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Application of fire safety engineering principles to the design of buildings —

Part 7: Probabilistic risk assessment

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Contents

Foreword

This Published Document (PD) was published under the Fire Standards Policy Committee and is published as part of the PD 7974 series. Other parts published or about to be published are as follows:

— *Part 0: General principles;*

— *Part 1: Initiation and development of fire within the enclosure of origin;*

— *Part 2: Spread of smoke and toxic gases within and beyond the enclosure of origin;*

— *Part 3: Structural response and fire spread beyond the enclosure of origin;*

— *Part 4: Detection of fire and activation of fire protection systems;*

— *Part 5: Fire service intervention;*

— *Part 6: Evacuation.*

These Published Documents are intended to be used in support of BS 7974, *Application of fire safety engineering principles to the design of buildings — Code of practice*.

It has been assumed in the drafting of this PD that the execution of its provisions is entrusted to appropriately qualified and competent people.

Drafting of this publication was completed in July 2001.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 80, an inside back cover and a back cover.

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Introduction

This Published Document provides guidance on the application of probabilistic risk assessment for fire safety engineering in buildings. This approach can be used to show how regulatory, insurance or other requirements can be satisfied. Probabilistic risk assessment, like fire safety engineering in buildings, is a developing field. As with all engineering and risk disciplines, models and data can never fully describe actual circumstances and so judgement is required in assessing whether a design is acceptable. This judgement should be based on the best and most appropriate facts and evidence available.

This Published Document may be applied to the design of new buildings and the appraisal of existing buildings. Probabilistic risk assessment may be used in conjunction with the other PDs (see Figure 1) and other guidance documents. It may also be used to justify approaches that differ from those in other guidance documents.

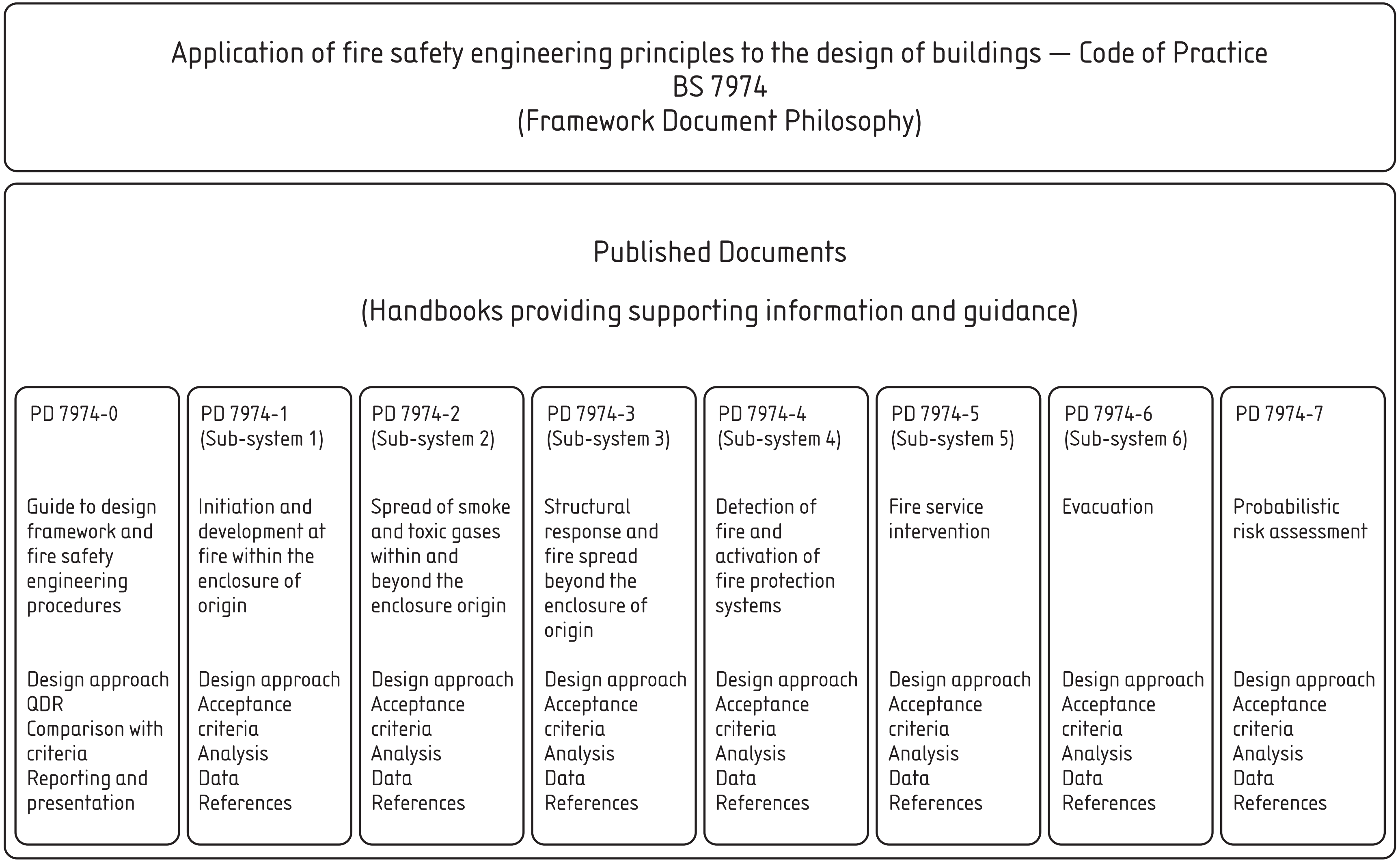


Figure 1 — BS 7974 and the Published Documents

1 Scope

This Published Document provides guidance on probabilistic risk analysis in support of BS 7974, *Application of fire safety engineering principles to the design of buildings — Code of practice*. It sets out the general principles and techniques of risk analysis that can be used in fire safety engineering. This Published Document also outlines the circumstances where this approach is appropriate and gives examples illustrating their use.

This Published Document also includes data for probabilistic risk assessment and criteria for assessment. The data included is based on fire statistics, building characteristics and reliability of fire protection systems. The criteria included cover life safety and property protection, both in absolute and comparative terms.

This Published Document does not contain guidance on techniques for hazard identification or qualitative risk analysis.

Probabilistic risk assessment of fire in buildings (with the exception of nuclear, chemical process, offshore and transport) is not widely used and so a discussion of possible future developments is included.

2 Terms and definitions, symbols and abbreviated terms

2.1 Terms and definitions

For the purposes of this Published Document, the following terms and definitions apply.

2.1.1
As Low As Reasonably Practicable
ALARP
where all reasonable measures will be taken in respect of risks which lie in the tolerable zone to reduce them further until the cost of further risk reduction is grossly disproportionate to the benefit

2.1.2
assessment
undertaking of an investigation in order to arrive at a judgement based on evidence

2.1.3
availability
ability of a system to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

2.1.4
common mode failure
failure that is the result of event(s) that, because of dependencies, cause(s) a coincidence of failure states of components in two or more separate channels of a redundancy system, leading to the defined system failing to perform its required function

2.1.5
conditional probability
probability of an event given the occurrence of a preceding event

2.1.6
consequences
severity of the outcome of an event

2.1.7
deterministic
based on physical relationships derived from scientific theories and empirical results that, for a given set of initial conditions, will always produce the same outcome

2.1.8
diversity
same performance of a function by two or more independent and dissimilar means

2.1.9
event
something happening or that has happened that can be made up of several but mutually exclusive occurrences

2.1.10
extreme value
statistical methodology dealing with the probability distributions of large and small values

2.1.11
failure cause
circumstances during design, manufacture or use which have led to failure

2.1.12
failure mode
predicted or observed results of a failure cause on a stated item in relation to the operating conditions at the time of the failure

2.1.13
fire hazard
physical situation with a potential for harm to life or limb, or damage to property, or both, from the effect of fire

2.1.14
frequency
probability that an event will happen over a period of time

2.1.15
hazard
situation with a potential for human injury

2.1.16
individual risk
frequency at which an individual can be expected to sustain a given level of harm from the realization of specified hazards

2.1.17
initiating event
event that leads to other events and one or more outcomes

2.1.18
maintenance
combination of all technical and administrative actions including supervision actions intended to retain a product in, or restore it to, a state in which it can perform a required function

2.1.19
mean time between failures
MTBF
total cumulative functioning time of a population divided by the number of failures

2.1.20
outcome
result of a chain of events

2.1.21
probability distribution
mathematical function expressing the probability attached to any value of a random variable

2.1.22
probabilistic model
methodology to determine statistically the probability and outcome of events

2.1.23
scenario
set of circumstances and/or an order of events in a fire incident that are feasible and reasonably foreseeable

2.1.24
redundancy
provision of more than one means of achieving a function

2.1.25
reliability
ability of an item to perform a required function under stated conditions for a stated period of time

2.1.26
revealed fault
fault, the occurrence of which is obvious by termination of the ability of the affected item to perform a required function

2.1.27
risk
probability of occurrence of a hazard causing harm and the degree of the severity of the harm

2.1.28
risk to life and health
expected extent of injury or loss of life from a fire, defined in terms of probability as the product of:

— frequency of occurrence of an undesirable event to be expected in a given technical operation or state; and

— hazard to life and health.

2.1.29
safety
freedom from an unacceptable risk of harm

2.1.30
societal risk
relationship between frequency of occurrence and the number of people in a given population suffering from a specified level of harm from the realization of specified hazards

2.1.31
stochastic model
methodology for evaluating, in probabilistic terms, the outcome of events as function of time

2.1.32
tolerable risk
maximum level of risk of a building that is acceptable to the approval body.

2.2 Symbols and abbreviated terms

A_b	Floor area within the building (m^2)
A_d	Area of the building damaged by fire (m^2)
$A_d(t)$	Area of the building damaged at t min (m^2)
A_F	Floor area of a compartment (m^2)
A_f	Area of compartment damaged at flashover (m^2)
A_{ig}	Area initially ignited (m^2)
A_T	Total area of bounding surfaces of a compartment (m^2)
A_V	Area of ventilation openings to a compartment (m^2)
a	Constant coefficient for the frequency of ignition
a_i	Fire state
a'	Constant coefficient for frequency of financial loss

b	Constant exponent for the frequency of ignition
C	Thermal characteristic of compartment boundaries
c	Constant coefficient for the area of fire damage
c′	Constant coefficient in defining financial loss from fire
$\tilde{c}$	Intercept of regression line
d	Constant exponent for the area of fire damage
E_i	Probability of a particular outcome in an event tree model
e_{ij}	Event defined as fire spreading from location i to location j
$\bar{e}_{ij}$	Event defined as fire not spreading from location i to location j
F	Frequency
F_{i}	Frequency of ignition
F_{v}	Frequency of financial loss
$G(A_{\mathrm{d}})$	Cumulative distribution function of damaged area
H_{c}	Heat of combustion (kJ/kg)
I_{ij}	Parameter dependent on the extent to which a cause, i, is responsible for starting a fire in the particular location, j, compared to an average building
J	Probability of a fire starting in a given type of building of given floor area
K	Component of fatality rate per fire
k	Number of deaths within a given period
L	Equivalent fire load (kg)
$\bar{L}$	Fire load density (kg/m^2)
M	Constant associated with a Pareto distribution
m	Rank order in extreme value analysis
$\dot{m}$	Rate of burning of fuel by mass (kg/s)
$\dot{m}_{\mathrm{i}}$	Rate of burning of fuel at the initial time of established burning (kg/s)
$\tilde{m}$	Gradient of regression line
N	Numbers of buildings of at risk
n	Number of fires during a given period
P	Probability of a given event
P_{A}	Root probability in a fault tree
P_{AND}	Conditional probability arising from an “AND” gate in a fault tree
P_{B}	Root probability in a fault tree
P_{b}	Probability of compartment failure, given occurrence of flashover
$P_{\mathrm{b(ns)}}$	Probability of compartment failure, given occurrence of flashover, for a unsprinklered compartment
$P_{\mathrm{b(s)}}$	Probability of compartment failure, given occurrence of flashover, for a sprinklered compartment
P_{c}	Probability of compartment failure
P_{d}	Fatality rate per fire; probability of one or more deaths
P_{F}	Probability of the outcome being negative (failure)
P_{f}	Probability of flashover
$P_{\mathrm{f(ns)}}$	Probability of flashover in unsprinklered compartment
$P_{\mathrm{f(s)}}$	Probability of flashover in sprinklered compartment
P_{g}	Maximum acceptable (target) probability of an unwanted event
P_{ign}	Aggregate probability of fire starting in a building
P_{ij}	Probability, if a fire occurs, that it will be due to cause i and be at location j

$P_k(\Delta t_{\mathrm{exp}})$	Probability of k or more deaths occurring during an exposure period of length Δt_{exp}
P_{OR}	Conditional probability arising from an "OR" gate in a fault tree
P_{S}	Probability of the outcome being positive (successful or safe)
P_{sp}	Probability of fire spread beyond room of origin
$\tilde{P}_{\mathrm{sp}}$	Logit of probability of fire spread beyond room of origin
P_{SV}	Probability of fire severity being less than or equal to S
$P(\phi, \Delta t_{\mathrm{exp}})$	Probability of exactly ϕ deaths due to an exposure of duration Δt_{exp}
$[P_n]$	Fire transition probability matrix for stochastic model of fire development
$\vec{P}_n$	Fire state vector for stochastic model of fire development
p	Number of factors which contribute to damage
p_{N}	Proportion of buildings of a given size at risk
p_{n}	Proportion of buildings of a given size involved in fire during a given period
$\dot{Q}$	Rate of heat release from the fire (kW)
$\dot{Q}_{\mathrm{g}}$	Rate of heat release during growth phase of a fire (kW)
R	Fire resistance (min)
R_{d}	Design value of fire resistance (min)
R_{k}	Characteristic value of fire resistance (min)
r	Value of coefficient of variation
S	Fire severity (min)
S_{d}	Design value of fire severity (min)
S_{k}	Characteristic value of fire severity (min)
s	Number of consecutive large losses
t	Time (s or min)
t_{e}	Time equivalent of fire exposure (min)
t_{i}	Time of ignition (s or min)
V	Financial value at risk in a building and its contents
$\bar{V}$	Value density (per m^2)
V_{d}	Financial loss due to fire
W	Factor affecting degree of damage
w	Ventilation factor for a compartment
X	Loss
x	Dependent variable
y	Independent variable
Z	$\ln X$
$Z_{(m)n}$	Logarithm of m^{th} loss of the losses from n fires arranged in decreasing order
α	Fire growth parameter for t^2 fire (kJ/s^3)
α_R	Partial safety factor related to fire resistance, R
α_S	Partial safety factor related to fire severity, S
α_Ω	Partial safety factor related to variable Ω
α_Ψ	Partial safety factor related to variable Ψ
$\alpha_{\Delta t,\mathrm{esc}}$	Partial safety factor related to time for escape, Δt_{exp}
$\alpha_{\Delta t,\mathrm{ten}}$	Partial safety factor related to time to untenability, Δt_{ten}
β	Safety index
χ	Stochastic variable

Δt	Length of time period (min or s)
Δt_{burn}	Duration of burning (min)
Δt_{det}	Detection time (min)
Δt_{esc}	Time taken from ignition for all occupants to evacuate to a place of safety (min)
Δt_{exp}	Duration of exposure to untenable conditions (min)
Δt_{pre}	Pre-movement time (min)
Δt_{ten}	Time taken for products of combustion to generate untenable conditions on escape routes (min)
Δt_{trav}	Travel time (min)
Δt_{S}	Time interval during which success is required
Δt_{F}	Mean time interval between failures
δ	Increase in the fatality rate (per minute)
ε	Ratio of the design fire load densities of sprinklered and unsprinklered compartments
Φ	Logarithmic state variable for structural fire resistance
ϕ	Number of deaths during a given exposure period
Υ	Fire growth parameter for exponential growth (s^{-1})
κ	Parameter defining exponential cumulative probability distribution of P_{SV}
λ	Constant associated with a Pareto distribution
$\lambda_{ii}^{(n)}$	Probability that fire will remain in state α_i during the interval between n and n +1 minutes from start
$\lambda_{ij}^{(n)}$	Probability that fire will move from state α_i to state α_j during the interval between n and n +1 minutes from start
μ	Mean of a distribution
ν	Coefficient of variation
Θ	State function
θ	Safety factor
σ	Standard deviation of a distribution
τ	Standardized normal variable
Ω	Stress variable
ω	Ratio of probabilities of failure, given flashover, for unsprinklered and sprinklered compartments
Ψ	Strength variable

3 Design approach

3.1 General

3.1.1 *What is Probabilistic Risk Analysis (PRA)?*

Probabilistic Risk Assessment or Analysis (PRA) is the generic term applied to studies where the objective is to generate a measure of risk. Risk is expressed as the likelihood that a set of consequences will occur, so the results of PRA studies produce numbers that represent the level of hazard posed to persons or property, but take into account how likely the event is. In practice, this can mean, for example, that a common yet low consequence event can be taken to be of similar concern to a rare yet high consequence event.

All PRA techniques are based on the simple concern that risk is a function of both consequence and frequency of hazard occurrence (see Figure 2). In some studies, the analysis will go no further than this principle. In other studies, the concept may be expanded to consider the interactions between a number of events. Other more complex analysis techniques may be used to solve problems arising from poor data availability.

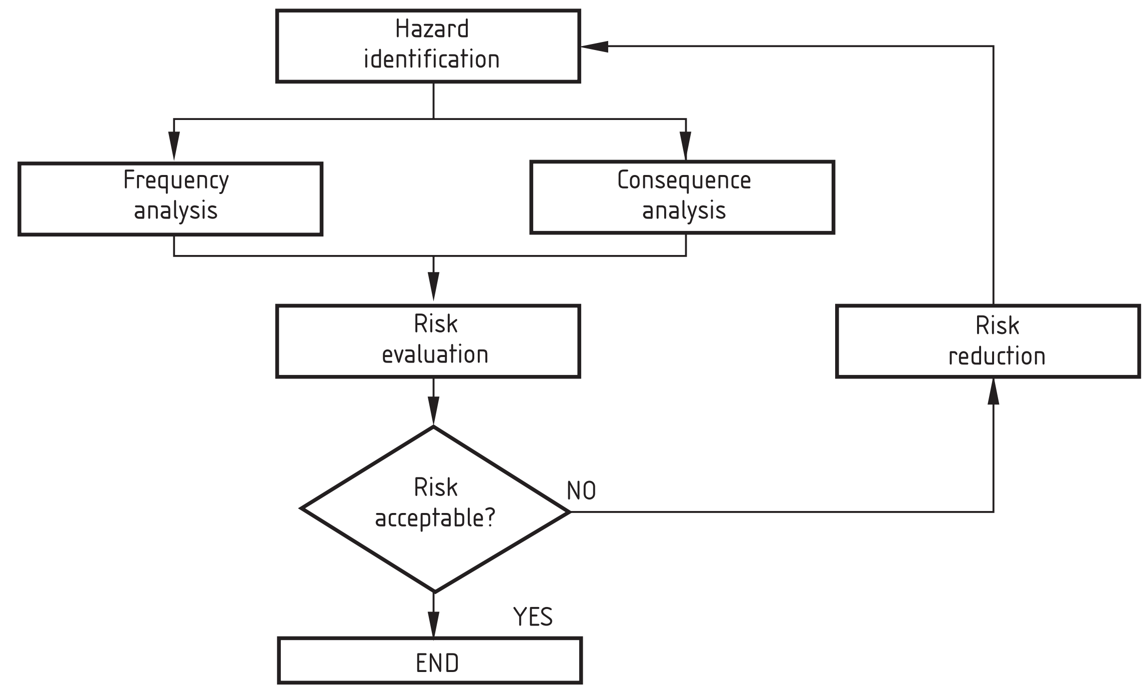


Figure 2 — General approach to probabilistic fire risk assessment

PRA has its roots in the process and financial services industries. The techniques now being applied to fire safety were previously used for assessment of issues as varied as safety at nuclear power stations and for predicting life assurance payments. PRA has been applied to fire safety problems for a number of years now, although this application is still very much in its infancy.

3.1.2 ***How can PRA be applied to fire safety problems?***

The consequences of fire can be severe. In a fire, property or life can be lost. Traditional fire safety techniques typically start with the assumption that a fire has started. The fire then grows and causes a number of subsequent events. For example, it may be assumed that sufficient smoke will enter an escape stair to render it unusable or that a fire will always be located in a room such that it blocks one of the exits. This approach may be acceptable for the "average building" and is the basis of prescriptive building codes.

Fire safety engineering, like prescriptive building codes, still assumes that a fire will occur and that it will grow. However, unlike prescriptive building codes, fire safety engineering breaks the problem down further. How the fire develops and interacts with the building structure and occupants is subjected to more detailed analysis to take into account the specific nature of individual buildings or scenarios. This approach is more flexible than the prescriptive approach. However, the typical "deterministic" fire engineering study will still make certain (generally conservative) assumptions about how the fire scenarios will develop.

PRA can take fire safety engineering studies beyond the deterministic models, where a certain set of assumptions are always taken to be true, by assessing the effects of fire not only in terms of the consequences, but also taking into account the likelihood that a given set of consequences will occur. The objective of this is to try to model real buildings and real fires in greater detail.

For example, many fires, even those started deliberately, will burn out or be put out before they become a significant hazard to life or property. A deterministic fire engineering analysis will not take this fact into account (instead, it would be assumed that the fire occurs and continues to grow). The deterministic model may, for example, assume that sprinklers operate, controlling the fire. A PRA based model would take this further by considering the likelihood that the sprinklers will not work and the subsequent consequences.

PRA allows deterministic fire safety engineering techniques to be enhanced by taking account of uncertainties and adding in the additional factor of probability to the assessment. This allows a number of useful extensions to fire safety engineering to be made. The principal example of this is the study of diverse systems which are designed to achieve the same objective (e.g. a mechanical and natural smoke extract system, both designed to vent smoke from a fire compartment). In a purely deterministic model, it would be assumed that the system operated and, assuming that the systems were designed correctly, the model would show that the same smoke layer conditions would result in either the mechanical or natural ventilation case.

A PRA could look deeper into the differences between the two systems and generate "failure data" for the two systems. Hence, whilst both systems might provide identical conditions in the event of a fire if they work correctly, one system might be found to be better than the other because it is more reliable. This sort of study is known as a comparative study and is well accepted, perhaps because it is a natural extension of more subjective approaches.

As well as comparative studies, PRA can be used for absolute studies. These are analyses where one is not comparing two situations, but instead is considering the performance of one situation against predetermined criteria (e.g. the probability that any given occupant will die in a particular office building in the event of fire). Absolute studies have traditionally been less readily applied. This could be because they force PRA practitioners and reviewers to consider that an undesirable event can (and, indeed, if one strictly applies PRA, will) ultimately occur. The classic (and arguably most controversial) absolute studies are where life is attributed a financial value and a study is then carried out to determine how many deaths are tolerable in any given timeframe, based on the cost to the organization under consideration.

3.1.3 *What are the limits of PRA?*

As a generic technique, PRA is relatively free of limits and can theoretically be applied to all aspects of fire safety engineering for all building types and designs. Given the wide appeal of PRA, one might expect it to be more prolific. However, the application of PRA can be severely limited by data availability.

