2.9 Risk management

In recent years, an activity known as risk management has grown up within insurance and industrial organizations (Crockford, 1980). This activity is concerned with the identification and handling of a wide range of risks that is inherent in the operation of an industrial organization. These risks may be due to many causes; there are however substantial similarities in the procedures for dealing with them. Fire and explosion risk is but one of a number that might give rise to major disasters. Wind, storm, earthquakes, and floods are also risks of this kind. There is a whole range of accident risks associated with safety of individuals. There are technical risks associated with new processes, marketing risks associated with inadequate monitoring of the market and change of market habits, labor risks with availability and control of staff, liability risks resulting from inadvertent damage to third parties, particularly by products being manufactured, and political and social risks from nationalization, government intervention and so on. Finally, there are the everyday security risks associated with criminal activities of various kinds. There is an increasing tendency for management of such risks in industry to fall within the responsibility of a risk management group or adviser.

Four common components of these risks may be identified

1. *The threat or the hazard.* These are the factors that could produce an adverse result. Many have been enumerated in the previous paragraph.
2. *Resources.* These are the assets, people, processes, and earnings that could be affected by these threats. In the stepwise fire safety system, these are identified in Step 1.
3. *Modifying factors.* These are features, both internal and external, that tend to increase or reduce the probability of the threat becoming a reality, or the severity of the consequences if it does. As far as fire is concerned, these would find expression within the range of data acquisition steps of Figure 2.1.
4. *The consequences.* This is the manner in which the threat manifests its effects upon the resources. For the stepwise fire safety system, this is pinpointed in the data processing steps, particularly 13 and 16.

In general, the items concerned, particularly the modifying factors, are monitored by checklists. An important part of risk management is stated to be the measurement of risk for each of the threats and for each of the resources and, with knowledge of the modifying factors, the estimation

Table 2.6. Statement of loss expectancy used in insurance industry

Estimated maximum loss (EML): Usually expressed as percentage of value of unit under consideration. The fraction is likely to be charged in a serious conflagration.

Maximum possible loss: Financial loss that would occur under catastrophic or extremely unfavorable conditions (Failure of two or more protective systems – active and passive).

Maximum probable loss: Maximum financial loss under normal conditions, for example one protective system failing.

Normal loss expectancy: Financial loss under average operating conditions – all protective systems functional.

of the probability of the threat materializing and the consequences that occur. Usually, these at present are stated to be of high, low, or medium probability with low, medium, high, and possibly catastrophic consequences. However, in some cases, a disciplined methodology is followed on the lines of equation 1.1 to calculate the expectation of loss (Hauan, 1980, Munday *et al.*, *1980*).

In the insurance industry, it is customary to use estimates of expected loss under different conditions in data for estimating premiums. Some of the definitions of loss expectancy are listed in Table 2.6. The association, as indicated in Table 2.6, of the loss with the failure of items of fire safety defense, would allow a quantification of the probabilities of the loss occurring.

Having identified the risk, a number of methods of handling the risk are available. These methods may be roughly equated with the subsystems of prevention, protection, and accommodation associated with Subsystems (i), (vii), and (ix) respectively of Table 2.4. Thus, the risk may be avoided or eliminated, or the probability of its occurrence reduced. This aspect of handling is known as *risk reduction* and may be equated to prevention. Risk protection is a second method of handling risk and may be identified directly with the objectives of protection mentioned earlier, particularly in the reduction in the effects if the hazard materializes. A method called *transfer* is the means of reducing the vulnerability of a particular risk by arranging for someone else to carry part or the entire burden. This is normally done by insurance and may be regarded as part of "accommodation." The expense of all these items in the fire safety system would be regarded as contributing to the fire costs f_c (Figure 1.1). Finally, there is "financing" or "retention" of risk in which one recognizes the risk and carries it oneself. This may also be regarded as an accommodation, but in this case, it would form part of the fire penalty or detriment costs. A contingency plan may be set up within the organization to cover the part of the risk that is not covered by insurance. In general, a small frequent risk may be quantified without too much difficulty and can be carried by the firm. The difficulty arises with very infrequent risks that can cause large losses. Major fire disaster is typical of these.