Deterministic and prescriptive fire engineering techniques have typically bridged the gaps between what data are readily available and what are absent by taking a conservative approach. The same approach cannot be readily used in PRA studies. Complex mathematical techniques such as extreme value theory are available to help fill in the blanks for missing data. However, in more simplistic studies, a lack of available data can seriously hinder application.

3.2 Application of probabilistic risk assessment to fire safety engineering

For most applications of fire safety engineering, deterministic analysis is all that is required to demonstrate that a design is acceptable. In addition, full probabilistic risk assessment can be very time consuming and expensive to undertake and so might not be practicable in many circumstances. However, probabilistic risk assessment can be most useful where:

a) input parameters are highly variable;

b) alternative solutions perform in very different ways from standard solutions; and/or

c) the consequences of failure due to fire are highly significant.

Probabilistic risk assessment can be used to:

a) identify and select fire scenarios for deterministic analysis;

b) set input data for deterministic fire engineering analysis;

c) analyse part of, or certain aspects of, fire safety of a building design; and/or

d) analyse the whole of fire safety of a building design.

This list is not exhaustive and these four areas of application are described in greater detail in **3.3**, **3.4**, **3.5** and **3.6**.

Probabilistic risk assessment can be used at any stage of fire safety engineering analysis after the Qualitative Design Review (QDR) is complete. Probabilistic fire risk assessment can be used as part of the analysis of any or all of the sub-systems.

3.3 Identifying and selecting fire scenarios for deterministic analysis

Fire safety design traditionally consists of identifying important parameters of a building design (e.g. purpose group and height above ground) and identifying a set of fire precautions to achieve an acceptable solution. For deterministic fire safety engineering, there is a need to identify the set of circumstances that are appropriate for analysis [the scenario(s)]. A scenario considers aspects like the design fire (size and rate of growth), number of people and which fire precautions are assumed to work and which are assumed, for the purposes of analysis, to have failed. The objective is to assess a reasonably severe scenario to assess whether the solution is acceptable. HAZard and OPerability (HAZOP) methods are an example of this from the process industry.

For example, a complete analysis of fire safety that takes the ninetieth percentile value of twenty factors in series is potentially analysing an event with a probability of 10^{-20}. If the acceptance criterion was an individual probability of death by fire of 10^{-6}, this is clearly an inappropriate scenario.

3.4 Setting input data for deterministic analysis

The process of fire safety design is complicated by the fact that certain input variables are highly stochastic in nature. For example, the heat of combustion of a polymer whose composition and production is tightly controlled can be determined and repeated with relatively little variance. Factors like this can be treated simply and deterministically in fire safety engineering because of their relatively low variability. Other factors can vary considerably from building to building and from time to time.

For example, the number of people in a space or the rate of fire growth can vary considerably even for small variations in time of day or physical arrangement, respectively. In deterministic analyses, a value of these factors that is credible and worst case tends to be used to ensure that the analysis errs on the side of safety. Where data exists, this kind of input variable can also be defined by setting a limiting probability of it being exceeded, as is the case of the percentiles of fire load distributions used for assessing periods of structural fire resistance.

3.5 Analysis of certain aspects of fire safety in building design

Comparing alternative fire safety design solutions is rarely straightforward because the different systems involved usually behave in different ways. They might have different:

a) levels of performance;

b) rates of failure on demand; and/or

c) failure consequences.

For example, a solution with a large single compartment and a sprinkler system could be proposed for a building as an alternative to a solution with many smaller compartments and no sprinkler system. In terms of possible fire sizes, excluding first aid fire fighting and fire brigade intervention, the two are very different. In the first, if the sprinkler system succeeds, the fire should be relatively small but, if the sprinkler system fails, the fire could involve the whole of the large compartment. Conversely if, in the case of the smaller compartment solution, compartmentation succeeds, the fire would only involve a smaller compartment and, if one compartment wall fails, the fire is only likely to involve two small compartments (common mode failures excepted). Probabilistic risk analysis can be used to assess the equivalency in these two cases taking into account their intended performance, probabilities of failure and/or the consequences of their failure.

3.6 Analysis of the whole of fire safety of a building design

For certain buildings, the potential consequences of a fire might be so significant in terms of the fire safety objective (e.g. life safety and business continuity) that the only way of rationally addressing fire hazards is to undertake a full probabilistic fire analysis for the whole building. Historically, these buildings included nuclear facilities and chemical process plants. Following the King's Cross underground and Piper Alpha offshore fires, they now include many transport and offshore structures. Increasingly, strategically important and other unique buildings such as airports and control centres also fall into this category. Probabilistic risk analysis in these circumstances usually follows a formal hazard identification process (such as a HAZOP, HAZard and OPerability study), forms part of a safety case for the facility, and is expressed as the frequency of an undesirable event.

4 Acceptance criteria

4.1 General

For probabilistic risk assessment, criteria are set such that the probability of a given undesirable event is acceptably low, or As Low As Reasonably Practicable (ALARP). The acceptance criteria vary depending on the fire safety objectives of the study. Criteria for life safety will be different to criteria for business continuity. Similarly, acceptance criteria will be different depending on the analytical approach adopted. Criteria for absolute levels of risk will be different to criteria for comparative risk analyses (see Table 1).

Table 1 — Typical types of acceptance criteria

Analysis method	Fire safety objectives	
	Life safety	Financial
Comparative	Level of risk equivalent to code compliant solution, e.g. AD B	Comparison of design alternatives (cost–benefit analysis)
Absolute	Number of casualties per year	Acceptable average loss per year

4.2 Comparative criteria

It can often be difficult to establish the level of risk in absolute terms. However, it can be relatively straightforward to demonstrate that a design provides a level of risk equivalent to that in a building which conforms to more prescriptive codes (life safety or financial). Since the study is purely comparative, it is unlikely that any assumptions or data regarding ignition frequencies or reliability of systems will have any significant influence on the outcome. This can be confirmed by sensitivity analysis.

Before it can be demonstrated that a solution offers the same level of risk as a prescriptive code, the intent of that code needs to be clearly understood. During the QDR, the intentions of each recommendation should be considered, as particular provisions might have more than one objective. Alternative design solutions can be developed to address the specific underlying objectives. The fire safety engineer should demonstrate that the solution proposed will be at least as effective as the conventional approach.

4.3 Absolute criteria

4.3.1 *Life safety*

Absolute acceptance criteria for life safety can fall into two categories: individual and societal.

Individual risk is the frequency at which an individual is expected to sustain a given level of harm from the realization of specified hazards. This is usually related to a specific pattern of life. For fire safety, this might be the individual risk of someone who works in an industrial or office building or of a shopper who visits a retail development once a week.

Societal risk is the relationship between frequency of occurrence and the number of people in a given population suffering from a specified level of harm from the realization of specified hazards. This is important because multi-fatality disasters are particularly repugnant to society. This may be expressed as the frequency with which ten or more people will die from fires in an assembly. This is normally significantly lower than an individual level of risk.

Another factor that is important in the acceptability of risks is the extent to which the risk is voluntary or involuntary, i.e. how much does the person at risk control the level of risk? For example, people in their own homes can have a much greater degree of control of their level of fire risk than, say, someone staying at a hotel.

For life safety, risks can be considered acceptable for two main reasons.

a) The risk due to fire can be so small compared to other risks that it can be considered negligible.

b) If the risk due to fire is not negligible, the benefits arising from the building can outweigh the risk to the extent that risk can be considered to be tolerable. For this approach to be valid, the cost of reducing the risk further should far outweigh the resulting reduction in risk. That is, the risk due to fire should be As Low As Reasonably Practicable (ALARP).

There is also a point where, no matter what the benefits, the level of risk due to fire is so high that it can never be tolerated and can only be considered to be intolerable. For levels of fire risk above this point, a reduction in the risk is the only way to achieve acceptability.

The levels of risk to individual members of the public from the activities on major industrial sites [1] are:

a) maximum tolerable risk to individual member of the public (deaths per year) is 10^{-4};

b) general acceptable risk to individual member of the public (deaths per year) is 10^{-6}.

The levels of societal risk from the failure of building structures due to fire [2] are:

a) risk for 10 or more deaths per building per year is 5×10^{-7};

b) risk for 100 or more deaths per building per year is 5×10^{-8}.

The nature of the above risks is that they are largely involuntary, but that there is an overall benefit to society from the activity.

The average levels of risks for a range of building types (for the years 1995 – 1999), in terms of both deaths per building per year and deaths per occupant per year, are expressed in Table 2. The data contained in Table 2, taken with other data, yield a level of individual risk for a member of the public at home from fire of 10^{-5} death per year, and elsewhere of 10^{-6} death per year. Using the data for multiple fatality fires, leads to societal risks of 10^{-8} per occupant per year for a fire with 10 or more fatalities, and 10^{-9} for a fire with 100 or more fatalities.

However, currently, there are no generally accepted absolute criteria in relation to fire safety, with the UK government committed to a significant reduction in fire related death, injury and damage. The enforcing body or authority concerned will need to accept that the level of risk proposed is As Low As is Reasonably Practicable (ALARP). Therefore any absolute criteria used in a probabilistic analysis would be expected to be significantly lower than the above figures.

In comparing the predicted level of risk with any criterion it is important to consider the assumptions made in the study. If the predicted level of risk only just satisfies an absolute criterion, then care should be taken to ensure that the assumptions made in the study clearly err on the side of safety.

Table 2 — Number of deaths per building and the number of deaths per occupant

Occupancy	No. of buildings	No. of occupants	Average/year [95/97/98/99]				
			No. of deaths	No. of injuries	No. of fires	Death/ building/year	Death/ occupant/year
Further education	1 051	845 617[a]	0.0	17	535	$< 2.4 \times 10^{-4}$	$< 3.0 \times 10^{-7}$
Schools	34 731	10 503 100[a]	0.0	51	1 669	$< 7.2 \times 10^{-6}$	$< 2.4 \times 10^{-8}$
Licensed premises	101 081	—	2.8	262	3 317	2.7×10^{-5}	—
Public recreation buildings	45 049	—	1.3	48	2 581	2.8×10^{-5}	—
Shops	354 475	—	3.3	284	5 671	9.2×10^{-6}	—
Hotels	28 371	389 174[a]	2.5	116	1 021	8.8×10^{-5}	6.4×10^{-6}
Hostels	9 829	—	0.5	60	1 338	5.1×10^{-5}	—
Hospitals	3 486	—	3.3	113	3 063	9.3×10^{-4}	—
Care homes	29 080	—	4.5	130	1 616	1.5×10^{-4}	—
Offices	209 627	4 107 000[b]	0.3	219	1 988	1.2×10^{-6}	7.3×10^{-8}
Factories	170 972	—	4.3	286	5 299	2.5×10^{-5}	—
all above occupancies	987 752	15 844 891	22.5	1 584	28 096	2.3×10^{-5}	6.5×10^{-6}

NOTE It might be more appropriate to use the number of deaths per occupant for large or complex buildings.

[a] Number of occupants equals the sum of the number of employees and other occupants.

[b] Number of occupants equals the number of employees only.

4.3.2 *Financial*

An organization or facility can decide, given its investments, competitive position, insurance cover, contingency plans, etc. that it can tolerate certain levels of loss or interruption with certain return periods. These are usually expressed in terms of a financial loss per year or level of financial loss and a frequency (or return period).

Using the techniques in this Published Document, it is possible to estimate the risk of damage that result from a fire. This information may then be used to estimate potential monetary losses and enable cost–benefit analysis to be undertaken to establish the relative value of installing additional or alternative fire protection measures.

These financial criteria, in terms of levels of loss or interruption, should be set in conjunction with the organization concerned and/or their financiers or insurer(s).

4.3.3 *Other objectives*

Other fire safety objectives can include the protection of heritage and the protection of the environment. Fire risk acceptance criteria may be provided by relevant guidance either explicitly or implicitly. Often there are no absolute criteria and so these can only be agreed by consensus between all the relevant regulators and stakeholders.

5 Standard probabilistic analysis

5.1 General

Due to uncertainties in fire safety in buildings, it may be realistic to treat these factors as non-deterministic random phenomena. This generally means adapting a probabilistic approach to the evaluation of fire risk and assessment of the fire protection requirements of a building. In this approach, there are essentially three types of models in which probabilities enter the calculations explicitly. These are:

a) simple statistical analysis;

b) logic tree analysis; and/or

c) sensitivity analysis.

These models are discussed in **5.2** and **5.4** below. More complex models and other types of analysis that are less widely used are discussed in Clause **6**. Further types of analysis, or variations on the types of analysis shown, can be used as appropriate and so the contents of Clauses **5** and **6** should not preclude the use of alternative forms of probabilistic fire risk analysis. Data can be found in Clause **7**.

5.2 Simple statistical analysis

5.2.1 *General*

The analysis of statistics is the basis of most probabilistic fire risk assessment, from the frequency of ignition to the conditional probability of failure of a fire protection system. Statistical analysis takes data that has been collected on building fires and transforms it into information that can be used to predict the likelihood of future events. This can take the form of the simple assessment of the average probability of an event over a set of buildings over a period of time to a complex regression analysis.

Statistical analysis has the advantages that it is based on actual events and that the results are usually simple to apply. It is, however, based on historical data that is then averaged, and so this assumes that future performance can be predicted from past experience and that an average measure can be applied to a particular building. In most cases, these assumptions are reasonable and, in most cases, there is less uncertainty in undertaking a risk assessment based on historical data than to take no account of the probability of failure of the various fire precautions in a building design.

The other limitation of statistical analysis is that it is often not possible to collect sufficient data to directly predict, with confidence, the kind of high consequence low frequency events, such as multiple fatality fires, that are of concern. Statistical data is much better for more frequent events such as ignition and the conditional probability of success or failure of fire precautions. These individual pieces of information can then be used to predict the frequency of low frequency events by using logic trees and other techniques.

5.2.2 *Frequency of ignition*

The frequency of ignition is one of the key parameters of most probabilistic risk assessments. It is usually the initiating event in most event trees and can be a base event in fault trees.

Statistical studies [3,4,5] have shown that the frequency of ignition is approximately given by:

$$F_i = aA_b^{\,b} \qquad (1)$$

where a and b are constants for a particular type of building related to occupancy and A_b denotes the total floor area of the building.

The parameter a includes the ratio of the number of fires, n, in a period to the number of buildings at risk, N (see Clause **6**), while b measures the increase in the value F_i for an increase in A_b.

A value of unity for b indicates that the probability of fire starting is directly proportional to the size of the building; this would also imply that all parts of a building have the same risk of fire breaking out. This is not true, since different parts have different types and numbers of ignition sources. Hence, the probability of fire starting is not likely to increase in direct proportion to building size, so b is likely to be less than unity. If two buildings are considered, one twice the size of the other, the probability for the larger building will be less than two times the probability for the smaller building. These theoretical arguments are confirmed by actuarial studies on frequency of insurance claims as a function of the financial value (size) of the risk insured [4,6].

Values of a and b for the majority of building types have been estimated from UK fire statistics and a special survey [7] and are set out in Annex A, Table A.1. For all manufacturing industries in the UK with A_b (m^2), the values of a and b were estimated as 0.001 7 and about 0.53 (respectively). Actuarial studies [6] in some European countries confirm that the value of b is about 0.5 for industrial buildings. For a particular building, the “global” value of F_i given by equation (1) can be adjusted by following the procedure described in **6.2.1**. The ratio of number of fires over the number of buildings at risk provides an overall measure, unadjusted for building size of the probability of fire starting (see Table A.2). Using data for the years 1968 to 1970 [8], a figure of 0.092 was estimated for all manufacturing industries in the UK for the risk of having a fire per annum, per establishment; an establishment can have more than one building. An estimate for probability of fire starting according to building size is also given by number of fires starting per unit of floor area see (Table A.3). It should be noted that the figures in Table A.1, Table A.2 and Table A.3 are now quite dated, but they are the best currently available.

5.2.3 *Probable extent of fire spread and area damage*

The probable area damaged in a fire in the building of origin can be estimated by considering different categories of fire spread and the probabilities associated with these cases. Fire statistics produced in the UK enable the extent of spread to be classified as follows:

a) confined to first item ignited;

b) spread beyond item but confined to room of origin;

  1) contents only;

  2) structure involved;

c) spread beyond room but confined to building of origin.

Fires spreading beyond the building of origin have not been included in the above classification. Table A.4 and Table A.5 give examples showing the probable (average) area damage for each fire spread category together with the relative frequency. In the case of sprinklered buildings, the percentage figures include one third of fires in these buildings that were estimated to be extinguished by the system but not reported to the local authority fire brigades [9]. These small fires were assumed to be confined to the item first ignited.

5.2.4 ***Frequency distribution of area damage***

Table A.4 and Table A.5 provide rough or approximate estimates for the probability of area damage exceeding the average damage for each fire spread category. For the production area of a textile industry building, e.g. the probability of area damage in a sprinklered room exceeding 5.1 m^2 is 0.28, the probability of damage exceeding 13.5 m^2 is 0.10 and the probability of damage exceeding 112.9 m^2 is 0.04. If the room is not provided with sprinklers, the probability of damage exceeding 4.8 m^2, 16.8 m^2 and 474.6 m^2 will be 0.57, 0.25 and 0.12 respectively. Figures such as these can be used to construct the frequency distribution of area damage.

However, a more accurate frequency distribution of area damage can be constructed by using the raw data available from the fire statistics compiled by the Home Office. Table A.6, Table A.7 and Table A.8 are examples of investigations based on this data. The figures for the sprinklered cases for the damage category 1 m^2 and under include one third of fires extinguished by sprinklers but not reported to the fire brigade. As discussed further in **6.2.2**, a Pareto probability distribution was fitted to this data to provide the estimate of the parameters λ and m given at the foot of the tables. This distribution was used to estimate more precisely the probability of damage exceeding a given level or exceeding the floor area of a compartment.

5.2.5 ***Damage and building or room size***

For a particular building belonging to a particular building type, the probable area damage in a fire is approximately given by the "power" function:

$$A_{\mathrm{d}} = cA_{\mathrm{b}}^{\ d} \qquad (2)$$

where A_b is the total floor area of the building as in equation (1), and c and d are constants for a particular building type. Based on a survey [7], the values of c and d for major groups of buildings can be estimated (see Table A.9). The product of equations (1) and (2) is an estimate of fire risk in a building of floor area A_b expressed on an annual basis.

There is evidence that a fire in a large building is more likely to be discovered and extinguished before involving the whole building, than in a small building. The proportion destroyed in a large building would, therefore, be expected to be smaller than the proportion destroyed in a small building. These arguments suggest that the damage rate (A_d/A_b) decreases with increasing values of A_b; in other words the value of d would be less than unity. This result is supported by statistical and actuarial studies cited earlier [4,5,6].

Provision of fire precautions in a building would reduce the damage rate and the value of d. With A_b in square metres and c = 2.25, [7] estimated a value of 0.45 for d for industrial buildings without sprinklers. The average damage of 16 m^2 for an industrial building of total floor area 1 500 m^2 equipped with sprinklers was also estimated. These figures inserted in equation (2) yield a value of d = 0.27 for an industrial building with sprinklers, if it is assumed that the value of c (= 2.25) denoting initial conditions would be the same whether a building is sprinklered or not.

Consider, as an example, the values from Figure 3 [10,11] relating to a building of size 8 000 m^2. The maximum damage (worst case) likely in this building in the event of a fire is 1 000 m^2, if sprinklered, and 2 000 m^2, if not sprinklered. According to these figures, with c = 4.43, d has the values of 0.60 and 0.68 for sprinklered and non-sprinklered buildings. The relationship between damage and building size is depicted in Figure 3. This figure is applicable to buildings larger than 105 m^2. If a maximum damage of 2 300 m^2 is acceptable, a textile industry building can be permitted to have a maximum size of 10 000 m^2 if it has no sprinklers. If sprinklers are installed, the maximum building size can be relaxed to 33 000 m^2; this permissible size may be reduced to 28 000 m^2 if a probability of 0.1 is assigned for the non-operation (unreliability) of sprinklers when a fire occurs.

If, for example, the values in Figure 4 [10,11] relate to a compartment of size 800 m^2. Equation (2) and the maximum damage of 75.1 m^2 and 197.4 m^2 for spread within a room provide values of 0.42 and 0.57 for d for the sprinklered and non-sprinklered cases respectively. Figure 3 shows the relationship between damage and compartment size and is applicable to compartments larger than 32 m^2. According to this figure, a sprinklered compartment of 4 000 m^2 would be equivalent in damage to a non-sprinklered compartment of 500 m^2. The permissible size of a sprinklered compartment may be reduced to 3 000 m^2 to take account of the probability (0.1) of non-operation of the system in a fire developing beyond the "established burning" stage.

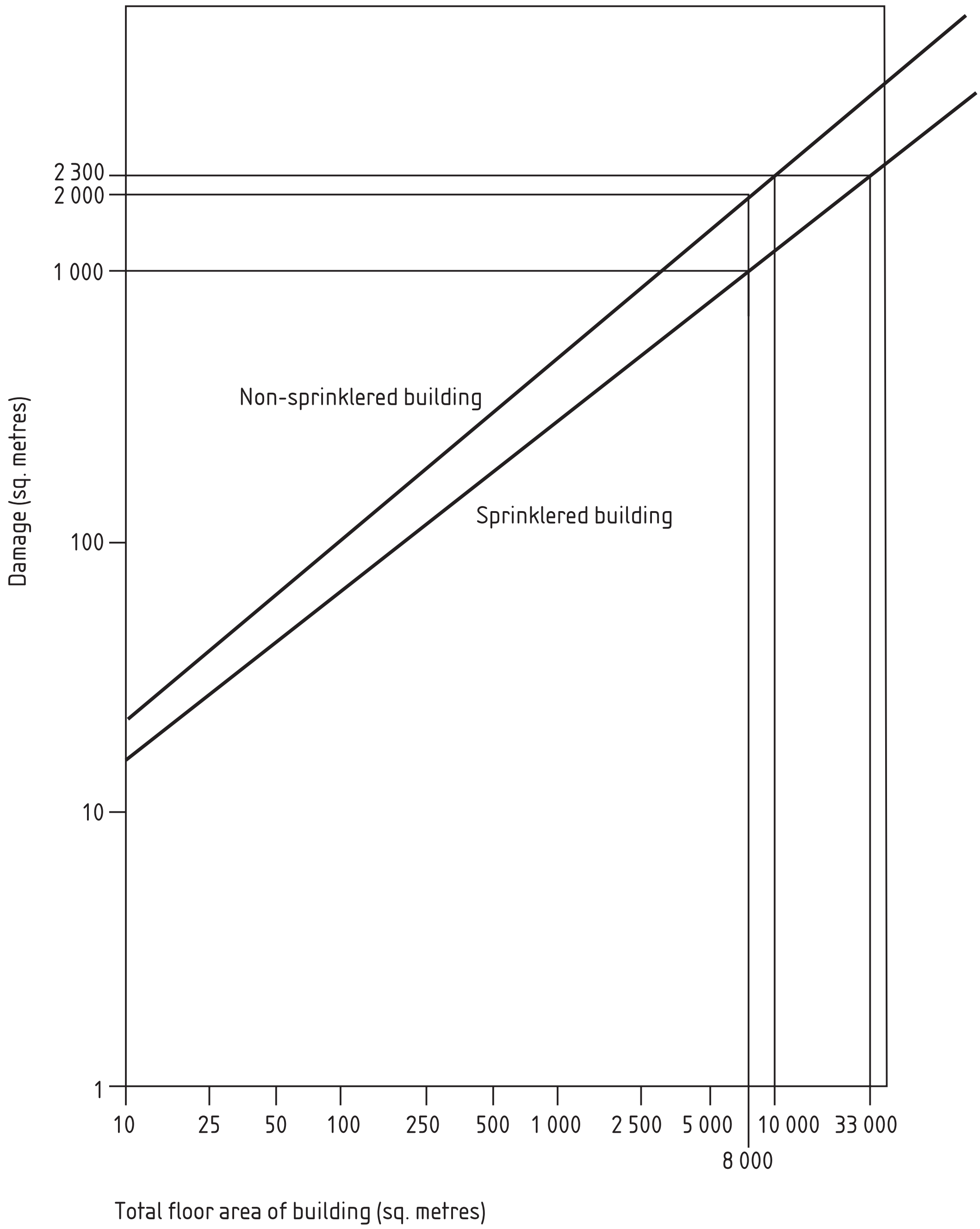


Figure 3 — Damage and building size, textile industry

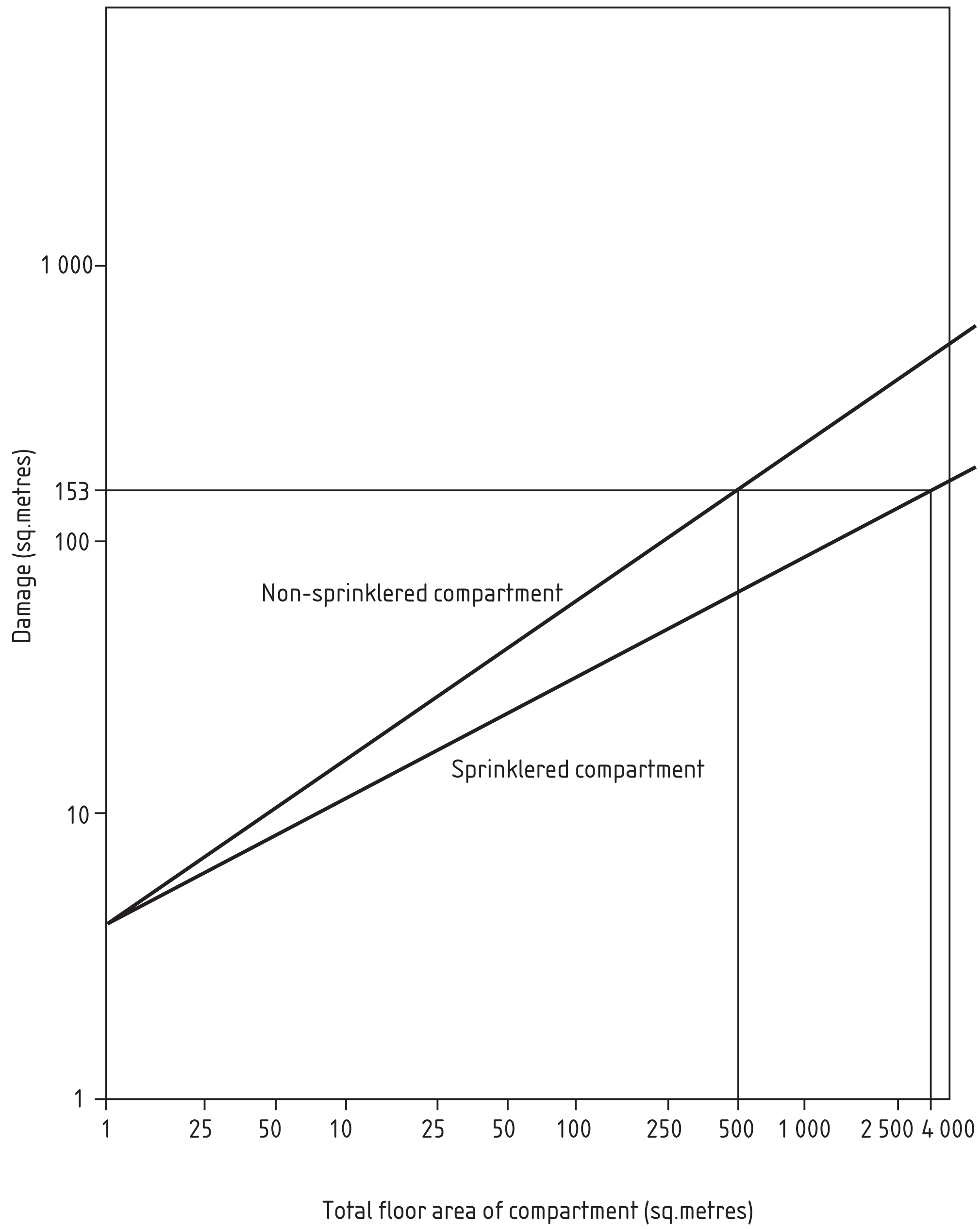


Figure 4 — Damage and compartment size, textile industry

5.2.6 *Financial loss*

The financial loss from fires can be estimated in a similar way to the area damaged. If it is assumed that the financial value V at risk in a building and its contents are spread uniformly over the floor area, the financial loss V^d expected in a fire is given, from equation (2), by:

$$V_d = c'V^d \quad (3)$$

If $\overline{V} = (V/A_b)$ is the value density per square metre of floor area then:

$$c' = c\,\overline{V}^{-d}$$

Likewise, equation (1) may be transformed to:

$$F_v = a'V^b \quad (4)$$

where:

$$a' = a\overline{V}^{-b}$$

Equations (3) and (4) and their product are used for determining approximately "risk premiums" for fire insurance [6]. Area damage can also be converted to financial loss by using an approximate value for loss per square metre of fire damage in equation (2) [7]. A better estimate of A_d or V_d can be obtained through an appropriate probability distribution (see Clause **6**).

5.3 Logic trees

5.3.1 *General*

For most practical problems in fire protection, it can be sufficient to carry out a probabilistic fire risk assessment based on or more logic trees. These provide a simple method for estimating the probability of occurrence of an undesirable event (or events), known as an outcome. Such events include the fire reaching flashover stage or spreading beyond the room of origin and smoke causing visual obscuration on an escape route. In this approach, the sub-events leading to the outcome are identified and placed in their visual sequential order. This process is continued until a basic event (or set of basic events), usually ignition, is identified for which the probabilities can be estimated from statistical data. Probabilities associated with sub-events are then continued in a suitable logical manner to derive the probability of occurrence of the outcome of concern. The calculation procedure is facilitated by the use of logic diagrams or trees that provide graphical representative of sequence of sub-events.

There are normally two types of logic trees used in a probabilistic risk assessment: event trees and fault trees.

5.3.2 *Event tree analysis*

Event trees are most useful when there is little data on the frequency of outcomes of concern that are very infrequent, e.g. multiple fire deaths. Event trees can be used to predict the frequencies of infrequent events by the logical connection of a series of much more frequent sub-events for which data is available.

Event trees work forward from an initiating event (such as ignition) to generate branches defining events and paths resulting from secondary (or nodal events) to give a whole range of outcomes. Some of the outcomes can represent a very low risk event others can represent very high-risk events.

The construction of an event tree starts by defining an initiating event leading to the final outcome, following a series of branches each denoting a possible outcome of a chain of events. Figure 5 is a general example of an event tree representing a range of outcomes resulting from an initiating event via two nodal events. Care should be taken that the event tree reflects the actual order of events in real fires and that all the nodal events of importance have been included.

The frequency associated with each branch (outcome) is given by multiplying the initiating frequency F and the relevant conditional probabilities of success and/or failure, (P_S and P_F respectively). For example:

$$F_2 = F \cdot P_{S1} \cdot P_{F2}$$

Figure 6 shows how an event tree could be applied to the early stages of a fire.

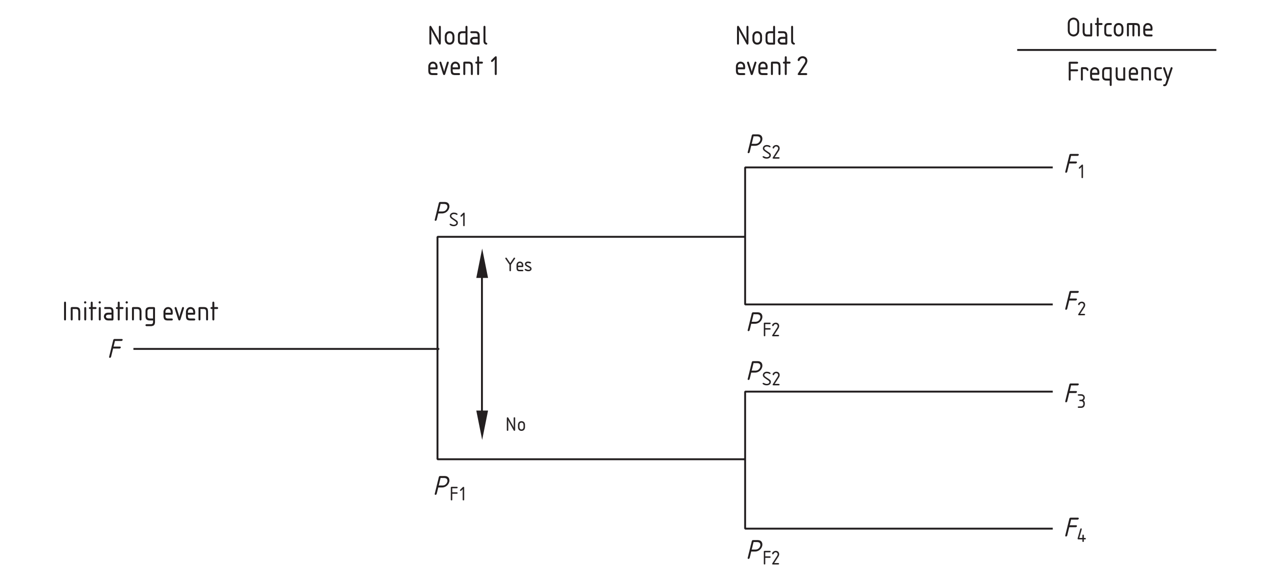


Figure 5 — General form of an event tree

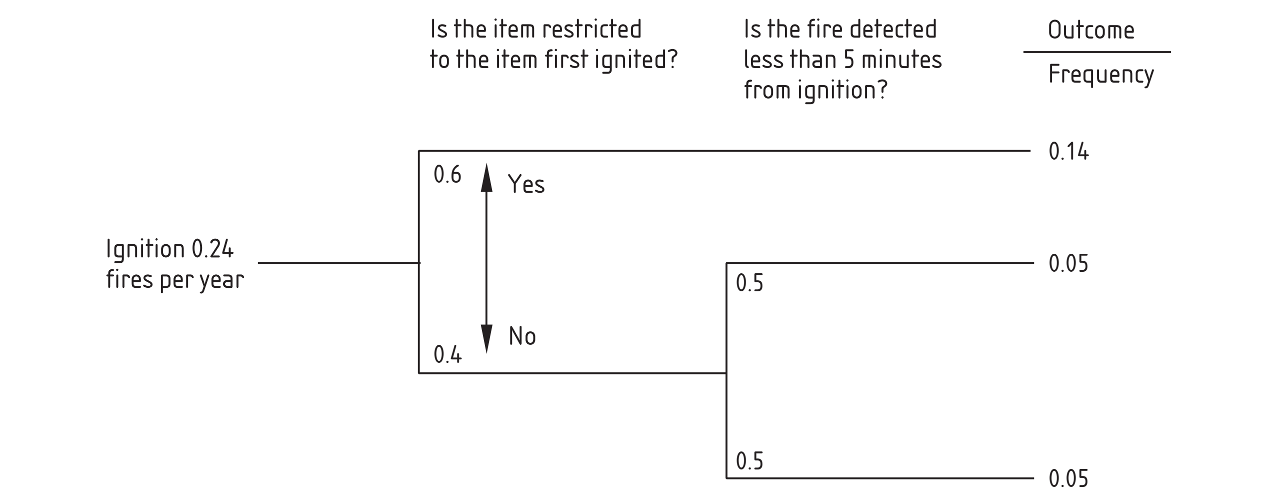


Figure 6 — Event tree of the early stages of fire event development

The initiating event is ignition. The two nodal events are "Is the fire restricted to the item first ignited?" and "Is the fire detected less than 5 minutes from ignition?" The outcomes in descending order are:

a) a fire where ignition occurs, but the fire does not grow beyond the item first ignited;

b) a fire that grows beyond the item first ignited, but is detected in less than 5 min from ignition;

c) a fire that grows beyond the item first ignited and is not detected in less than 5 min from ignition.

The frequencies of the outcomes can be calculated as described and indicate that, although ignition can be expected just under once in four years, the frequency of events where a fire would be expected to grow and not be detected is about once in twenty years. This could be used to measure the benefit of materials that are fire retardant and ignition sources that are low in number and energy. This event tree could also be used to demonstrate that an alternative mode of fire detection is equivalent to that of a code compliant solution. Care should be taken to ensure that the conditional probability of the first nodal event does not include events that can only follow the second nodal event, e.g. first aid fire fighting.

5.3.3 ***Example of probabilistic fire risk assessment using an event tree***

5.3.3.1 *General*

This subclause shows how event tree analysis can be used as part of a probabilistic fire risk assessment [12]. Fire risk assessment can be used to assess the risk/cost benefit of fire precautions for property protection. The following example is a risk assessment carried out for a major bus operator [13,14].

Concern was expressed by a major bus operator with respect to the risk to business from fires in bus garages. In particular, the operator was interested in whether or not they should install sprinkler systems in their existing bus garages or take some action. The cost of this would be considerable and so the bus operator commissioned a study to quantify the benefits in terms of property protection.

This risk assessment (see Figure 2) involves:

a) identifying events that could give rise to the outcome of concern;

b) estimating how often the events happen;

c) estimating what the severity of the outcome of those events would/will be; and

d) assessing the implications of the level of risk.

5.3.3.2 *Identifying events*

The events of concern are fires causing significant damage to vehicles and property in bus garages. From operating experience, fire safety judgement and full scale fire tests, these events were narrowed down to one "reasonable worst case" event: a seat fire at three points on a double-deck bus parked amongst others.

The risk parameter chosen for the study was the cost of fires per calendar year. This could allow bus operators to put these risks in context with historical data on other risks.

5.3.3.3 *Estimating the frequency of events*

To estimate how often the fire event happens, historical data was collected on how often fires occur on buses in garages. Because fires on buses are relatively infrequent, there was insufficient information to estimate how often the event occurs. Therefore, an event tree was constructed to help generate the missing information.

An event tree is a logic diagram, which predicts the possible outcomes from an initial event (see Figure 7). e.g. an initial event of "Seat fire in the lower saloon of a double-deck bus" could have outcomes of "Damage less than £200 000" and "Damage greater than £500 000". The likelihood of each outcome depends on other factors such as "Is the fire noticed at an early stage?", "Does the fire spread to neighbouring buses?" or "Is the fire put out with fire extinguishers?".

The conditional probability of each of these other factors is estimated using historical data and expert judgement. Therefore, using the likelihood of an initial event and the probabilities of the other factors, an estimate can be made of how often an event occurs [15,16,17]. Typical data can be found in Table A.17.

5.3.3.4 *Estimating the severity of the outcome*

There are several ways to estimate the severity of the outcome: from historical information, using simple analytical methods, using computer models, and/or using full scale tests. Each approach has its advantages and disadvantages. Historical data describes what the outcomes have been in the past but might not be complete or relevant. Simple analytical methods can predict the severity of outcome cost effectively but the answer is only as good as the assumptions made. Computer models can predict the severity of outcomes more closely but can be expensive and time consuming. Full scale testing probably gives the most accurate assessment of the severity of outcomes but it is usually even more costly and time consuming.

In this case, the severity of the outcome (i.e. losses due to damaged buses/garage) depended heavily on the spread of fire from bus to bus and the effective spray density of different sprinkler systems. Therefore, a combination of full scale testing and computer modelling was used to predict fire growth, fire spread and the effectiveness of sprinklers [18].

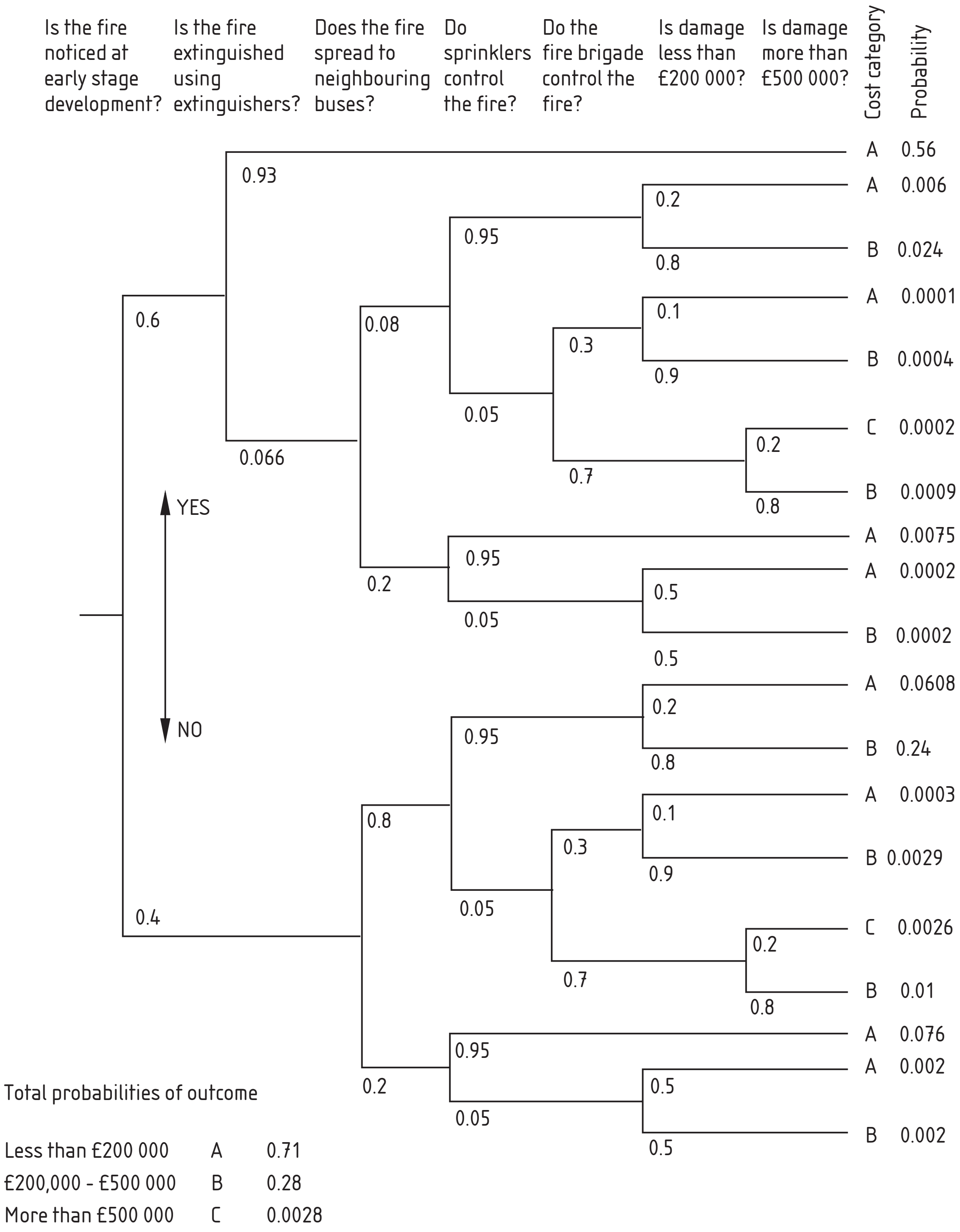


Figure 7 — Simplified event tree for bus garage fires

5.3.3.5 *Results*

The risk assessment indicated that for the event identified, a higher than ordinary level of sprinkler spray density was necessary to prevent fire spread from bus to bus. The frequencies of fires in bus garages was about 0.1 per year. The fire risk was then calculated for the bus garages with and without sprinklers. The difference between the two figures is the benefit rate from reduced property losses by fitting sprinkler systems and this was of the order of £2 000 per year (but this varied with the size of garage).

Historical accident data indicate that the predicted risk of damage is pessimistic: very few records of such fire damage could be found. Having quantified the benefits of sprinklers in reducing risks in bus garages, cost–benefit analysis can determine whether they would represent a good investment in fire safety [19,20].

5.3.3.6 *Cost–benefit analysis*

The first step was to determine the total costs of the sprinkler installation. This not only included the initial installation costs but also covered the annual running costs. The following list, whilst not meant to be exhaustive, covers the main costs included in this case:

— design fees;
— installation/construction;
— commissioning/training of staff;
— maintenance/running, etc.

The capital cost for the sprinkler system was £25 000 with an annual maintenance cost of £100. The benefits of the new installation included:

— reduced property loss;
— reduced consequential losses;
— reduced insurance premiums;
— improved life safety, etc.

The benefit rates from the quantified fire risk assessment were added to the difference in insurance premium to give the total benefit rate of £2 500 per garage year.

This is the figure used in the investment appraisal. The following table shows the discounted cash flow over a 30 year period. The discount factor used is 10 %: this is the norm for commercial premises and is spread over a 30 year life span (the life of the sprinkler system). The financial data in Table 3 do not represent those of any particular garage or operator, but might be typical of some circumstances.

Table 3 — Discounted cash flow for bus garage sprinkler system

	Year	Capital cost £	Annual cost £/yr	Total cost £/yr	Savings £/yr	Net costs/ savings £/yr	Discount factor (10 %)	NPV of costs/ savings £	Cumulative NPV
	0	25 000		25 000	0	25 000	1	25 000	25 000
	1		100	100	–2 500	–2 400	0.909 1	–2 182	22 818
	2		100	100	–2 500	–2 400	0.826 5	–1 983	20 835
	3		100	100	–2 500	–2 400	0.751 3	–1 803	19 032
	4		100	100	–2 500	–2 400	0.683 0	–1 639	17 392
	5		100	100	–2 500	–2 400	0.620 9	–1 490	15 902
	....	....	....	....	....	....	....	....	....
	26		100	100	–2 500	–2 400	0.083 9	–201	3 014
	27		100	100	–2 500	–2 400	0.076 3	–183	2 831
	28		100	100	–2 500	–2 400	0.069 3	–166	2 664
	29		100	100	–2 500	–2 400	0.063 0	–151	2 513
	30		100	100	–2 500	–2 400	0.057 3	–138	2 375
Total				28 000	–75 000	–47 000		2 375	

The cost–benefit analysis showed a small positive net present value at the end of 30 years. The positive figure indicated that, strictly speaking, the installation of bus garage sprinkler systems did not represent a good investment. However, the smallness of the value indicated that this was a marginal case.