In general, the requirements for fire safety design and management of any specific hazard mean that precautions are needed in the three domains of prevention, protection, and accommodation. The balance between these three will depend on the understanding of the hazard and the degree of benefit associated with the presence of the hazard. When there is no benefit associated with a hazard, as for example with disease, then as understanding of the hazard increases, there will be a tendency for the management to become dominated by prevention. Where, as in fire, a considerable benefit accrues in situations that give rise to the hazard (Section 1.2), then management will generally consist of precautions in all three domains.

2.10 Trade-off, equivalency, cost benefit, and cost effectiveness

There are many factors that can influence fire safety that would find their place in one or more of the data acquisition steps in the fire safety system. A common activity in fire safety design is to seek to trade-off a particular design feature, which is being called for by regulations, but which is proving difficult or expensive to implement, with a less expensive or less inconvenient feature. What is called for in these circumstances is that the new approach should provide "equivalent" fire safety. If the fire safety system lends itself to a quantitative approach, the fire safety objective could normally be expressed within one of the data processing Steps 7, 9, 11, 13, and 16, particularly, 9, 13, and 16. It is important, however, that the subsystem chosen should be large enough to accommodate the factors that are being considered. If there is no interaction between these factors and other factors in the fire safety system, then estimation of trade-off can be quite straightforward, that is, by how much does each of the factors in the absence of the others improve the fire safety. Complications may arise if one or more of the factors also affects the performance of other components of the system.

A common situation is trade-off between sprinklers and fire resistance. This can be accommodated in Subsystem (ii). In this case, the objective can be defined in Step 9, in that, for example, the fire proceeding beyond a compartment has a certain limited probability. However, if sprinklers, fire resistance, or improvement in fire properties of combustible linings is to be traded off with certain aspects of means of escape, then this would need to be done within the larger Subsystem (vii), since the objective would need to be expressed in Step 13 and the relevant data concerning means of escape are not fed in until Step 12. On the other hand, if the activities, precautions, and hazard areas concerned are covered by a recognized points scheme, equivalence may be regarded as achieved by balancing the allocated points appropriately.

By far the most frequent trade-off calculation compares standard fire protection methods with insurance costs. The standard fire protection methods may be assigned a cost that is part of f_c (see Figure 1.1). The insurance company presumes that this would result in a lower value of f_a and a lower value of insurance cost is charged such that the total cost of fire precautions f_c met by the insured may be reduced. The actual trade-off of a lower value of f_c with a lower insurance premium is, however, carried out by the insurer.

In general, fire safety design tends to be a trade-off between increased cost of fire prevention, protection, and accommodation methods f_c and a lower expected cost of fire detriment f_d. This is the essence of the cost-benefit approach to fire safety. It may be found by investigating the loss and effect of different levels of fire precautions and the resultant effect on f_c that there is an optimum value where the sum $(f_p + f_c)$ is a minimum. However, this is not invariably the case (Rasbash, 1980), as it depends on the rate at which expected fire losses are reduced as fire precaution costs are increased. This is illustrated in Figure 2.3 (a), (b), and (c). (a) indicates a situation in which the rise of precaution costs is less than the initial effect these have on the fire losses. Under these conditions, an optimum is possible. (b) indicates a situation in which the increasing cost of precautions is always more than the reduction in fire losses – no optimum is possible. (c) indicates a situation in which there is a certain high minimum precautions cost. An optimum will appear in total cost, this optimum may still be higher than total cost, in the absence of the precautions considered. A situation of this kind may arise in protecting a risk with precautions that have substantial real basic cost, for example, sprinklers.