In the light of the risk assessment, the bus operator decided that they had sufficient redundancy and diversity of bus supply through ownership (in several garages), leasing and buying and insurance not to require bus garage sprinklers. However, the risk assessment had highlighted several other areas, such as fire safety management and the separation of the IT centre that were much more cost-effective, and these were implemented.

5.3.3.7 *Conclusions*

A study to assess the benefits of installing sprinkler systems in bus garages indicated that there were business continuity and property protection benefits to the operator. However, the cost–benefit analysis and the operators contingency plans meant that there was no cost–benefit or consequence case for installing sprinklers in bus garages. As a result of the risk assessment, the operator did implement other forms of safeguard and fire precaution.

5.3.4 ***Fault tree analysis***

Fault trees trace the root causes of a given final event of concern by working backward logically to base events. A fault tree is a graphical representation of logical relations between an undesirable top event and primary cause events.

The construction of a fault tree starts with the definition of the top event identified at the hazard identification stage. The tree is constructed by placing various cause events in correct sequential order. This is generally done by working backwards from the top event and specifying the events causes, faults or conditions that could lead to the occurrence of the top event, working backwards from each of these which in effect become secondary top events and so on. This process is continued and terminated when a final set of base (or root) events, faults or conditions are identified. A diagrammatic representation of the process would then generate the branches of a tree. Probabilities are assigned to the root events.

The events in a fault tree are connected by logic gates that show what combination of the constituent events could cause the particular top event. These are mainly AND gates in which all the constituent events have to occur and OR gates in which only one of the constituent events need to occur to cause the occurrence of the specific top event. The probability of occurrence of the top event is calculated using Boolean algebra. Simple fault trees can be calculated directly using Boolean algebra. More complex fault trees require that “minimum cuts sets” or “path sets” be established using “Boolean reduction” techniques. Figure 8 shows a general fault tree and the use of the logic underlying the AND and OR gates. Computer software is available that can speed up the use of complex fault trees.

An example of a simple fault tree applied to fire detection is given in Figure 9. Here the top event is the “failure to detect a fire within 5 min of ignition”. The causes of this top event can be followed through the four root causes for which data can be generated.

OR gates are usually calculated by adding the root probabilities together and subtracting their multiplied value.

$$P_{\mathrm{OR}} = (P_{\mathrm{A}} + P_{\mathrm{B}}) - P_{\mathrm{A}}P_{\mathrm{B}}$$

AND gates are calculated by multiplying the root probabilities together.

The top events of fault trees can very often supply the conditional probabilities for event trees.

$$P_{\mathrm{AND}} = P_{\mathrm{A}}P_{\mathrm{B}}$$

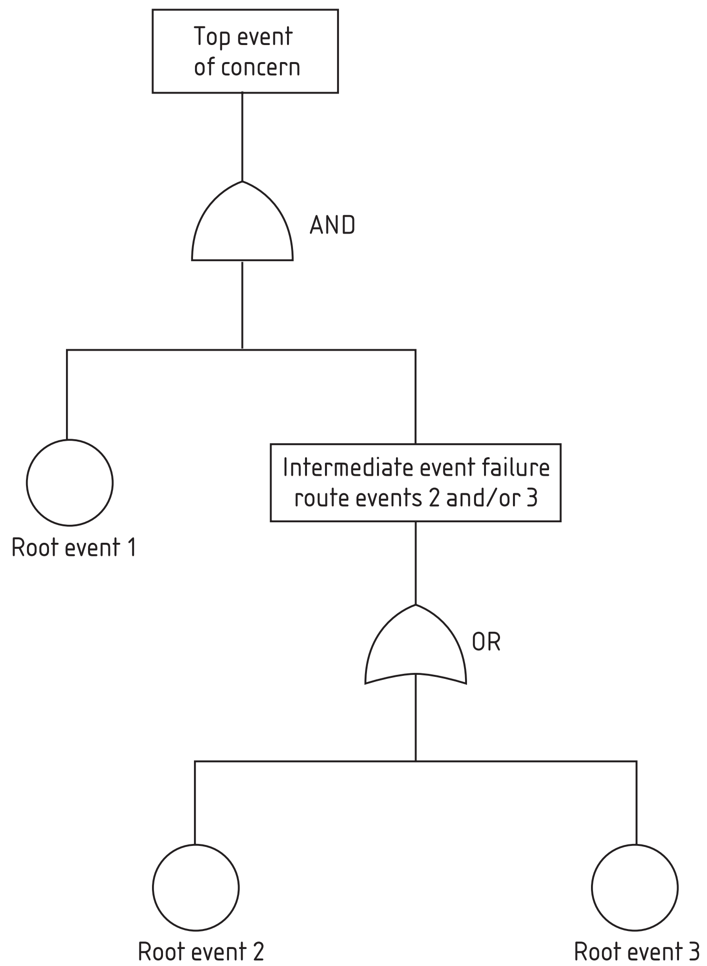


Figure 8 — General form of a fault tree

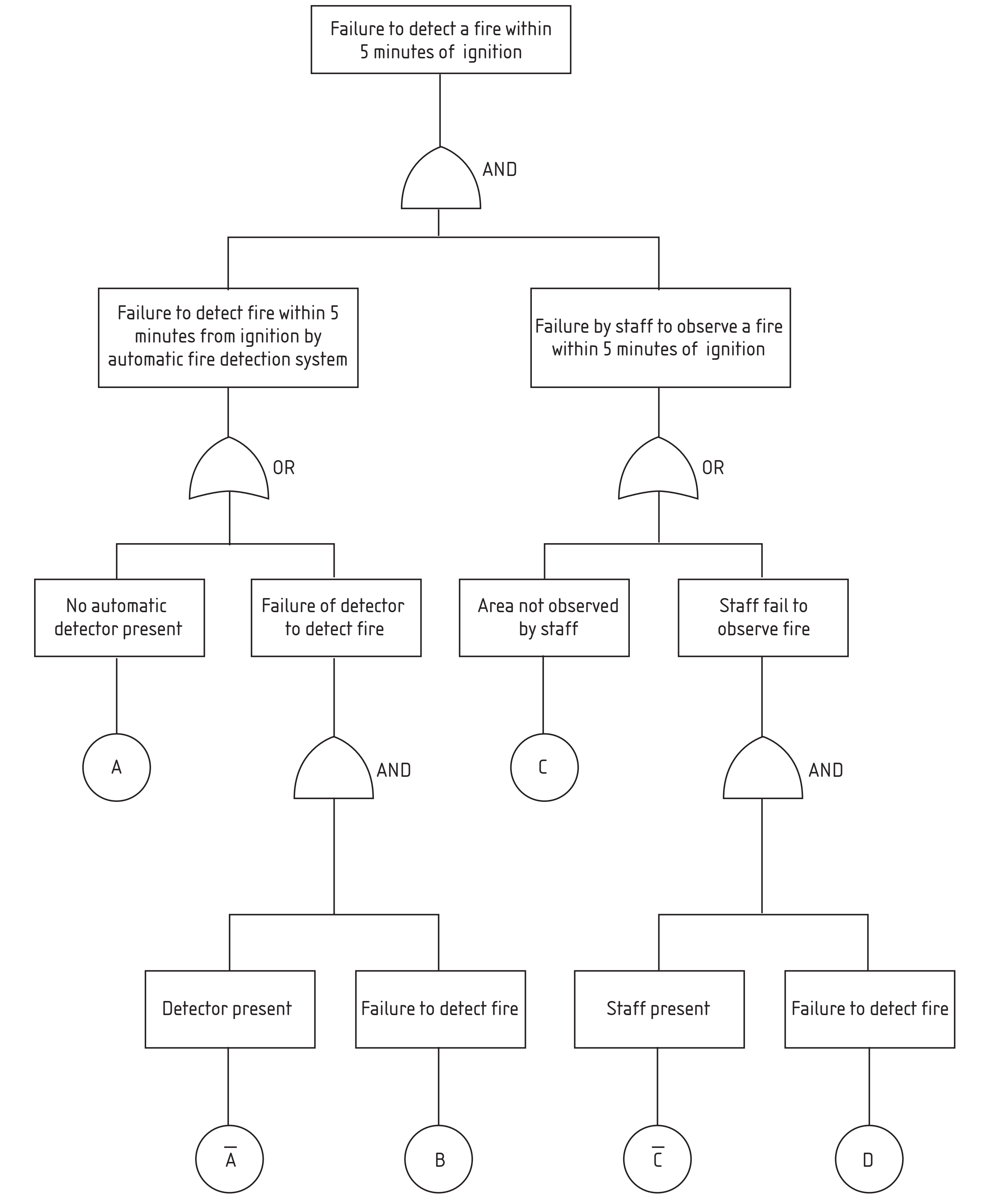


Figure 9 — Fault tree for the failure to detect a fire within 5 min of ignition

5.4 Sensitivity analysis

Sensitivity analysis can be used to draw useful conclusions in the first instance or to assess the robustness of a decision based on probabilistic risk assessment.

Probabilistic risk assessment, like all fire engineering analysis, uses analysis techniques and data to answer questions regarding fire safety design. The analysis techniques and data might have simplifying assumptions and limitations that mean that they might not replicate the details of actual events. However, if meaningful conclusions are to be drawn from an analysis, they should be sufficiently representative that the correct fire safety design decision is taken.

If the results of the probabilistic risk analysis are well within the acceptance criteria, then sensitivity analysis might not be needed. If, however, the results of the probabilistic risk analysis are close to the acceptance criteria, then variations in the variables can have a significant affect on the conclusions from the analysis and sensitivity analysis should be used to assess this.

The first step of sensitivity analysis is to identify the variable(s) that are likely to have the greatest impact on the results of the analysis. The variables can be identified as:

a) those where a small change is magnified due to its role in an equation or analysis; and/or

b) those whose value is subject to substantial variability or uncertainty.

For example, a variable that has a value to the ⅓ power in an equation might not have a large impact on the final results of the analysis. Variations in another variable that is to the 4^{th} power in an equation might have a significant impact on the results of the analysis. If a variable is the only variable in an equation or it is used several times in the analysis then it, too, can have a significant impact on the results of the analysis.

The variables identified as potentially having a significant impact on the results of the analysis can then be investigated in one of three ways:

a) a single variable with an alternative value;

b) a single variable over a range of values;

c) a multiple point assessment of multiple variables.

A sensitivity analysis of a single variable with an alternative value is the simplest approach. The analysis is repeated with an alternative (usually more onerous) value to assess whether the conclusion of the analysis are robust. If the assessment criteria are still satisfied, then the conclusions of the analysis are further reinforced.

Often sensitivity analysis based on a single alternative value of a variable is not very conclusive. Therefore, sensitivity analysis of a variable over a range of values is used. The analysis is repeated and a graph is produced showing the variation of the results of the analysis against values of the variable. This provides much greater insight into the relationship between the variable and the output of the analysis. If the results of the analyses lie across the acceptance criteria then a critical value of the variable can be identified and an assessment can be made of its implications.

Advanced methods of sensitivity analysis are available that allow more than one variable to be varied at a time. Using these methods, the results of the analysis can be presented in a table or, after applying regression analysis, as a mathematical expression.

6 Complex analysis

6.1 General

The standard approaches described in Clause **5** are those that can be used to address the most commonly found risk issues with fire safety engineering. Most contain simplifying assumptions that might not be appropriate in all cases. Some issues require a more complex form of analysis. Therefore, Clause **6** contains six types of models that can be used on more complex issues. These are:

a) other statistical models;

b) reliability analysis;

c) stochastic models;

d) Monte Carlo analysis;

e) partial safety factors;

f) Beta method.

These models are discussed in **6.2**, **6.3**, **6.4**, **6.5**, **6.6** and **6.7**. Further types of analysis, or variations on the types of analysis shown, can be used as appropriate, and so the contents of Clauses **6** and **7** should not preclude the use of alternative forms of probabilistic fire risk analysis.

6.2 Other statistical models

6.2.1 *Frequency of ignition*

Subclause **5.2.2** refers to a simplified method of determining the frequency of ignition. This method can make allowances for variations in each area when judged against the "average area", but does not allow for variations in the building.

This subclause provides a method for taking variations in the building (other than floor area) into account, but the method can require extensive statistical surveys or data [4,5].

Probability of an accidental fire (i.e. not arson) starting in a building would depend on the presence or absence of causes or sources that can be classified into two broad groups: human and non-human.

The first group consists mainly of children playing with fire, e.g. matches, careless disposal of matches and smokers' materials and misuse of electric and other appliances.

The second group includes defects in, or faulty connections to, appliances using electricity, gas and other fuels. The appliances may be further classified according to cooking, space heating, central heating and other uses. This group also includes causes such as mechanical heat or sparks in industrial buildings, natural occurrences and spontaneous combustion. Some materials in a building could be ignitable even by a low energy smouldering source, e.g. latex foam and finely powdered rubber.

The nature and number of ignition sources and materials vary from one part of a building to another. In an industrial building, for example, three major types of area can be identified: production, storage and other areas. Given that a building is involved in a fire, the conditional probabilities reflecting the relative or comparative risks due to various causes in different types of area of the building can be estimated from group statistics such as those in Table A.10. In this case, the conditional probability due to, say, smoking materials in the store/stock room is 0.012 9 (= 15/1162).

The conditional probabilities based on figures such as those in Table A.10 would pertain to an "average" or "reference" building in the type or risk category considered. For a particular building in any type or risk category, an estimate of the conditional probability (given fire) for the i^{th} cause in the j^{th} part of the building is given by:

$$I_{ij}P_{ij} \quad (5)$$

where P_{ij} is the probability for this cause and part of the building, obtained from the figures given in Table A.10.

The parameter I_{ij} will be assigned the value zero if the i^{th} cause is totally absent in the j^{th} part of the building considered for risk evaluation. If the cause is present, I_{ij} should be given a positive value, depending on the extent to which this cause can be responsible for starting a fire in the j^{th} part; this value can be greater than unity. A value equal to unity can be assigned if the building is similar to the "average building" in this respect.

The application of this method has been illustrated with the aid of an example relating to fires caused by smokers' materials. For this cause, equation (5) can be adjusted to take account of factors such as smoking lobbies and publicity measures warning people about the fire risk due to this cause. The assignment of value to the parameter I_{ij} has to be somewhat subjective with its accuracy depending on the extent and accuracy of relevant information used in the calculations.

Each possible cause or source of ignition in each part of the building considered should be identified and its I_{ij} value estimated. The aggregate probability of fire starting for the building is then:

$$P_{\text{ign}} = J\sum_i \sum_j I_{ij}P_{ij} \quad (6)$$

where J is the likelihood of fire starting in a building of total floor area A_b (in m^2) given by equation (1). The value given by the double summation in equation (6) can be greater or less than unity depending on the extent to which the various causes are present or absent in the building. It will be equal to unity only if the building considered is approximately identical to the average characteristics of the underlying population of buildings, in regard to causes or ignition sources. Estimation of J is discussed below.

The aggregate probability [equation (6)] can be greater or less that J. This allocation approach has been used in fire risk assessment of nuclear power plants [21]. For any type of building, the probability of fire starting J will increase with the number of ignition sources and hence the size of the building expressed in terms of total floor area A_b (in square metres). An estimate [4] of J for any period is given by:

$$J = \frac{n\,p_n}{N p_N} \qquad (7)$$

where n is the number of fires during the period, N is the number of buildings at risk, p_n is the proportion of buildings of size A_b involved in fires during the period and p_N is the proportion of buildings of size A_b at risk.

The parameters n and p_n can be estimated from fire statistics, but special surveys have to be carried out for estimating N and p_N. It might be possible to analyse some other statistics to obtain approximate measures of N and p_N. For example, the distribution of manufacturing units according to employment size is given in the Business Monitor (PA series) published periodically by the Office for National Statistics. This information can be combined with an estimate of average area occupied by each person. If the information can be available for all the parameters, J can be estimated by taking logarithms of terms on both sides of equation (7) and performing a simple regression analysis. Before carrying out this analysis, p_n and p_N should be estimated as functions of A_b. J is approximately given by F_i in equation (1).

6.2.2 *Probability distribution of damage*

The nature of probability distribution of loss X has been investigated [22,23,24]. According to these studies, fire loss distribution is skewed (non-normal) and, in general, the transformed variable Z (equal to ln X) has a probability distribution, $F(Z)$, belonging to the "exponential type". This type, defined by Gumbel [25] with reference to the limiting (asymptotic) behaviour of a random variable at the tail, includes exponential, normal, log normal, chi square, gamma and logistic distributions. Among these distributions, normal and exponential distributions for Z have been widely recommended by actuaries, based on analyses of data from fire insurance claims. These correspond to log normal and Pareto distributions for loss X on the original scale.

If figures for financial loss are available for all of the fires that have occurred in a risk category, standard statistical methods or a graphical method can be applied for identifying the probability distribution which best fits the data analysed. But, in most countries, these data are generally available only for large fires. Large fires are, in the UK, currently defined as fires costing £50 000 or more property damage. The threshold level, £10 000 until 1973, has been gradually increased over the years due to inflation and the need to keep the number of large fires reported by insurance companies at a manageable level. This led to the development of extreme value statistical models discussed in the next clause.

However, a probability distribution can be constructed for the area damaged A_d when data are available for a significant number of the fires. The probability of damaged area being less than or equal to a specified value of A_d is given by $G(A_d)$ and probability of damage exceeding the specified value by $[1 - G(A_d)]$.

Figure 10 is an example (from the textile industry) and is based on fire brigade data. It shows the relationship between A_d and $[1 - G(A_d)]$ for a building with sprinklers and a building without sprinklers. A_d is on a log scale since this random variable, like financial loss, has a skewed probability distribution such as log normal. The values of the parameters of this distribution vary from one type of building to another and with the effectiveness of fire protection measures.

From Figure 10, an initial damage of 3 m^2 is likely to occur before the heat generated in a fire is sufficient to activate a sprinkler system. For both types of buildings, the probability of damage exceeding 3 m^2 is 0.58. It is apparent that, in the range greater than 3 m^2, a successful operation of sprinklers would reduce the probability of damage exceeding any given value. For example, the probability of damage in a fire exceeding 100 m^2 is about 0.18 if the building has no sprinklers and 0.08 if the building is equipped with sprinklers.

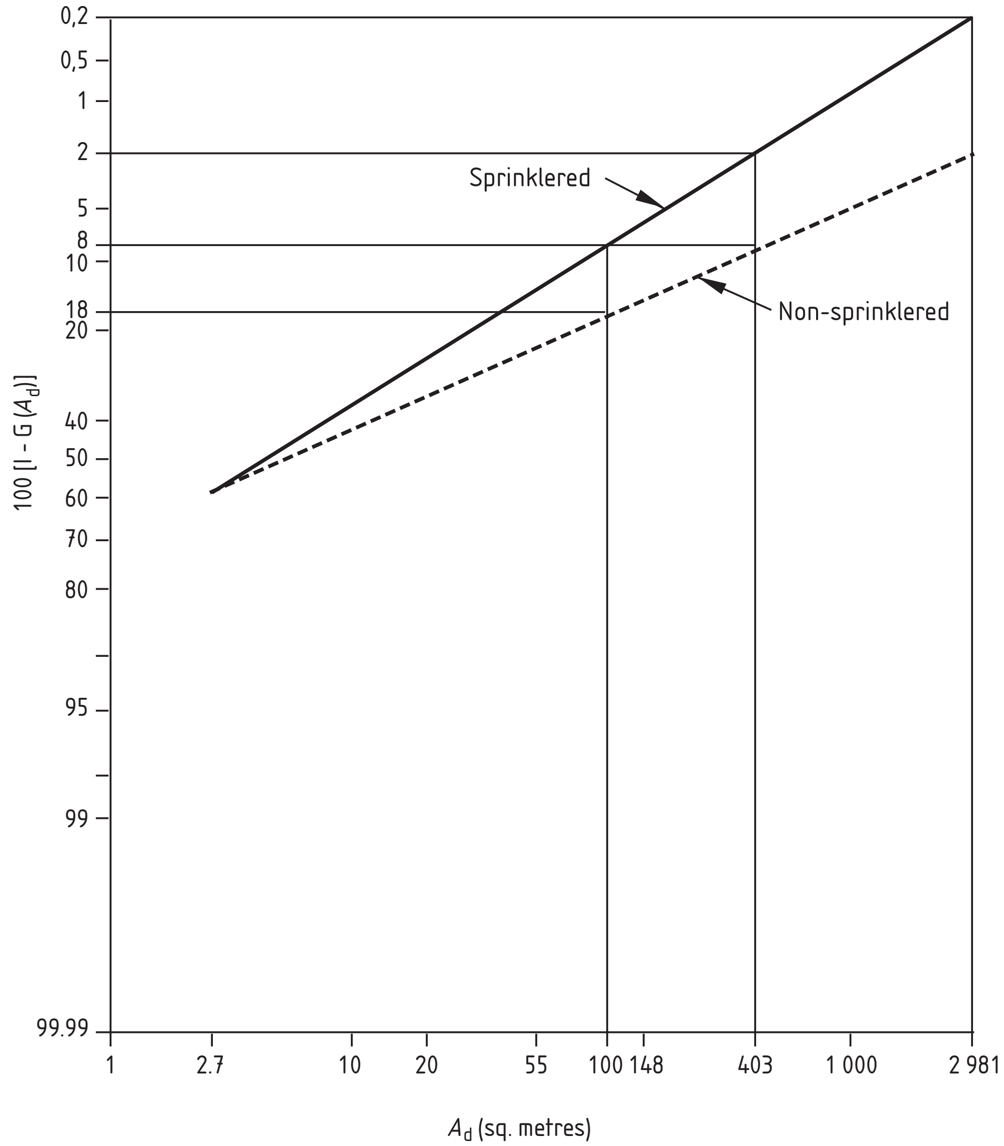


Figure 10 — Probability of area damaged, textile industry

Based on consequences in terms of damage to life and property, a damaged area of 500 m^2 may be considered to be acceptable if this is the size of a compartment without sprinklers. In this case, the probability of damage exceeding 500 m^2 is 0.08 if not sprinklered and 0.02 if sprinklered. This result also provides a basis for permitting an increase in the size of a sprinklered compartment considerably beyond 500 m^2 if a level of 0.08 is acceptable for the probability of a fire spreading beyond the compartment.

A log normal distribution has been fitted to the raw data pertaining to Figure 10, disregarding fires with damage less that 1 m^2 and following a method appropriate for "truncated" distributions [5]. For the range exceeding one square metre, values of 0.02 and 2.46 were obtained for the mean and standard deviation of Z, the logarithm of area damaged for a sprinklered building. The expected (average) damage was calculated as 41.6 m^2. For a non-sprinklered building, the mean and standard deviation of Z were 0.75 and 2.87 leading to an expected damage of 216.7 m^2.

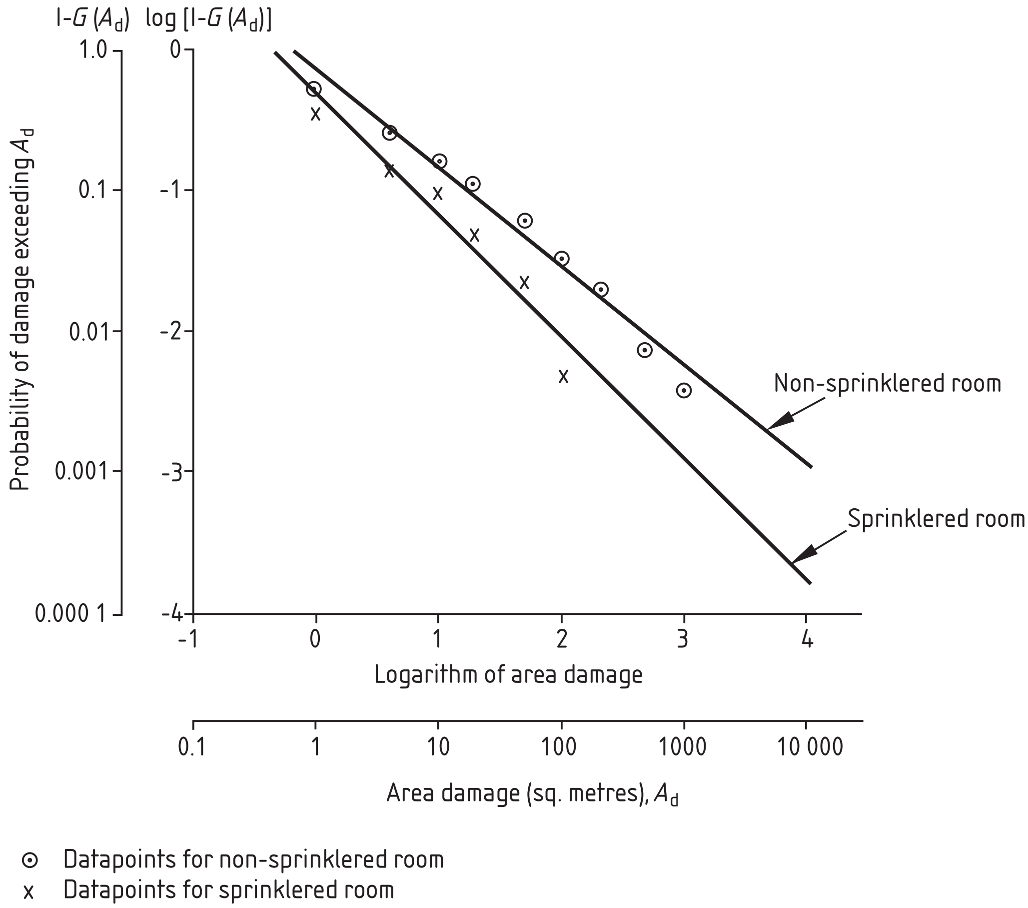


Figure 11 — Pareto distribution of area damage – retail premises (assembly areas)

Figure 11 is an example based on Pareto distribution for area damage. If this distribution is appropriate, logarithm of damage and logarithm of the survivor function $[1 - G(A_d)]$ should have an approximately straight line relationship, as in Figure 10. Values for plotting the points in Figure 11 were obtained from the figures for the frequency distribution of damage in Table A.7.

Probability distributions such as those in Figure 10 and Figure 11, which can be estimated for any type of building, are overall distributions for a given type. For a building of given size (m^2) belonging to a type, the expected (average) damage can be estimated by applying a statistical technique to expected truncated distributions. Formulae for estimating the financial loss in a building with certain financial value at risk have been derived [20] for log normal and Pareto distributions.

6.2.3 *Extreme value distributions*

Large losses fall at the "tail" of the parent distribution of loss discussed in the previous section. These losses constitute a very small percentage of total number of fires in a risk category and hence, are not amenable to analysis by standard statistical methods. Extreme order theory provides a mathematical framework for making the best use of the information provided by large losses [22,23,26,27]. The asymptotic theory of extreme values discussed in these studies provides approximate results for an "exponential type" distribution. According to this theory, the number of fires (n) occurring during a period should be large, say, more than 100. Also, preferably, at least 20 large losses should be available for analysis. Due to these requirements, in some cases, it might be necessary to consider fires occurring in a group of buildings with similar fire risk over, say, four or five years.

A detailed discussion about extreme value theory is beyond the scope of this Published Document. Basic features of this theory are as follows. The logarithms of losses in n fires occurring in a risk category over a period of years constitute a sample of observations generated by the parent distribution $F(Z)$. If these loss figures are arranged in decreasing order of magnitude, the logarithm of the m^{th} loss may be denoted by $Z_{(m)n}$, referred to as an extreme order statistic. For the largest value, the subscript m takes the value one (first rank). Over repeated sample (periods), $Z_{(m)n}$ is a random variable with an extreme value probability distribution. Extreme Order Theory is concerned with the individual probability distributions generated by extreme order statistics of varying rank m and their joint distribution.

In the absence of any knowledge about the exact nature of the parent distributions, the parameters of the extreme value distribution of $Z_{(m)n}$ can be estimated from observations on $Z_{(m)n}$ in repeated samples. Three methods available for this purpose [26] involve corrections due to the varying value of n (number of fires) from period to period apart from the correction of loss for inflation. The estimated values of the parameters for different ranks (m) would describe the behaviour of the tail of the parent distribution as a function of n (see Figure 12). The parameters also provide an indication of the nature of the parent distribution. Parent distributions satisfying this behaviour can be fitted to the large losses and the errors estimated in order to select a distribution that would provide the best fit.

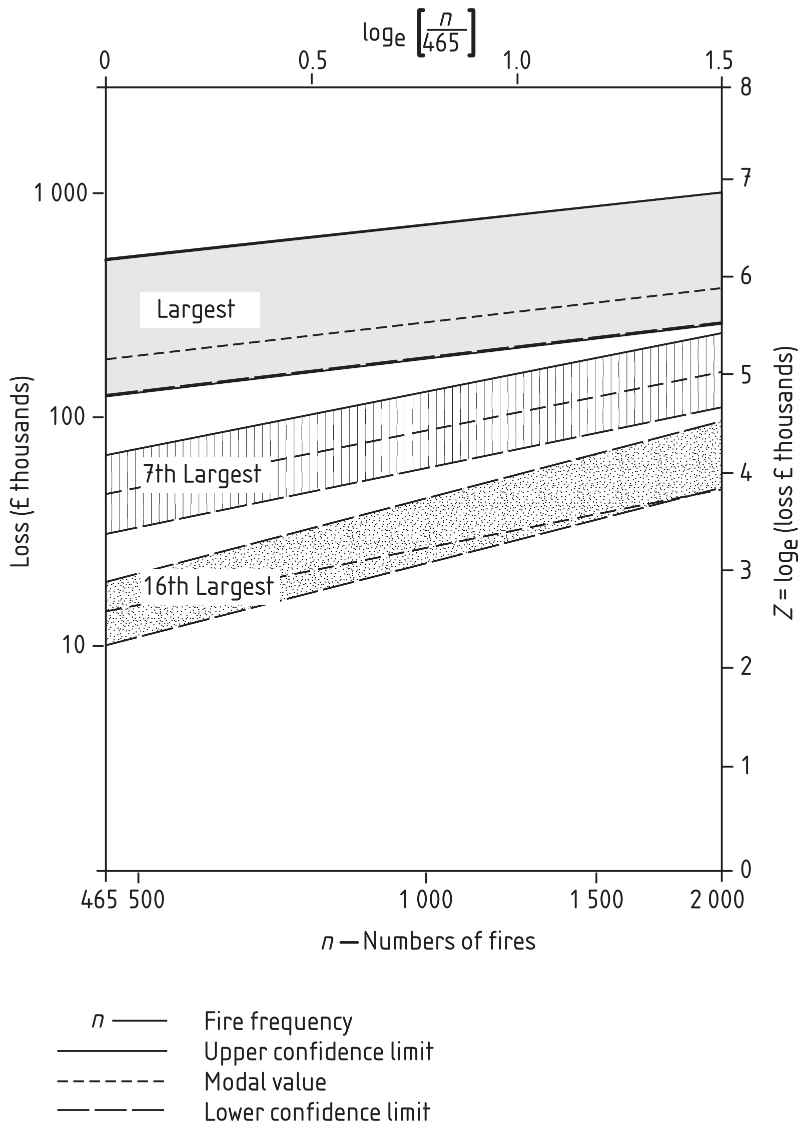
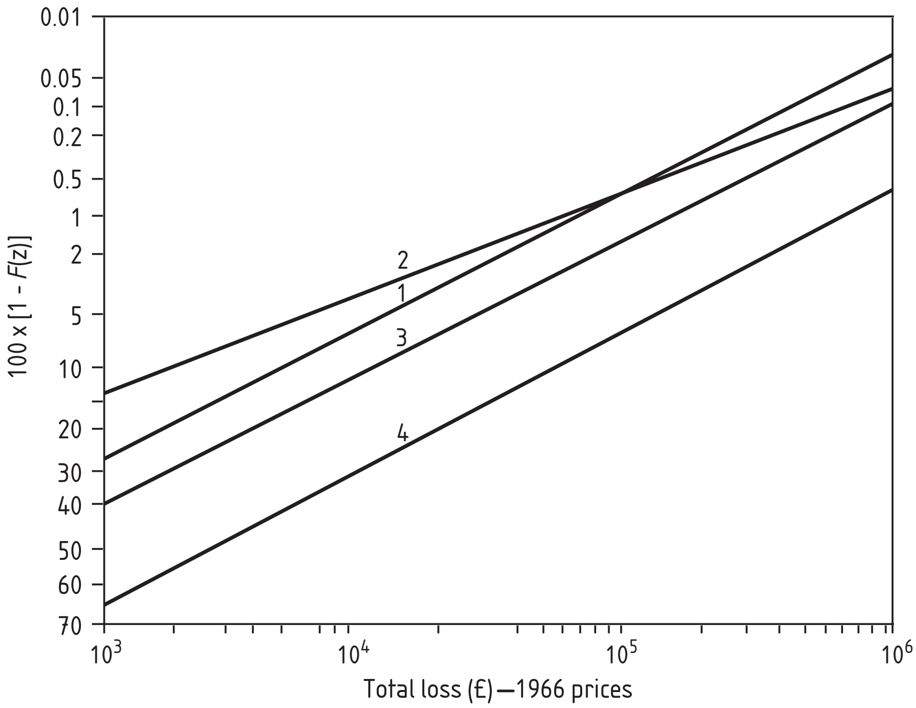


Figure 12 — Fire frequency and large losses

Another application of the extreme value theory is concerned with the estimation of the mean (μ) and standard deviation (σ) of Z, logarithm of loss, in all fires, large and small. But this estimation has to be based on, say, s consecutive large losses, m = 1 to s, above a threshold level. Information on financial loss may be available only for s large fires out of n fires. For obtaining the best estimates of μ and σ in all n fires from s large losses two methods have been developed: Generalized Least Square and Maximum Likelihood. The first method provides "unbiased" estimates but involves complex calculations for which a computer program has been developed. The second method is quite easy to apply and only requires a pocket calculator. This method provides "biased" estimates but formulae have been developed to adjust the results for biases. Both the methods require an assumption, e.g. log normal to be made about the "parent" distribution of loss.

Assuming a log normal distribution and applying the Generalized Least Square Method [9], the average losses due to fires in industrial and commercial buildings with and without sprinklers has been estimated (see Table A.12 and Figure 13).



Line	Subpopulation	Parameters
1	Sprink/single-storey	μ = -0.616 σ = 1.024
2	Sprink/multi-storey	μ = -1.419 σ = 1.340
3	Non-sp/single-storey	μ = -0.334 σ = 1.062
4	Non-sp/multi-storey	μ = -0.401 σ = 0.992

Figure 13 — The survivor probability distribution of fire loss for each class in the textile industry

6.2.4 *Fire growth rate*

A central parameter in the design of buildings and provision of fire protection measures is the rate at which a fire grows in the room of origin and subsequently spreads to other parts of a building. This rate depends primarily on the heat output from the materials ignited apart from other factors such as room dimensions and ventilation. For evaluating the fire growth rate, fire safety engineers generally recommend the use of the following simple equation, commonly known as the t^2 fire:

$$\dot{Q}_g = \alpha(t - t_i)^2 \quad (8)$$

where $\dot{Q}_g$ is the heat release rate of the fire during the growth phase (in kW), t is time (in seconds), t_i is the time (in seconds) at which ignition occurs, usually taken as zero, and α is the fire growth parameter (in kJ/s^3).

The actual fire growth rate varies according to the types of material present and the configuration of the enclosure. The values of α are given for four basic fire growth curves: slow, medium, fast and ultra-fast. This classification has been suggested for different types of occupancies.

Equation (8) is based on a series of fire tests and analysis of some real fires. It estimates the likely rate of growth during the early stages of fire development involving the material or object first ignited.

The development of a fire in a room or compartment containing several objects arranged in a certain manner can also be analysed statistically. For statistical approach to determine the rate of growth of a fire in a room or compartment, the (deterministic) growth of fire as a function of time can be better described by the following exponential model than the t-squared curve [28,29,30].

$$A_d(t) = A_{ig}\exp(\gamma t) \quad (9)$$

where $A_d(t)$ is the area damaged in t min, A_{ig} is the area initially ignited, and γ is the fire growth parameter.

Equation (9) follows some scientific and experimental studies according to which the heat output from a fire increases exponentially with time. Heat output is approximately proportional to area damage. Conceptually, $A_d = 0$ for $t = 0$ but this condition is not satisfied by equation (9). This equation can be modified to force or bend the exponential curve to pass through the origin but this does not appear to be a sound engineering practice. Moreover, the initial stage of a fire can be very variable in length of time; it can last for hours (smouldering) or it can be over in minutes. Equation (9) is generally applicable for the period after the onset of "established burning".

It should be emphasized that $A_d(t)$ in equation (9) is the final (cumulative) size of fire in terms of area damaged at the time (t) of its extinguishment. Fire statistics do not and cannot provide information on the size of the fire at any specific time, say, when the fire brigade arrives at the scene of the fire. The derivative (dA_d/dt) provides an estimate of the additional area damaged during the short period (t to $t + dt$):

$$\frac{dA_d}{dt} = A_{ig}\gamma\exp(\gamma t) \quad (10)$$

Fire statistics compiled by the Home Office provide, for each fire, information on $A_d(t)$ and the duration of burning, Δt_{burn}, as the sum of the following four periods:

— Δt_1 is ignition to detection or discovery of fire;

— Δt_2 is detection to calling of fire brigade;

— Δt_3 is call to arrival of the fire brigade at the scene of the fire (attendance time);

— Δt_4 is arrival to the time when the fire was brought under control by the fire brigade (control time).

An estimate of Δt_1 is given according to the following classification:

a) discovered at ignition ($\Delta t_1 = 0$);

b) discovered under 5 min after ignition;

c) discovered between 5 min and 30 min after ignition;

d) discovered more than 30 min after ignition.

For estimating the total duration Δt_{burn}, average values of 2, 17 and 45 min can be adopted for the second, third and fourth classes of Δt_1. The growth of the fire will be practically negligible during the fifth period of t from control to extinction of the fire.

Using fire statistics [28], equation (9) was applied in a pilot investigation concerned with the economic value of early detection in textile industry fires, assuming that Δt_1 is reduced to 1 min. For fire spread beyond the initial stage (item first ignited) taken as zero time and the commencement of established burning with t expressed in minutes, the overall value of fire growth rate was found to be 0.083 if not sprinklered and 0.031 if sprinklered. A_{ig} was 4.43 m^2 in both the cases. Since the fire resistance of the structural barriers affected the overall growth rates, growth rates for fire development within a room were estimated in a later study [5]. These values were 0.117 for a sprinklered room and 0.196 for an unsprinklered room.

The values of γ mentioned above for fire spread within a room gave "doubling times" of 5.9 min and 3.5 min for sprinklered and unsprinklered rooms respectively. The "doubling time" is given by:

$$\text{doubling time} = (1/\gamma)\log_e 2 = (1/\gamma)0.693\,1 \quad (11)$$

and is a constant for the exponential model in equation (9). This is the time taken by a fire to double in size. For example, if it takes 6 min for the area damaged to increase from 10 m^2 to 20 m^2 it will also take only 6 min for the damage to increase from 20 m^2 to 40 m^2, 30 m^2 to 60 m^2, 50 m^2 to 100 m^2 and so on.

With appropriate assumptions about the ratio of vertical rate of fire spread to horizontal rate, growth rates and doubling times, as discussed above in terms of area damage (horizontal spread), can be converted to growth rates and doubling times in terms of volume destroyed [30]. As might be expected, the growth rate will be higher, and doubling time shorter, in terms of volume involved than growth rate and doubling time in terms of area alone. Rate of fire growth in a real fire in terms of heat output can be expected to be positively correlated with the rate of growth in terms of volume destroyed.

The exponential function in equation (9) can be expanded into a power series such that terms involving powers of γt higher than, say, $\gamma^3 t^3$ can be neglected if γt is small. The exponential model includes a term involving t and, hence, is more generalized than the t^2 curve.

The exponential model can be expanded to provide growth rates separately for the period Δt_A, (= $\Delta t_1 + \Delta t_2 + \Delta t_3$) before the arrival of the brigade at the scene of a fire and Δt_B, (= Δt_4) after the arrival until the fire is brought under control. The growth rates for these two periods have been estimated [30] for some industrial buildings and three areas of fire origin: production, storage, and other area. For these industries and areas and for the early period Δt_A, the growth rates and their confidence limits for some materials ignited first have been estimated.

In a later study [31], the fire growth rates for railway properties, public car parks, road tunnels and subways and power station have been estimated. In this paper, the authors have explained the distinction between the average growth rate in all fires and the growth rate in an individual fire; these two rates were estimated together with their confidence limits.

The rate (dL/dt) at which the equivalent fire load (L) in a compartment is consumed in a fire can be expected to be equivalent to $\dot{m}$ (in kg/sec), the rate at which fuel mass is destroyed. If the fire load density is $\bar{L}$ (in kg/m^2), it follows that:

$$\dot{m} = (dL/dt) = \bar{L}(dA_d/dt) \quad (12)$$

where dA_d/dt is given by equation (10) with t in seconds. From equations (10) and (12):

$$\dot{m} = \dot{m}_i \exp(\gamma t) \quad (13)$$

where:

$$\dot{m}_i = \bar{L} A_{ig} \gamma \quad (14)$$

is the loss rate of fuel mass at the initial time of commencement of established burning. Also:

$$\begin{aligned} \dot{Q} &= \dot{m} H_c \\ &= \dot{m}_i H_c \exp(\gamma t) \end{aligned} \quad (15)$$

where, $\dot{Q}$ (kW) is the rate of heat output and H_c is the effective heat of combustion of the fuel, assumed to be equal to 18 000 kJ/kg generally.

For equation (9), the fire growth rate γ has been regarded as a constant and is the average rate over the duration of burning. Realistically, γ will be increasing in the early stages of a growing fire until fire-fighting by sprinklers or fire brigade commences; fire-fighting will gradually reduce the value of γ. In order to study this variation in γ, the fire growth rate for each of the fire spread categories mentioned in Table A.4 was estimated [32] and, for sprinklered and unsprinklered rooms, further broken down into fires with and without fire brigade intervention. The estimation was carried out for four types of industrial building: retail and wholesale, distributive trade and office buildings.

In the studies mentioned above, area damaged by direct burning has been used for the variable $A_d(t)$, in order to estimate the rate of growth of fire, i.e. heat output. Based on this rate, the rate of growth of smoke can be estimated by ascertaining the correlation between the two rates. Smoke can be expected to grow exponentially faster than heat, with a value for the parameter γ two or more times the value for heat development. Rate of growth of smoke can also be estimated directly to some extent by using data on total area damage including smoke and water damage. This information is available in the UK fire brigade fire incident reports.

The exponential model for fire growth was developed in order to assess the economic value of early fire detection in reducing property damage by reducing the fire detection or discovery time Δt_1 [28]. The model can be used to assess the economic value of reducing other time components of total duration of burning (Δt_{burn}), particularly the attendance (Δt_3) and control time (Δt_4). The maximum fire growth estimated for a real fire scenario [32] can be used to judge the validity of the growth rate estimated by a deterministic model such as a field model.

6.2.5 ***Life risk***

Most of the fire deaths occur in dwellings. The majority of these deaths are due to a relatively small number of causes such as careless disposal of smokers' materials, incidents with space heaters (mainly misuse or placing articles too close to them), ignition of matches (mostly by children playing with them) and misuse of cooking appliances. Electricity is the major fuel in regard to deaths caused by the misuse of space heaters and cooking appliances.

Of the fire deaths in dwellings, the majority, about 60 %, were found in the room of origin, 20 % elsewhere on the floor of origin and 15 % on floors above the floor of origin. Fire, smoke and toxic gases generally spread upwards and are more likely to be encountered by people in upper floors if they remain in their places of occupation or attempt to escape to safe places in or outside the building involved in fire.

While fire is a major threat to occupants in its immediate vicinity, it is generally smoke and toxic gases that pose a greater threat than flame (heat) to occupants who are remote from the fire. A high percentage of fatalities in the room of fire origin are caused by burns, apart from gas or smoke which is the major cause accounting for more than 50 % of the fatalities in dwellings.

For avoiding death or injury in a fire, an occupant should reach a safe place before heat, smoke, or toxic gases block an escape route. The total time Δt_{esc} taken by the occupants to reach the safe place should be less than the time Δt_{ten} taken by a combustion production to travel from the place of fire origin and produce untenable conditions on the escape route. The probability of one or more deaths in a fire is the fatality rate per fire, $P_d \cdot P_d$ is the product of the rate δ, quantifying the increase in the fatality rate per minute, and the time Δt_{exp} (= $\Delta t_{esc} - \Delta t_{ten}$) in minutes, denoting the duration of exposure to untenable conditions of a combustion product:

$$P_d = \delta(\Delta t_{esc} - \Delta t_{ten}) = \delta \Delta t_{exp} \qquad (16)$$

The values of P_d and δ vary depending on the building type (hotel, department store, etc.), the combustion product (heat, smoke, etc.), and the untenable condition, e.g. visual obscuration.

For any type of occupancy and combustion product, the value of P_d can be estimated with the aid of fire statistics for each of the four classes of discovery time Δt_{det} defined as Δt_1, in **6.2.4**. According to Table A.13 [33], excluding fires discovered at ignition (Δt_{det} = 0), the value of P_d increases with increasing values of Δt_{det}. The value of P_d is higher for fires discovered at ignition than for fires discovered under 5 min after ignition. This might be due to the fact that people in the rooms of fire origin, where the majority of fire deaths occur, do not have sufficient time to escape from being affected by untenable conditions.

The overall fatality rate per fire P_d is 0.012 5 for single occupancy dwellings and 0.012 2 for multiple occupancy dwellings. These rates are due to the fact that the overall average value of Δt_{det} is 13 min for both of the two occupancies. The overall average value for Δt_{det} has been estimated with the assumption mentioned in **6.2.4** that the average discovery times are 2, 17 and 45 min for the three classes with $\Delta t_{det} > 0$.