Trade-off or equivalency exercises may also indicate a set of precautions where the total cost f_c is a minimum given that f_p is a constant. This particular approach, which is a cost effectiveness approach, needs to be adopted where it is difficult to express f_d in financial terms, for example where the major objectives are associated with life safety, that is, either 1 or 2, in Table 2.2.

2.11 How safe is "safe enough?"

As indicated earlier, absolute fire safety is unobtainable and in fire safety design one is inevitably aiming at a level of fire safety that may be regarded as "safe enough." What should this be? (Given

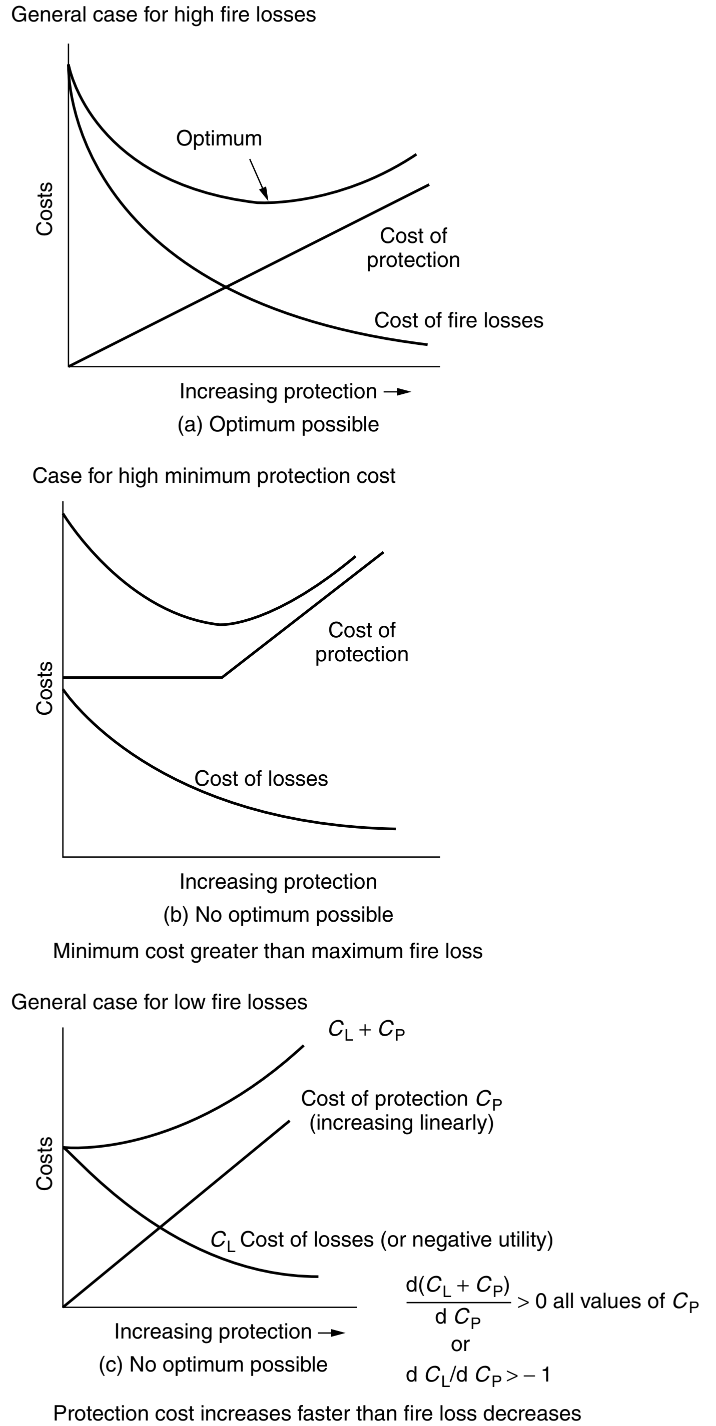

Figure 2.3. Cost effectiveness of fire protection. (a) Optimum possible; (b) No optimum possible – Minimum cost greater than maximum fire loss and (c) No optimum possible – protection cost increases faster than fire loss decreases