The total evacuation time Δt_{esc} is the sum of three periods, Δt_{det}, Δt_{pre} and Δt_{trav}, demarcated sequentially by times at which a fire is discovered (or detected) after ignition started. Evacuation commences after discovery of the fire and a safe place, e.g. entrance to a protected staircase, is reached after the initiation of evacuation. Estimates for Δt_{pre} ("recognition time" or "gathering phase") and Δt_{trav} ("travel time") can be obtained from human behaviour studies or evacuation exercises. An estimate for Δt_{ten} can be obtained by carrying out computer simulations based on deterministic models (zone, field, etc.).

In the absence of information on Δt_{pre}, Δt_{trav} and Δt_{ten}, equation (16) may be rewritten as a simple linear regression model:

$$P_d = K + \delta \cdot \Delta t_{det} \quad (17)$$

where:

$$K = \delta \cdot (\Delta t_{pre} + \Delta t_{trav} - \Delta t_{ten}) \quad (18)$$

According to Table A.13, the value of δ, denoting the increase in the fatality rate per minute, is 0.000 8 for single occupancy dwellings and 0.000 6 for multiple occupancy dwellings. These results imply that, for every 10,000 fires in these occupancies, about 7 deaths can be averted for every minute saved (reduced) in the average discovery times of fires. Such a result can, perhaps, be applied to any reductions in the attendance time (Δt_3) or control time (Δt_4) relating to the performance of a fire brigade. According to Table A.13, the value of K is 0.001 6 and 0.001 5 for single and multiple occupancy dwellings.

The values of δ and K mentioned above were obtained by a simple interpolation of overall figures for a fourteen year period. Better estimates of these parameters can be obtained by using the data for individual years and performing a regression (least square) analysis based on equation (17). Statistics can be obtained from the UK fire statistics to evaluate the parameters δ and K separately for the three main causes of death: gas or smoke, burns or scalds, and other causes.

In the above analysis, the parameter δ has been regarded as a constant but, in reality, it would depend on the time periods Δt_{det}, Δt_{pre} and Δt_{trav} and the three components of Δt_{ten} for the time taken by smoke, heat and toxic gases to produce untenable conditions on escape routes. The values of δ separately for the six time components mentioned above can be estimated by expanding equation (17) into a multiple linear regression model and evaluating its parameters if sufficient data are obtained from statistical and other sources. It could be worthwhile to perform the simple regression analysis in equation (17) or the multiple regression analysis separately for the two cases: room of fire origin and other rooms.

Automatic fire detection systems would reduce considerably the discovery time (Δt_{det}) for fires in buildings without these systems. Sprinklers would reduce the discovery time and also increase the time (Δt_{ten}) taken by a combustion product to produce untenable conditions on an escape route. This double action would reduce both Δt_{det} and K in equation (17), thus reducing significantly the fatality rate P_d. Conceptually, the value of Δt_{ten} will be infinity for a fire extinguished by a sprinkler system. The extent to which detection and sprinkler systems are likely to reduce the fatality rate in single and multiple occupancy dwellings has been estimated [33].

If the value of δ is small, the value of P_d in equation (16), given by $\delta \Delta t_{exp}$, is an approximation for the function $[1 - \exp(-\delta \Delta t_{exp})]$, denoting the probability of one or more deaths according to a Poisson probability distribution applicable to a random variable such as number of deaths in a fire taking integer values. According to an extended form of this discrete (discontinuous) distribution, the probability $P(\phi,\Delta t_{exp})$ of exactly ϕ deaths occurring in a fire due to an exposure period of Δt min to untenable conditions is given by:

$$P(\phi,\Delta t_{exp}) = \exp(-\delta \cdot \Delta t_{exp})(\delta \cdot \Delta t_{exp})^{\phi} / \phi! \quad (19)$$

where:

$$\phi! = \phi(\phi - 1)(\phi - 2)........$$

The probability of no death is given by $\phi = 0$ in equation (19) or by $\exp(-\delta \cdot \Delta t_{exp})$ which, if δ is small, can be approximated to $1 - \delta \cdot \Delta t_{exp} = 1 - P_d$, as defined in equation (19). $P_d = \delta t$ is the fatality rate per fire estimated by the ratio between number of deaths and number of fires. This value, which denotes the probability of one or more deaths, may be used in equation (19) to provide an estimate of the probabilities for various values of the number of deaths denoted by ϕ.

The probability of occurrence of a multiple death fire (k or more deaths) is given by:

$$P_k(\Delta t_{\text{exp}}) = \sum_{\phi = k} P(\phi, \Delta t_{\text{exp}}) = 1 - \sum_{\phi = 0}^{k-1} P(\phi, \Delta t_{\text{exp}}) \quad (20)$$

For $k = 2$:

$$P_2(\Delta t_{\text{exp}}) = 1 - \exp(-\delta \cdot \Delta t_{\text{exp}}) - \exp(-\delta \cdot \Delta t_{\text{exp}})\delta \cdot \Delta t_{\text{exp}} \quad (21)$$

The values of P_{d} and $P_k(\Delta t_{\text{exp}})$ can be adjusted to take into account the number of people (occupants) at risk in a particular building or the average number at risk in a particular type of building.

A more precise value of P_{d} (= $\delta \cdot \Delta t_{\text{exp}}$) can be estimated by fitting the Poisson distribution, equation (19), to data such as those in Table A.14. According to this table, the probability of two or more deaths occurring in a fire is 0.001 2 and 0.000 8 for the two occupancies considered. Instead of the Poisson, other discrete probability distributions, e.g. negative binomial, might provide a better fit to a frequency distribution of number of deaths. If this distribution is estimated for each year or each period of, say, two or three years considered as a sample, over repeated sample (periods), the occurrence of a multiple death fire in a group of large buildings will follow an extreme value distribution, as in the case of a large financial loss. An extreme value distribution from "parent" discrete distributions such as Poisson and negative binomial has a complex mathematical form, the structure of which is currently being investigated.

Data such as those in Table A.13 and Table A.14 provide estimates of the current level of life risk quantified as P_{d}. It may be considered desirable to reduce life risk to a level P_{d}', less than the current level P_{d}, by providing staircases of appropriate widths to a building according to a design value for travel time $\Delta t'_{\text{trav}}$ and the corresponding travel distance. This value $\Delta t'_{\text{trav}}$ can be determined according to the equation

$$\Delta t'_{\text{exp}} = P_{\text{d}}'/\delta \quad (22)$$

where:

$$\Delta t'_{\text{exp}} = \Delta t_{\text{det}} + \Delta t_{\text{pre}} + \Delta t'_{\text{trav}} - \Delta t_{\text{ten}} \quad (23)$$

The value of discovery time Δt_{det} depends on whether the building is equipped or not with fire protection systems such as automatic detection systems and sprinklers. Human behaviour studies and evacuation exercises can provide an estimate for the pre-movement time, Δt_{pre}. Deterministic models can provide estimates for Δt_{ten} and $\delta \cdot \Delta t_{\text{ten}}$ is the time taken by, say, smoke to travel from the room of fire origin and produce untenable conditions in an escape route. The parameter δ is the increase in the probability of death for every extra minute of exposure to untenable conditions. The product ($\delta \cdot \Delta t'_{\text{exp}}$), thus estimated in equation (19) or in equation (20), can be used to estimate the probability of occurrence of a multiple death fire.

While the parameters Δt_{det} and Δt_{pre} may be assumed to be constants for a building of given type, Δt_{trav}, Δt_{ten} and δ vary depending on the location of the place of fire origin, the escape routes and the nature of the combustion product. Mean values for these three parameters can be estimated by considering different locations of fire origin in the building, escape routes and combustion products. Computer simulations based on deterministic models of evacuation and spread of combustion products can provide these mean values and their standard deviations.

6.2.6 *Regression analysis*

Simple linear regression analysis is concerned with fitting a straight line of the following form:

$$y = \tilde{m}x + \tilde{c} \quad (24)$$

to pairs of observations (y_i, x_i) available for a sample of, say, fires in a risk category. The subscript i denotes the i^{th} fire in the sample. The value of the "dependent" variable y_i corresponds to that of the "independent" variable x_i. The independent variable is a factor such as duration of burning that affects a dependent variable such as area damage. The regression parameter $\tilde{m}$ is an estimate of the increase in the value of y for unit increase in the value of x. $\tilde{c}$ is a constant, being the estimated intercept at the y axis.

A graphical analysis may be performed in the first instance to test whether a straight line can be drawn approximately to pass through the scatter of points representing the pairs of observations (y_i, x_i). In some cases, it might be necessary to use the logarithm of the dependent variable or the logarithms of both the variables for y_i and x_i for fitting the straight line. For example, according to equation (2), logarithm of area damage has a linear relationship with the building size expressed in terms of total floor areas. The exponential model in equation (9) is another example in which the logarithm of area damage has a linear relationship with duration of burning.

If a graphical analysis reveals a linear relationship between y_i (or its logarithm) and x_i (or its logarithm), the values of the parameters $\tilde{c}$ and $\tilde{m}$ in equation (24) providing the "best" fit can be estimated by applying the method know as "least square". Computer packages are available for this method. With the values of $\tilde{c}$ and $\tilde{m}$ thus estimated, equation (24) can be used to estimate the expected or average values of y for a given particular value of x. Computer packages also provide an estimate of the "residual error" which can be used to obtain the "confidence limits" for the expected value of y.

In the simple, single linear regression described above, it is assumed that the value of the dependent variable y is significantly affected by the magnitude of a single factor (independent variable) x. This might not be strictly true, since a number of factors might jointly affect y, each factor contributing some amount towards y. For example, the area likely to be damaged in a fire might be affected by building size, building height, compartment size, ventilation, number of compartments, number of floors, fire resistance and the presence or absence of fire protection measures such as automatic detectors, sprinklers and smoke control systems. There are also other factors such as fire brigade attendance time and control time, rate of fire spread, and so on. Some factors will affect property damage, some life damage (e.g. number of escape routes, widths of escape routes) and some both property and life damage. Once these factors are identified, their contribution to the damage can be estimated by performing a multiple regression analysis with data on damage and factors for each fire for a sample of fires. Such data should be available and, if not, should be collected or estimated and their numerical values used in analysis.

If p factors (independent variables) are considered in a multiple regression, their contributions to damage (dependent variable) quantified by the regression parameters β_j (j = 1,2,...p) are estimated by the model:

$$Z = \beta_0 + \beta_1 W_1 + \beta_2 W_2 + \ldots\ldots \beta_p W_p \qquad (25)$$

where Z is the logarithm of damage and W_j is the numerical value (or its logarithm) of the j^{th} factor. For a qualitative factor such as sprinklers, the value +1 may be assigned if the building is equipped with sprinklers, or –1 if not so equipped. For quantitative factors, the parameter β_j measures the increase in the value of Z for unit increase in the value of W_j. The constant β_0 measures the fixed effect not depending on the factors included in the model; it is an average value for the effects of factors not included in the model.

In the application of the model in equation (25), for the i^{th} fire, Z_i is the logarithm of damage and W_{ij} is the corresponding value of the j^{th} factor. If data are available for n fires and p factors, n sets of (p + 1) values provided by Z_i (i = 1,2,...n) and W_{ij} (i = 1,2,…n; j = 1,2,…p) are used in a Least Squares Multiple Regression Analysis to estimate the parameters β_j (j = 0,1,2,…p). Computer packages are available for performing this analysis.

Once the parameters β_j are estimated, the expected value of the logarithm of damage denoted by μ can be estimated for any given set of values for the factors W_j (j = 1,2,...p) with the aid of equation (25). If Z has been expressed as ln(X), the expected value of X is given by $\exp\{\mu + (\sigma^2)/2\}$. Computer packages provide an estimate of the standard deviation σ of the "residual error" in fitting the model in equation (25). A normal distribution is assumed for the residual error. The median value of X is given by exp(μ). The probability of damage exceeding the median value is 50 %. The upper confidence limit for the damage is the antilog of ($\mu + \sigma\tau$) where the value of τ, in this case, can be obtained from a table of the standard normal distribution. For example, if τ = 1.96, the corresponding value of damage is the expected maximum damage, the probability of exceeding which is 0.025.

Most computer software packages on multiple regression provide an estimate of the correlation between the dependent variable Z and each of the independent variables W_j (j = 1,2,…p). An independent variable (factor) whose correlation with Z is very low (close to zero) can be excluded from the analysis and the parameters β_j of the others factors re-evaluated. The contribution to damage Z from a factor with low correlation will be negligible.

Software packages also provide estimates of the correlations between independent variables. If two independent variables W_j and W_k are highly correlated, such a high degree of interaction will confuse the interpretation of the predicted value of Z due to "co-linearity". In such a case, only one of the two variables, W_j and W_k, may be included in the final analysis.

Instead of area damage, the probability P_{sp} of fire spread beyond the room of origin may be used as the dependent variable in a single or multiple regression model. In this case, the "logit", $\tilde{P}_{sp}$, given by:

$$\tilde{P}_{sp} = ½\ln\{P_{sp}/(1 - P_{sp})\} \qquad (26)$$

should be used in the estimation process, instead of P_{sp}, for rendering the effects of factors approximately additive. In the "logit" model, the probability of area damage exceeding, say, 100 m^2 or financial value exceeding, say, £100 000 can be used for P_{sp}.

The "logit" model has been applied to estimate the influence of various factors on the probability of a fire spreading beyond the room of origin. According to this study, there were significant differences in this probability between buildings used for different purposes and between some single storey and multi-storey buildings. The biggest factor affecting fire spread was the time of discovery of the fire, the chance of spread at night being twice that of the day; this was probably because of delays in the discovery of fires. The chance of spread was considerably smaller for modern buildings than for older buildings, particularly for multi-storey buildings. This was, perhaps, the result of increased building (fire) control and safety consciousness. The fire brigade attendance time had no influence on fire spread.

The "logit" model has also been applied [26] to quantify the relative effects of types of building construction, number of stories, sprinkler protection, type of fire department and the Insurance Overall Rating on the probability of loss size. The objective was to predict the probability of loss being above or below $10 000 given the particular characteristics of a group of risks. The "logit" transformation, equation (26), was applied to the probability loss exceeding $10 000. For purposes of illustration, insurance claims for fire losses for four years in industrial property classified as "machine shops" were used. In particular, the overall insurance rating adopted by Factory Mutual was found to be of great value for predicting size and degree of loss, i.e. fraction of the value of the property that was lost. Sprinklers were also found to be a major factor in determining both expected size and degree of loss.

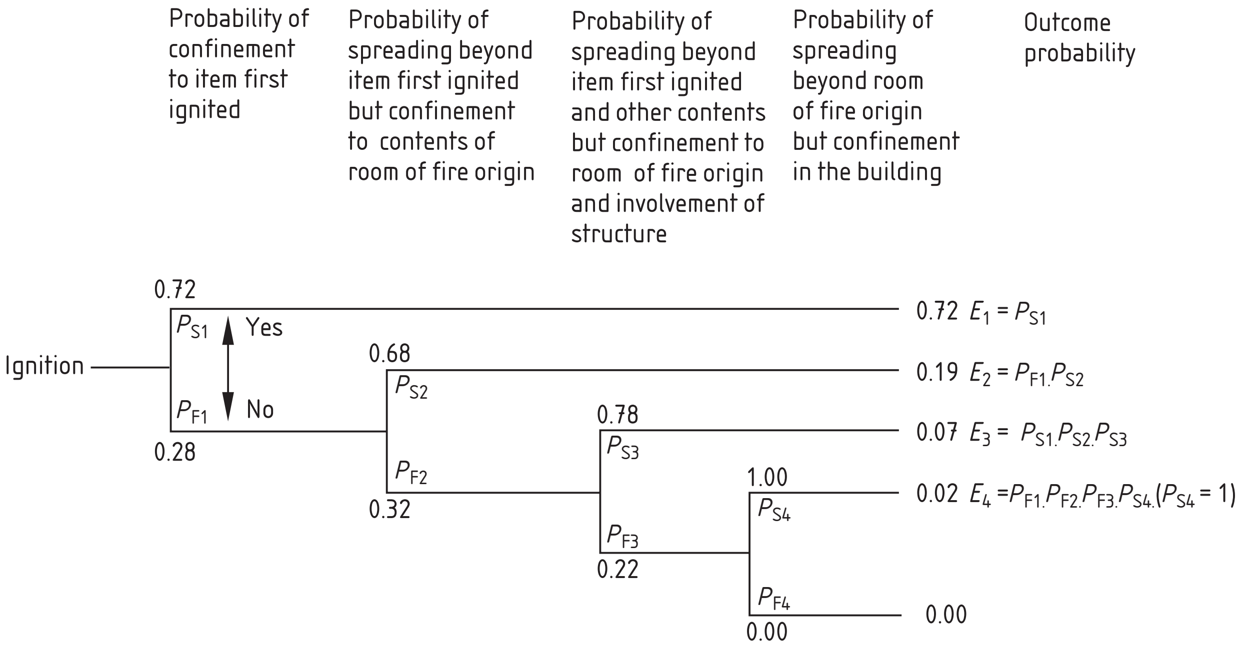
6.2.7 *Probability of flashover*

Flashover of a fire in a compartment is often defined to occur when the upper half of the compartment reaches a temperature of 600 °C. However, for the present purposes of statistical analysis, as a result of the nature of the available fire data collected, flashover is defined as the stage when the fire spreads beyond the object first ignited and involves some of the other objects and the heat energy begins to impact on the surrounding structure. The proportionate number of cases in which the fire has spread beyond this stage gives an estimate of the probability of occurrence of flashover. For estimating this probability, an event tree such as those in Figure 14 may be constructed. The probability required is given by $E_3 + E_4 = P_{F1} \cdot P_{F2}$ which, for the textile industry, is 0.09, if sprinklered, and 0.28, if not sprinklered. In the model in Figure 14, $P_{S4} = 1$ and $P_{F4} = 0$ since fire spread beyond the building of origin is not considered. In the case of sprinklers the figure of 0.72 for E_1 includes one third of fires extinguished by the system but not reported to the fire brigade.

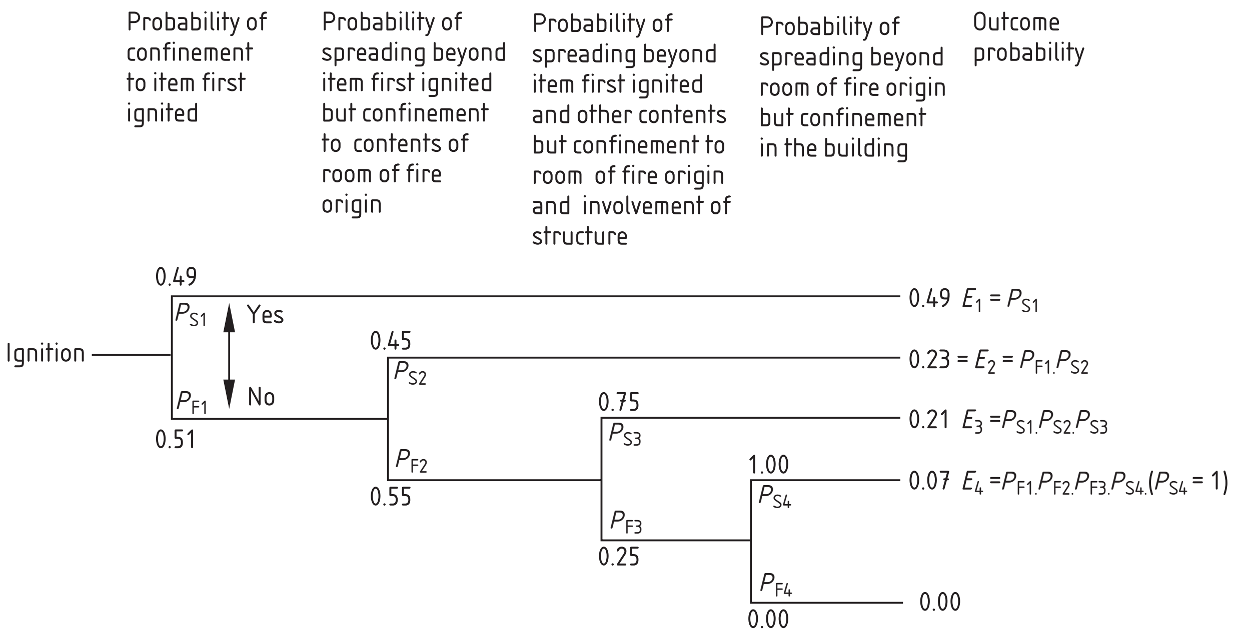
Probability of flashover would depend on the place of origin of a fire. This problem was investigated [32] for a few types of industrial and commercial buildings, as shown in Figure 15, for example. The results obtained are reproduced in Table A.15. According to these figures, as might be expected, the probability of flashover is higher in storage areas than in production or other areas. Sprinklers reduce the probability of flashover to a considerable extent. The parameter ω, denoting the ratio between the probabilities of flashover in unsprinklered and sprinklered rooms, varies between 2.25 in the storage area of the textile industry to 10.33 in the storage area of retail premises.

When flashover occurs, some floor area A_d of a room will be damaged by heat. According to Figure 15, for example, area damage would exceed 15 m^2 when flashover occurs in a fire in the production area of a textile industry building. During the post-flashover stage in such a fire, about 475 m^2 will be damaged if the room has no sprinklers. This will be reduced to 113 m^2 if sprinklers are installed.

The probability of flashover is given by the probability of area damage exceeding A_f which, for the example in Figure 15 or Table A.15, is 0.1 with sprinklers and 0.25 without sprinklers. A better estimate for the probability of damage exceeding A_f, i.e. for probability of flashover, is provided by the probability distribution of area damage. For example, according to the event tree model, A_f for the assembly area is 4 m^2 without sprinklers and 7 m^2 with sprinklers. Probability of damage exceeding A_f is 0.40 and 0.09 without sprinklers and with sprinklers respectively. But, according to Figure 11, probability of damage exceeding the respective A_f is 0.27 without sprinklers and 0.09 with sprinklers. The probability of damage exceeding an average value of 5 m^2 for A_f is 0.23 without sprinklers and 0.12 with sprinklers.

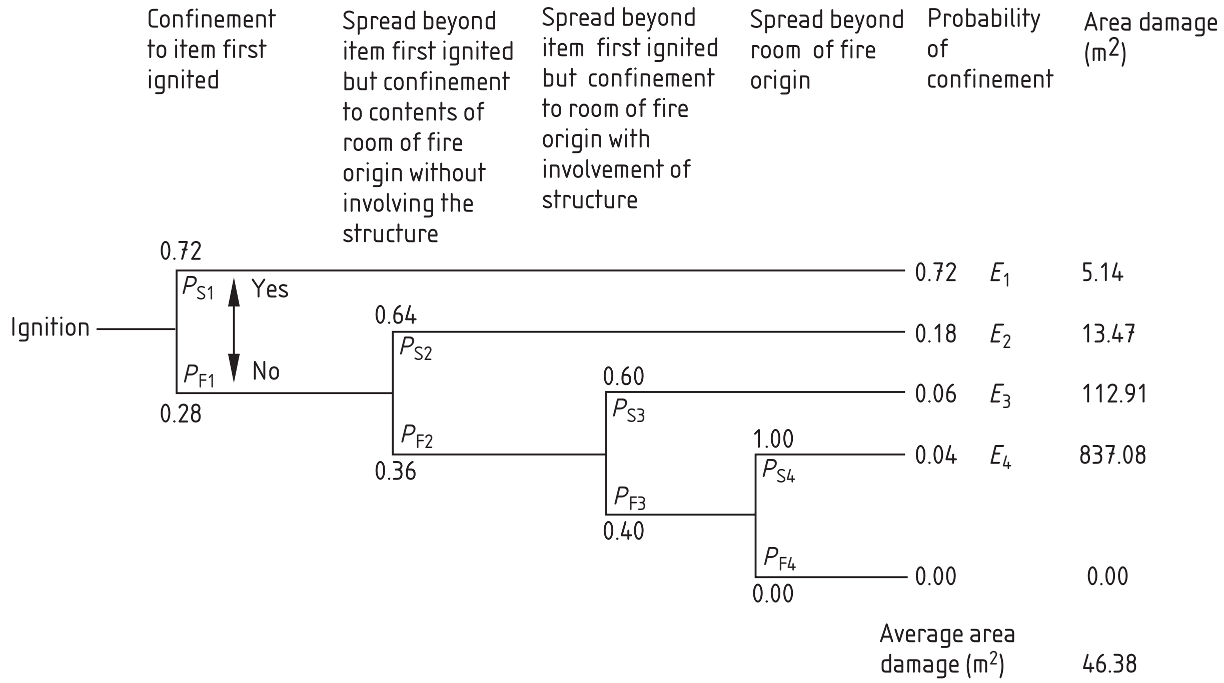


a Event tree for sprinklered fire scenario

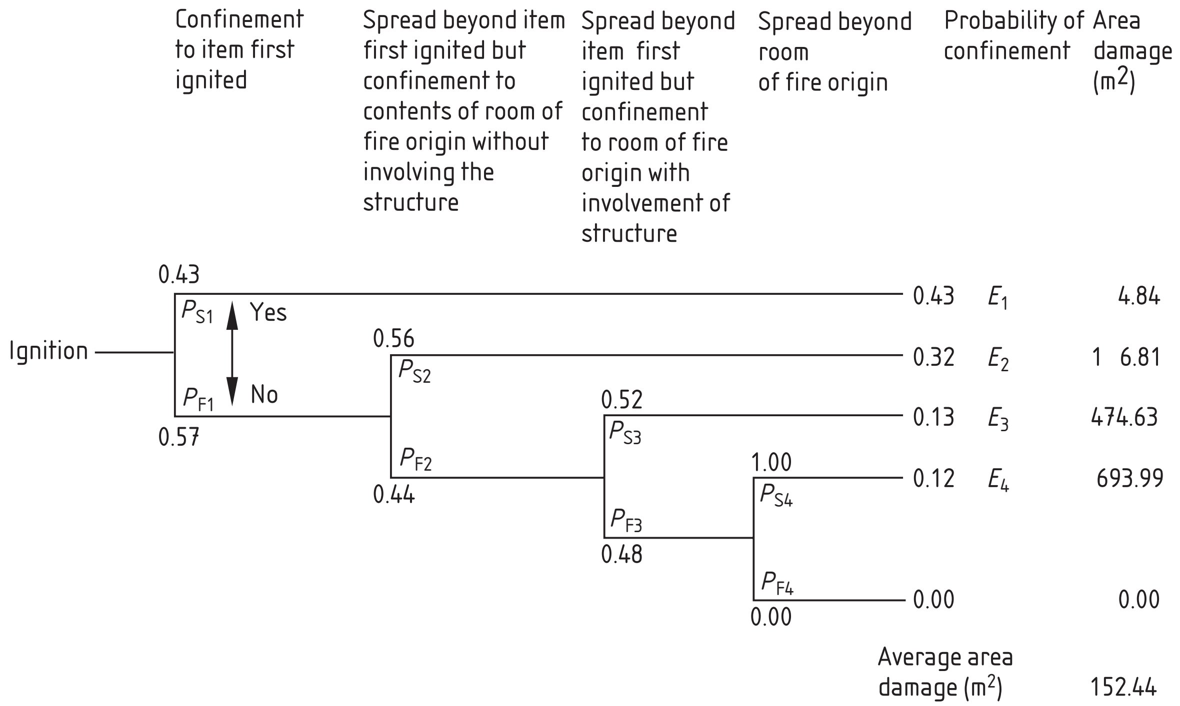


b Event tree for non-sprinklered fire scenario

Figure 14 — Event trees for sprinklered and non-sprinklered fires



a Event tree for sprinklered fire scenario



b Event tree for non-sprinklered fire scenario

Figure 15 — Event trees for sprinklered and non-sprinklered fires in the production areas of the textile industry

It could be argued that the area damage at flashover would be the same whether sprinklers protect a room or not. However, the time to reach the flashover stage would be higher for a sprinklered room since sprinklers would reduce the rate of fire growth. For a particular room with given dimensions, fire load and ventilation, it is more appropriate to estimate the time to flashover by applying a deterministic formula and then to estimate the probable area damage A_f at flashover with the aid of an exponential model of fire growth. The probability distribution of area damage would then provide an estimate of the probability of damage exceeding A_f.

Probability of flashover estimated by an event tree model or probability distribution of area damage would generally be applicable to a "reference compartment" of "average size" in a given type of building. These probabilities can be adjusted [11] for a particular building with given or known compartment size. Probability of flashover would decrease with increasing compartment size [11]. In a large compartment, the total fire load would generally be distributed in such a way that there will be a lesser overcrowding of objects. Consequently, probability of fire spread from object to object in a large compartment would be less than that for a smaller compartment, thus decreasing the probability of flashover. In a bigger compartment, more floor area would have to be damaged to produce sufficient heat to cause flashover and it would take a longer time for this phenomenon to occur. The extra time thus available would increase the chance of a fire to be detected and extinguished.

The total fire load and hence the potential for a fire to reach a high level of severity would increase with an increase in compartment size. However, this increase this is not likely to be significant, particularly in an actual fire occurring in a compartment [11]. Severity attained in an actual fire is proportional to logarithm of damage and damage has a "power" relationship with compartment size as in equation (2).

Hence if S_2 and S_1 are severities expected in rooms of sizes A_2 and A_1 from equation (2),

$$\frac{S_2}{S_1} = \frac{\ln c + d \ln A_2}{\ln c + d \ln A_1} \qquad (27)$$

With $c = 4.43\ \text{m}^2$ and $d = 0.57$, fire severity in an unsprinklered textile industry building would increase by 8 % if the compartment size is doubled form $A_1 = 500\ \text{m}^2$. If the compartment size is trebled, severity would increase by 12 %. These results generally agree with those based on deterministic formulae, if, as discussed by Malhotra [34], it is assumed that the ratio of ventilation openings in the external wall is maintained at a constant level.

6.2.8 *Probability of compartment failure*

The probability of compartment failure due to the effects of fire can be estimated statistically. This approach does not take into account the possibility of compartment failure pre-flashover due to faults in compartmentation (e.g. open doors and lack of fire stopping). However, these failure modes could be addressed in a broader study.

If flashover occurs in a fire, the compartment can experience thermal failure when the ability of the structural element (wall, floor or ceiling) to resist fire is exceeded by a high level of severity produced by the fire during the post-flashover stage. The probability of occurrence of this undesirable event is the product P_c of the two components.

$$P_c = P_f/P_b \qquad (28)$$

where P_f is the probability of flashover and P_b is the probability of compartment failure given flashover.

An acceptable level for P_b can be determined according to an estimated probability of flashover P_f, and an acceptable level thus specified for the product P_c, depending on the damage to life and property if the failure occurs.

$$P_b = P_c/P_f \qquad (29)$$

The model mentioned above was applied [10,35] in order to determine the extent to which the fire resistance of a sprinklered compartment can be reduced. A simple method was proposed based on equation (30):

$$P_{b(s)} = \omega P_{b(ns)} \qquad (30)$$

where ω is the factor given in Table A.15 and $P_{b(s)}$ and $P_{b(ns)}$ are the probabilities of failure given flashover for sprinklered and unsprinklered compartments. In equation (30):

$$\omega = P_{f(ns)}/P_{f(s)} \qquad (31)$$

where $P_{f(ns)}$ and $P_{f(s)}$ are the probabilities of flashover for unsprinklered and sprinklered compartments. From equations (28) to (31):

$$P_{b(s)}P_{f(s)} = P_{b(ns)}P_{f(ns)} = P_c \qquad (32)$$

In the simple model mentioned above, the fire resistance required for an unsprinklered compartment is determined by adopting a design value for the fire load density, according to a high fractile value of its frequency distribution. For example, if the level specified for the probability of compartment failure is 0.2, the fire load density $\bar{L}$, corresponding to the 80 % fractile of its frequency distribution, is inserted in equation (33).

$$t_e = Cw\bar{L} \qquad (33)$$

t_e is the "equivalent time of fire exposure", C is the thermal characteristic of the compartment boundaries and w is the ventilation factor based on window area and height, bounding surface areas and floor area. The fire severity S may be taken as equal to t_e in minutes.

The above model was applied to office buildings, retail premises and hotels in order to evaluate the sprinkler factor ε, defined as the ratio between the design fire load densities for sprinklered and unsprinklered compartments [35]. For the unsprinklered compartment, the design value corresponded to the 80 % fractile value of the frequency distribution of fire load density and hence to a probability of compartment failure of 0.2. With values of ω greater than 3 and $P_{b(ns)} = 0.2$, the values of $P_{b(s)}$ as given by equation (30) were greater than 0.6 for the occupancies considered. Hence the design fire load density for the sprinklered compartment corresponded to fractile values less than 40 %.

Accordingly the value of the factor ε, which depends on the distributions of fire load density for the three occupancies, ranged from 0.53 to 0.68. These results showed that the fire resistance of sprinklered compartments of these occupancies can be about 60 % of the resistance specified for unsprinklered compartments.

Although the method discussed above is simple and is considered as sufficient for determining fire resistance, it is not a statistically valid procedure since it does not take into account the uncertainties governing fire severity encountered in an actual fire. Studies have shown that severity S has an exponential cumulative probability distribution.

$$P_{sv} = 1 - \exp(-\kappa S) \qquad (34)$$

P_{sv} is the probability of severity being less than or equal to S and $(1 - P_{sv})$ is the probability of severity exceeding v. According to Baldwin [36], $\kappa = 0.04$ for office buildings, such that the mean value of S is 25 min ($= 1/\kappa$) according to a property of exponential distribution. If fire resistance R for office buildings is set equal to 30 min, the probability of severity exceeding R or of compartment failure will be 0.30 as given by $\exp(-30\kappa)$. If $R = 60$ min, probability of failure will reduce to 0.09. Severity can also have a normal distribution since it is proportional to logarithm of area damage that has a normal distribution.

In the above method, fire resistance has been treated as a constant whereas severity has been treated as a random variable. Fire resistance, however, is also a random variable, due to uncertainties caused by several factors. Sufficient data are not available at present to estimate the probability distribution of fire resistance. Exponential normal or log normal has been suggested for this distribution, purely from heuristic reasoning.

6.3 Reliability analysis

6.3.1 *General*

Most fire protection and detection systems are installed because they are needed to satisfy the Building Regulations or at the request of an insurance company covering the risk. The deterministic approach to fire safety engineering assumes that the installed system will work on the day. Deterministic fire safety engineering does not quantitatively address the reliability of systems. This subclause considers system reliability; it shows how reliabilities can be calculated and suggests values of reliability for different systems and hazards. For completeness, a brief introduction is given to reliability theory [37].

6.3.2 ***Reliability***

Reliability is a measure of the ability of an item to perform its required function in the desired manner under all relevant conditions and on the occasions or during the time intervals when it is required so to perform [38].

Reliability is normally expressed as a probability. For example, a system that fails randomly in time but once a year on average will have a probability of failing (P_F) in any one particular month of a 1/12, i.e. P_F = 0.083 3. Conversely, the probability of success (P_F), i.e. not failing, during that particular month is 9/10 = 0.916 7, which is the same as $1 - P_F$, i.e. $P_S = 1 - P_F$ and by transposition $P_F = 1 - P_S$.

Mathematically, these expressions can be expressed as:

$$P_S = \exp(-\Delta t_S / \Delta t_F)$$

$$P_F = 1 - \exp(-\Delta t_S / \Delta t_F)$$

where Δt_S is the time interval during which success is required and Δt_F is the mean time between failures.

For values where $\Delta t_S / \Delta t_F$ = 0.1 or less, P_F is approximately equal to $\Delta t_S / \Delta t_F$.

$$P_S = 1 - P_F$$

$$P_S = \frac{1 - \Delta t_S}{\Delta t_F}$$

$$P_S = \frac{\Delta t_F - \Delta t_S}{\Delta t_F}$$

For example, if the mean time between failures is one year and the time interval during which success is required is one year, then the probability of failure P_F is not actually 12/12, i.e. 1 but:

$$P_F = 1 - \exp(-\Delta t_S / \Delta t_F) \text{where } \Delta t_S / \Delta t_F = 1$$

$$= 1 - 0.37$$

$$= 0.63$$

That is a 63 % chance of failure in a year. The probability of success is given by:

$$P_S = 1 - P_F$$

$$= 1 - 0.63$$

$$= 0.37$$

That is a 37 % chance of not failing in any one particular year.

In practice, when considering the reliability of fire protection systems, it is easier to talk in terms of unreliability or probability of failure (P_F). Taking the previously discussed case as an example, where the mean time between failures was one year, P_F = 0.083 3 and P_S = 0.916 7. If the mean time between failures were improved by a factor of 10, i.e. to 10 years, then P_F changes from 0.083 3 to 0.0083 3 but P_S only changes from 0.916 7 to 0.991 67. For a system where failure creates a potential hazard, e.g. failure of a compartment wall or suppression system, the probability of failure P_F is a more direct measure of the risk involved.

6.3.3 ***Availability***

Availability is the proportion of the total time that a system is performing in the desired manner. For protection or warning systems such as a fire alarm system, failure of the system does not in itself create an immediate hazard. Only if the failure exists when a fire occurs does an unprotected hazard result.

Taking the original example of a system with a mean time between failures of one year and assuming that the fault is immediately alarmed but takes one week to repair then, on average, the system is out of action one week per year, i.e. its unavailability is 1/52 = 0.019 and its availability is 51/52 = 0.981.

Assuming that the fault is not alarmed, but is only revealed when a comprehensive weekly test is performed, the outage time can vary from near zero (i.e. fault occurs immediately prior to test) to nearly one week (i.e. fault occurs immediately after the test). The average outage will therefore be half a week. The unavailability from this cause will therefore be 0.5/52 = 1/104 = 0.009 6. It should be noted that this is half the probability of failure P_F for a similar one week period.

The total outage time will be the sum of the two types of outage, i.e. from immediately revealed faults and from faults only revealed at regular test intervals. As with reliability, the unavailability is a more sensitive indicator of how well a system performs.

Assuming the original system with a one year mean time between failures is a fire alarm system and that the total outage is on average one week per fault, the unavailability will be 1/52. Assuming that fires occur randomly in the protected area, again with an average mean time between fires of one year, the probability of a fire occurring within the particular week when the equipment is dead is 1/52 per fire. Since there is only one fire per year on average, there is likely to be a fire at the same time as the fire alarm system is not working only once in 52 years (mean time between hazards). In other words, the mean time between undetected fires is the mean time between fires, divided by the fractional dead time of the fire alarm system.

$$\text{Mean time between hazards} = \frac{\text{Mean time between fires}}{\text{Unavailability of fire alarm system}}$$

$$= \frac{1}{1/52}$$

$$= 52 \text{ years}$$

6.3.4 *Factors influencing system reliability*

When considering the reliability of any system, various factors have to be taken into account. For example, the quality of the components used in the system and their suitability for the particular application; the stress imposed on these components by the designer; additional stresses imposed by the environment in which the system is installed; the tolerance of the design to variations in component performance; the test procedures adopted for the system, and the time intervals between these tests. All these factors could cause a consequent, and possible unacceptable, reduction in the system reliability [39].

When considering reliability issues, care needs to be taken when analysing data and interpreting the results. According to UK fire statistics, in a significant proportion of fires, the sprinklers might not operate due to the fact that the fire is “small” such that the heat generated is insufficient for activating the sprinkler heads. Mechanical defects and the systems having been turned off are main reasons for the non-operation of sprinklers. Although sprinklers operate in only 9 % of all fires, they do so in 87 % (= 39/45) of the cases in which their action is required. This denotes a probability of 0.87 for sprinkler operation in “big” or “growing” fires. Some of the fires in which sprinklers operate are extinguished by the system itself, and some by the fire brigade.

6.4 Stochastic models

The statistical and probabilistic models discussed so far are useful for assessing fire risk in a group of buildings with similar risk. The estimates provided by them are generally applicable to a building of “average” characteristics but, as suggested, can be adjusted to provide an assessment of fire risk in a particular building within a group. However, it can be desirable to assess the risk in a particular building based mostly on the characteristics of that building.

This is possible by applying the stochastic model that can predict the spatial spread of fire in a building as a function of time. A detailed review of these models has been carried out [40]. Two of these models, Markov and Network models, are widely used for predicting fire spread in a building. The basic features of these two models are discussed in this subclause.

A fire in a room usually starts with the ignition of one of the objects. Next, it spreads to other objects depending on the distance between the objects and other factors such as fire load and ventilation. This process produces a chain of ignitions that can lead to fully developed fire conditions defined as “flashover”. There will, however, be a chance that the fire chain can break at some stage for various reasons with the fire getting extinguished before spreading further. Statistics of real fires support this hypothesis.

As described above, a fire passes through several stages in the course of its development with a chance of getting extinguished during any stage. It stays for a random length of time in each stage before moving to the next stage. Its movement (spread) from stage to stage is governed by “transition” probabilities. These probabilities arise due to uncertainties in the pattern of fire development caused by several factors. The spread of fire is essentially a stochastic phenomenon although the fire experiences certain deterministic (physio-chemical and thermodynamic) processes during its development.

Stages of fire growth can generally be defined as "states". The fire spreads, moves or makes a transition from state to state. If the fire is in state a_i at the n^{th} minute, it can be in state a_j at the $(n + 1)^{th}$ minute according to the transition probability $\lambda_{ij}^{(n)}$. The probability of remaining in state a_i at the n^{th} minute without making a move to another state is denoted by $\lambda_{ii}^{(n)}$. For each minute, with m states, the transition probabilities $\lambda_{ij}^{(n)}$ can be represented in a $m \times m$ matrix $[P_n]$ where, for any i, the sum of λ_{ij} for $j = 1$ to m is unity.

The probabilities of the fire being in different states at time n is represented as the vector $\vec{P}_n$ with the elements $q_i^{(n)}$, $i = 1,2,\ldots m$, where $q_i^{(n)}$ is the probability of fire being in the i^{th} state at time n. The probabilities $q_i^{(n)}$ for the m states add up to unity. The vector given by the product $\vec{P}_n \times [P_n]$ represents the probabilities of fire burning in different states at time $(n + 1)$, i.e. one minute later. If the fire starts in state a_l, the first element in the vector $\vec{P}_0$ for the initial time denoted by $q_l^{(0)}$ is unity and the rest of the other $(m - 1)$ elements in this vector are zero. With this initial condition, the probabilities of the fire being in different states at different times can be obtained by performing the matrix multiplication $\vec{P}_n \times [P_n]$ repeatedly, starting with $\vec{P}_o \times [P_o]$ if the probabilities for the transition matrix P_n for different times n can be evaluated.

In a simple Markov model, the transition probabilities $\lambda_{ij}^{(n)}$ are considered as constants λ_{ij} (per minute) independent of the time variable n. Berlin [41] applied this model and estimated λ_{ij} for six states defined as realms for residential occupancies: no-fire state, sustained burning, vigorous burning, interactive burning, remote burning and full room involvement. The realms were defined by critical events characterized by heat release rate, flame height and upper room gas temperature. Estimation of λ_{ij} for different i and j was based on data from over a hundred full-scale fire tests. Berlin also estimated the maximum extent of flame spread, the probability of self-termination and distribution of fire intensity. The fire growth model of Beck [42] was based on the six realms defined by Berlin.

The state a_i in a Markov model may represent i objects in a room burning and λ_{ij} the probability of transition from this state to state a_j with j objects burning. Data on heat output or release rate, ventilation and distances between objects in a room can provide estimates of λ_{ij} (per minute). Then, for a given number m of objects and initial conditions, the probabilities of the fire being in different states at different times can be estimated by performing repeated matrix multiplication. If extinguishment of fire is not considered, with no recession, there is no transition to a lower state from a higher state. Under such an assumption, flashover may be defined as the state when, say, 3 or 4 objects are ignited. The model would then provide estimates of the probabilities of flashover, $q_3^{(n)}$ or $q_4^{(n)}$, for different times n.

The State Transition Model (STM) is a particular, simple version of a Markov model with stationary (constant) transition probabilities. An event tree, such as one as described in Figure 14 or Figure 15, constitutes a simple STM in which fire in a room is described as developing through four successive stages or states, E_1, to E_4. A fire can "jump" to E_4 from E_1 or E_2 without passing through E_2 and E_3, but such "jumps" have not been considered in this simple STM. The parameters P_{Si} and P_{Fi} in Figure 14 and Figure 15 are values to which the transition probabilities ultimately tend over a period of time; they are not probabilities per minute. E_1, E_2, E_3 and E_4 are also limiting probabilities of a fire being extinguished ultimately in the four states. The parameters P_{Si} and P_{Fi} can be expressed, on per minute basis, by estimating the duration for which their values in the event tree are applicable. Using fire statistics [40], a state transition model has been developed in which the transition probabilities are estimated as functions of time.

The STM approach can also be adopted for evaluating the probability of fire spreading from room to room in a building. Each room or corridor in a building has an independent probability of fire spreading beyond its boundaries. This probability for a room or compartment is the product of probability of flashover and the conditional probability of structural (thermal) failure, given flashover. Using these probabilities for different rooms and corridors, fire spread in a building can be considered as a discrete propagation process of burning among points which abstractly represent the rooms, spaces or elements of a building. For an example based on three rooms, work by [43] proposed a method based on partitioning of the transition matrix for estimating the average time for transition to the fourth state denoting the burning of all the three rooms.