the assessment of risk, this is the question that needs to be faced in judging "risk evaluation" (Section 1.7)). In recent years, this question has come to be considered on a much broader scale related to how safe man-made enterprises should be in general, particularly enterprises such as industrial and nuclear power plants that have a potential of producing a catastrophe (CIRIA, 1981, Royal Society, 1983). The answer that is emerging is that the level of safety that is acceptable, particularly for life risk, should be at least that which has been acceptable for risks of a similar kind in the past, having in mind not only the nature of the risk but also the characteristics of the population bearing the risk (Rowe, 1977). A great deal of statistical and anecdotal information of man-made and natural disasters of different kinds has been collected (Rasmussen, 1975, Nash, 1977), which forms a background to this approach. A difficulty arises when one is concerned with an enterprise that gives rise to hazards of a kind that have not been experienced before. Risks from the fallout of radioactive material following a disaster in a nuclear power plant or development of malignant species, if control is lost in genetic engineering enterprises, are candidates for such concern. The perception of risk plays an important part on what is or is not acceptable. A detailed review of this aspect of safety evaluation is available (Royal Society, 1983).

A discussion document of the UK Health and Safety Executive (HSE, 1987) explored in depth the tolerability of risk from nuclear power stations. They suggested that it would be intolerable if a member of the public were exposed to a risk of death of 1 in 10^4 per annum from any large-scale industrial hazard. The risk would be broadly acceptable if it was below 1 in 10^6 per annum. Between these two criteria, the principle of "as low as reasonably practical (ALARP)" should operate. The chance of an accident at a nuclear installation that would bring about more than 100 deaths by cancer should be less than 1 in 10^6. More recently, somewhat more stringent criteria, particularly for individual risk, have been recommended for land-use planning near major industrial hazards (HSE, 1989).

With fire safety, one is dealing with a hazard that is well known to mankind and for which exists a long history of disasters followed by regulation and sufficient safety. Moreover, in recent years, many countries have taken to collecting comprehensive statistics on the occurrence and effects of fire. The potential quantitative measure exists, therefore, of the current levels of fire safety within a community. Assuming such levels are acceptable, this information can be analyzed to produce benchmarks for safety that can be used in a quantitative approach to fire safety design. On this basis, Rasbash (1984) has put forward criteria for acceptability for death by fire to an individual and for multiple fatality fire disasters. For fire risk to an individual, target acceptable probabilities of 10^{-5} to 10^{-7} per annum were suggested according to the nature of the person at risk and the benefit obtained from the risk activity. A summary of recommendations for multiple fatality fire disasters for specific buildings is given in Table 2.7, which is based on the frequency of such fires in Western countries mainly during the period 1946–1982. Such criteria may be used in a manner similar to the use of criteria in quantitative risk assessments for industrial processes. However, the requirement would appear to be more stringent than those suggested above for industrial nuclear installations. Thus, instead of 100 deaths, a target probability of fire risks of 1×10^{-6} per annum is associated with the occurrence of more than five deaths. This target is the product of Fp_i (equations 1.1, 1.2, 1.3), where F is the frequency of fire occurrence and p_i is the probability that given a fire a harmful effect of more than five deaths will occur. The value of F for buildings considered in Table 2.7 is on the order of once in 10 to 100 years (Chapter 7). This implies that given a fire, one is looking for a value of p_i of about one in 10,000 to 100,000 to achieve an acceptable level of safety.

In practice, a difficulty arises in quantitative fire safety design for buildings in general. It is due primarily to limited control and widespread potential for fire, which means there is a dearth of information on many of the factors contributing to fire safety, particularly human factors. (There may be less difficulty for hazardous industrial processes under strict control). As a result, it is