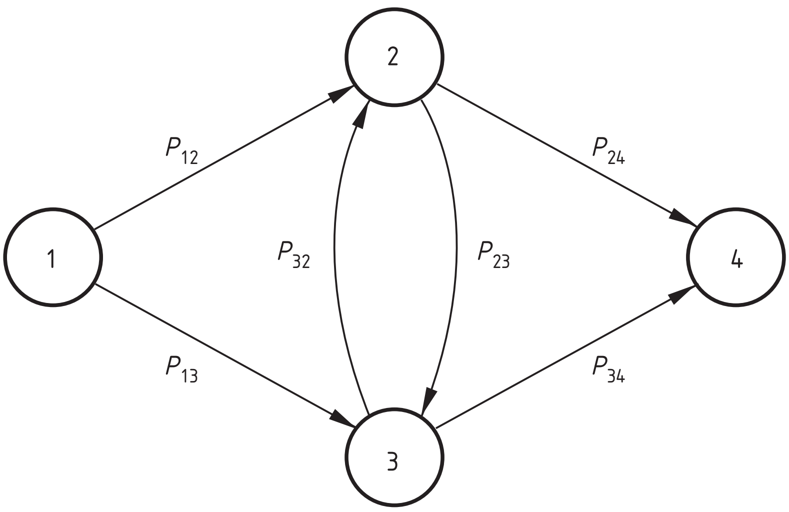
The major weakness of the Markov model is the assumption that the transition probabilities remain unchanged regardless of the number of transitions representing the passage of time. However, the length of time a fire burns in a given state would affect future fire spread. For example, the probability of a wall burn-through increases with fire severity, which is a function of time. The time spent by fire in a particular state can also depend on how that state was reached, i.e. whether the fire was growing or receding. Some fires grow quickly and some grow slowly depending on high or low heat release. In a Markov model, no distinction is made between a growing fire and a dying fire.

The STM can provide, for each room in a building, cumulative probability P_c at time t_c when the structural boundaries of the room are breached. The duration Δt_c is the sum of Δt_f, representing the time to the occurrence of flashover, and Δt_b, representing the time for which the structural barriers of the room can withstand fire severity attained during the post-flashover stage. The probability P_c is the product of probability P_f of flashover and probability P_b of structural failure given flashover.

The pairs of values (P_c and Δt_c) for different rooms can then be used in an expanded STM for predicting fire spread in a building as a function of time. This procedure will involve tedious and complex calculations. The problem may be simplified by representing a building as a network by defining rooms or compartments as nodes and defining the links between these nodes as possible paths for fire spread from compartment to compartment.

Consider, as an example, the simple layout of Figure 16a) relating to four rooms and the corresponding graph shown in Figure 16b) which also shows the probability (P_{ij}) of fire spread between each pair of rooms (i, j).

a



b

Figure 16 — Room layout and corresponding schematic

This figure has been used [44] to consider the probability of barrier failure given flashover (i.e. ignoring the possibility that flashover might not occur). The specific problem considered by these authors was to compute the probability of fire spreading from room 1 to 4 which might follow any of the four paths:

— (1)⟶(2)⟶(4);

— (1)⟶(3)⟶(4);

— (1)⟶(2)⟶(3)⟶(4);

— (1)⟶(3)⟶(2)⟶(4).

Using the space event method, it is possible to consider all possible "events" or combinations of fire spreading or not spreading along various links. If e_{ij} represents spread of fire along link *ij*, and $\bar{e}_{ij}$ represents fire not spreading along the link, then one event might even be:

$$[e_{12}, \bar{e}_{13}, e_{23}, \bar{e}_{32}, \bar{e}_{24}, e_{34}]$$

There will be $2^6 = 64$ events. All of the events will be exclusive, as any pair of events will contain at least one link for which fire spreads in one event and does not spread in the other. The probability of each event occurring is the product of the probabilities of its elements, assuming that the elements are independent. Thus, for the example given above, the event probability will be:

$$P_{12}(1-P_{13})P_{23}(1-P_{32})(1-P_{24})P_{34}$$

and the overall probability is the sum of all 64 event probabilities.

The complete event space was represented as a tree with 64 branches, a procedure known as "depth-first search of a graph" for identifying or searching possible paths of links, leading to node (room) 4 from node 1. The calculation was carried out for each pair of rooms and the results were assembled in a "fire spread matrix" with unit values for the diagonal elements. The core of this model is a probabilistic network analysis to compute the probability of fire spreading to any compartment within a building. The dimension of time was not explicitly considered in this model, although it was implicit in many of the functions used. In a similar network model [45], the probability of spread is dependent on time.

A model in which a floor plan is first transformed into a network has been proposed [46]. Each link in the network represents a possible route of fire spread and those links between nodes corresponding to spaces separated by walls with doors are possible exit paths. The space network is then transformed into a probabilistic fire spread network as in example in Figure 17 with four rooms, room 1 to room 4 and two corridor segments, C_1 and C_2. With room 1 and room 1′ (with the "prime" denoting post-flashover stages), the first link is represented by:

Room 1 ⟶ Room 1′

(P_f, t_f)

where P_f represents the probability of flashover and t_f represents the time to flashover.

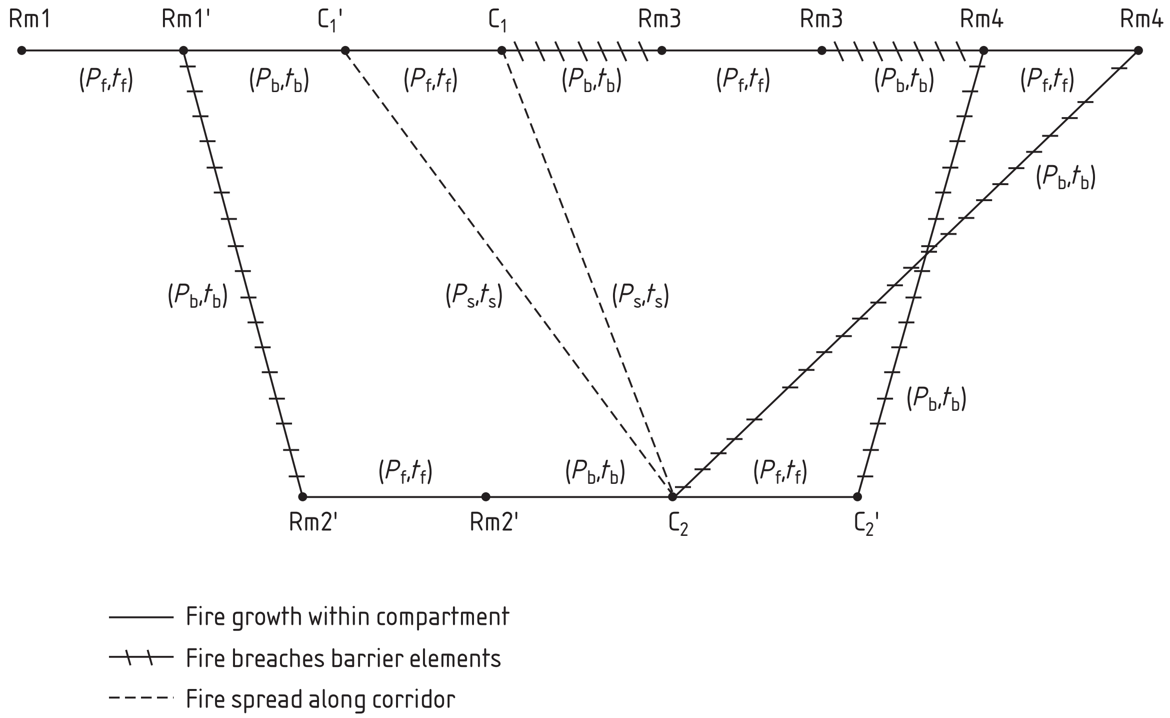


Figure 17 — Probabilistic network of fire spread of room 1 to C_2

In Figure 17, three different types of link are identified. The first corresponds to the fire growth in a compartment, the second to the fire breaching a barrier element and the third to fire spread along the corridors. To each link i, a pair of numbers (P_i,t_i) is assigned, with P_i representing the distributed probability that a fire will go through link i, and t_i representing the time distribution that it will take for such a fire to go through link i. The section of the corridor, C_1, opposite room 1 is treated as a separate fire compartment and is assigned a (P_f,t_f) for the link from C_1 to C_1'. The number pair (P_s,t_s) represents the probability and time for the pre-flashover spread of fire along the corridor from C_1 to C_2. Once full involvement occurs in the section C_1 of the corridor outside room 1 (i.e. node C_1' is reached) the fire spread in the corridor is influenced more by the ventilation in the corridor and by the contribution of room 1 than by the materials properties of the corridor itself. Thus there is a separate link, C_1' to C_2 which has its own (P_s,t_s). The number pair (P_b,t_b) represent the probability of failure of the barrier element with t_b representing the endurance of the barrier element.

Once the probabilistic network has been constructed, the next step is to solve it by obtaining a listing of possible paths of fire spread with quantitative probabilities and times associated with each path. For this purpose, a method based on the "emergency equivalent network" may be adopted [46], to compute the expected shortest distance through a network. (The word shortest has been used instead of "fastest" to be consistent with the literature). This new "equivalent" network yields the same probability of connectivity and the same expected shortest time as the original probabilistic network. In this method, each link has a Bernoulli probability of success and the link delay time is deterministic.

It should be noted that there are multiple links between the nodes in the equivalent fire spread network. For example, the door between room 1 and the corridor could be either open or closed at the time the fire flashed over in room 1. It is assumed, as an example, that there is a 50 % chance of the door being open and that an open door has zero fire resistance. Furthermore, it is assumed that the door, if closed, would have a five-minute rating. With further assumptions, the equivalent fire spread network (Figure 18) may be constructed, with twelve possible paths for the example in Figure 17, to find the expected shortest time for the fire in room 1 to spread to the portion of the corridor C_2.

A similar network (Figure 19) can be constructed for a case with self-closing 20 min fire rated doors. This has ten possible paths. For the two equivalent networks, all the possible paths are listed in the tables with increasing time and with all the component links identified. Each of the paths describes a fire scenario. For instance, the scenario for path 1 in the table for Figure 18 would be where the fire flashes over, escapes from room 1 through an open door into the corridor C_1 and spreads along the corridor to C_2. The probability for that scenario is 0.13. The time of 17.5 min is the sum of 10 min for flashover and 7.5 min for fire spread from C_1 to C_2.

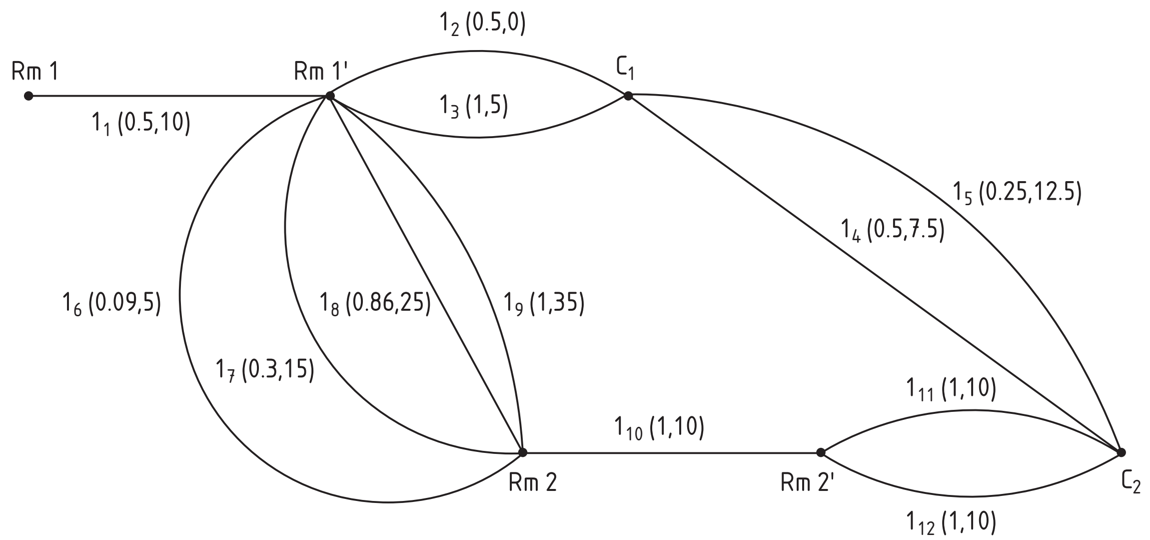


Figure 18 — Equivalent fire spread network with 5 min unrated corridor doors

Table 4 — Fire spread equivalent network assuming 5 min unrated corridor doors

Paths i	Component links	Probability P_i	Time t_i min
1	1-2-4	0.13	17.5
2	1-2-5	0.06	22.5
3	1-3-4	0.25	22.5
4	1-6-10-11	0.02	25.0
5	1-3-5	0.13	27.5
7	1-6-10-12	0.05	30.0
8	1-7-10-12	0.08	35.0
9	1-8-10-11	0.21	35.0
10	1-8-10-12	0.43	40.0
11	1-9-10-11	0.25	50.0
12	1-9-10-12	0.50	55.0

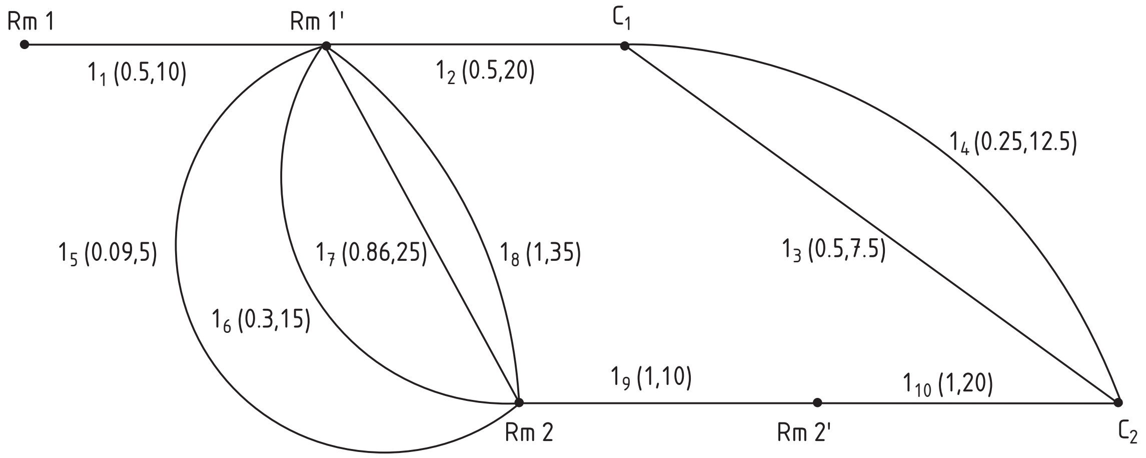


Figure 19 — Equivalent fire spread network with self-closing 20 min rated corridor doors

Table 5 — Equivalent network assuming self-closing 20 min rated corridor doors

Paths i	Component links	Probability P_i	Time t_i min
1	1-2-3	0.25	37.5
3	1-5-9-10	0.05	45
4	1-6-9-10	0.15	55
5	1-7-9-10	0.43	65
6	1-8-9-10	0.50	75

6.5 Monte Carlo analysis

6.5.1 *General*

Fire safety engineers are required to deal with complex fire scenarios that include human reactions and behaviour in addition to physical and chemical fire process evolved by a variety of burning materials. Physical models representing such scenarios involve intractable mathematical relationships that cannot be solved analytically. Also, sufficient and realistic experimental or statistical data are unlikely to be available for estimating all the parameters of a physical model. For such complex models, solutions can only be obtained by numerical methods using a step-by-step simulation procedure.

Simulation involves the construction of a working mathematical model representing a dynamic system in which the processes or interaction bear a close resemblance or relationship to those of the specific or actual system being simulated or studied. The model should include realistic input parameters capable of generating outputs that are similar or analogous to those of the system represented. Then, by varying the numerical values of the input parameters, it is possible to predict the time varying behaviour of the system and determine how the system will respond to changes in structure or in its environment. Such simulation experiments can be performed on a computer by developing an appropriate software package.

Simulation models can be either discrete or continuous. As time progresses, the state of a building changes continuously as a small fire develops into a big fire. The physical and chemical processes involved in such a fire growth lend themselves to a continuous simulation model. On the other hand, discrete simulations are more appropriate for determining "design times" concerned with fire detection and fighting and building evacuation. These times define critical events occurring discretely during a sequence of clear-cut stages. In a continuous model, changes in the variables are directly based on changes in time. The various aspects of computer simulation for fire protection engineering together with some examples have been discussed [47].

6.5.2 *Monte Carlo simulation*

Monte Carlo analysis is a simulation technique applicable to problems involving stochastic or probabilistic parameters. For example, some input parameters, such as compartment size and ventilation factor, might be of deterministic nature such that, for each of these parameters, a range of possible values can be used in simulation experiments. On the other hand, some input parameters might be random variables taking values according to probability distributions during the course of fire development. Examples of such variables are: rate of flame spread and fire growth, temperature of the fire, smoke concentration, ambient air temperature, wind speed and wind direction, number of doors open, number of windows open and the response of occupants to fire alarms.

Consider, as an example, a stochastic parameter χ_i with a value at time t during the course of fire development of $\chi_i(t)$. The exact value of $\chi_i(t)$ might not be known, but it might be possible to estimate its mean $\mu_i(t)$ and standard deviation $\sigma_i(t)$ and the form of its probability distribution. Suppose this distribution is normal such that the standardized counterpart τ_i of $\chi_i(t)$ has a standard normal distribution. Then, with τ_i = 1.96, the probability that the value of the stochastic parameter χ_i at time t is less than or equal to the value given by the following equation is 0.975:

$$\chi_i(t) = \mu_i(t) + \sigma_i(t)\tau_i$$

The probability of the value of the stochastic parameter exceeding the value given by the above equation is 0.025. This particular value of $\chi_i(t)$ can be regarded as the probable maximum while the value corresponding to $\tau_i = -1.96$ in the above equation would be the probable minimum. The probability of the value of the stochastic parameter being less than this minimum is 0.025.

Instead of the maximum or minimum value, a series of random values of $\chi_i(t)$ can be generated by "spinning the Monte Carlo wheel" in the computer and randomly selecting values of the standard normal variable τ_i. Virtually every computer is equipped with a subroutine that can generate random numbers. This process will provide a random sample for estimating the time-varying relationship between the input parameter χ_i and an output variable y_j. The output variable can be a quantity such as an area damage representing property damage or number of fatal or non-fatal casualties representing life loss. Methods have been developed for generating distributions such as normal, as well as any empirical distribution.

The probability distribution of an output variable y_j can now be estimated with the aid of random sample values of several input variables χ_i generated by Monte Carlo simulation. Some input variables can be of deterministic nature and some of stochastic or probabilistic type. It would be possible to regress the output y_j on the input variables using a multiple linear regression analysis technique discussed in **6.2.6**. In this analysis, as discussed in **6.2.6**, it might be necessary to use the logarithm of y_j and the logarithms of some of the input variables to reduce the relationship between the output and input variables to a linear form. The multiple regression equation then provides an estimate of the expected value of the output of y_j for a given set of random or extreme (maximum or minimum) values of the input variables χ_i at any time t during the period of fire development.

Monte Carlo simulation can be used to generate sample values for constructing probability distribution of an input variable which might not be known due to lack of data or whose mathematical structure is too difficult to be derived theoretically. This method provides the mean, standard deviation and other parameters of the variable to confirm or reject theoretical results.

The object of Monte Carlo simulation is to take account of uncertainties governing the input and output variables involved in the fire safety system and to estimate the effects of input variables on the output variables. Suppose that at a given time the output variables y_j (j = 1,2,...N) are dependent on the input variables χ_i (i = 1,2,…n) according to a set of functions:

$$y_j = f_j(\chi_1, \chi_2, \ldots \chi_n)$$

Then, in the neighbourhood of $\chi_1, \chi_2, \ldots \chi_n$, y_j can be evaluated approximately by expanding the function in a Taylor series and then omitting all terms after the second. This method provides the variance-covariance matrices for the input and output variables [47].

Suppose the following linear hypothesis is valid.

$$y_j = \hat{a}_0 + \hat{a}_1\chi_1 + \hat{a}_2\chi_2 + \ldots \hat{a}_n\chi_n$$

If χ_i (i = 1,2,…n) are independent random variables with mean $\bar{\chi}_i$ and variance σ^2_i, the mean and variance of y_j are given by:

$$\bar{y}_j = \hat{a}_0 + \hat{a}_1\bar{\chi}_1 + \hat{a}_2\bar{\chi}_2 + \ldots \hat{a}_n\bar{\chi}_n$$

$$\sigma^2_j = \hat{a}_1^2\sigma_1^2 + \hat{a}_2^2\sigma_2^2 + \ldots \hat{a}_n^2\sigma_n^2$$

For the input variable χ_i, consider, as an example, the rate of heat output $\dot{Q}$ that can increase with time t according to a t^2 or exponential function. This function will provide an estimate of $\dot{Q}$ at time t which can be regarded as the expected or mean value $\mu_Q(t)$ of $\dot{Q}$. But $\dot{Q}$ is a random variable, since ventilation and other factors affect it. Hence, as discussed earlier,

$$\dot{Q}(t) = \mu_Q(t) + \sigma_Q(t) \cdot \tau_i$$

where $\sigma_Q(t)$ is the standard deviation of $\dot{Q}(t)$ and the random variable τ_i may be assumed to have a standard normal distribution. Experimental data provide an estimate of $\sigma_Q(t)$ for any material or object.

Random values of $\dot{Q}(t)$ can then be generated by simulating random values of τ_i.

The mass loss rate of fuel $\dot{m}$ is another input variable with a mean value and standard deviation that can be estimated directly from experimental data or by considering the relationship

$$\dot{Q} = \dot{m} H_c$$

where H_c is the effective heat of combustion of the fuel usually assumed to have the value 18 000 kJ/kg.

$\dot{Q}$ is measured in kW and $\dot{m}$ in kg/s.

The parameters $\dot{m}$ and $\dot{Q}$ are directly correlated with the rate at which the floor area of a compartment is destroyed per unit of time (see **6.2.4**). Area damage is an output variable which is also affected by other input variables such as fire load compartment dimensions ventilation factor and delays in detecting and commencing fire fighting.

Computer models for simulating various aspects of fire risk have been developed. Examples of these can be found in the literature [48,49,50,51,52,53].

6.6 Partial safety factors

6.6.1 *Introduction*

For many fire safety engineering components or subsystems, the performance may be formulated in terms of two random variables Ω and Ψ. The variable Ω represents stress and Ψ represents strength.

Taking the compartment in a building as an example, Ω is the severity of fire to which the structural boundaries of the compartment are exposed and Ψ is the fire resistance of the boundaries. Both fire severity and fire resistances are usually expressed in units of time. Another example is concerned with building evacuation in which Ω is the time taken by a combustion product to produce an untenable condition or an escape route and Ψ is the time since the start of ignition taken by an occupant to get through the escape route.

In the first example, the compartment would "fail" with consequential damage to life and property if Ω exceeds Ψ, particularly during the post-flashover stage. In the second example, "egress failure" would occur with fatal or non-fatal casualties if Ψ exceeds Ω. The objective of fire safety design is to reduce the probability of failure to an acceptably small level. Two methods are generally adopted for estimating this probability. The first method (discussed in **6.6**) involves partial safety factors and is semi-probabilistic. The second method (discussed in **6.7**) is probabilistic and involves probability distributions of Ω and Ψ; it is also known as the Beta method.

6.6.2 *Characteristic values*

The first step in this analysis is to select appropriate values for Ω and Ψ which are typical or characteristic values representing the two random variables. These values can be, for example, the mean or average values μ_Ω and μ_Ψ of Ω and Ψ, or other statistical parameters such as median (50th percentile) or mode (the most probable value with the highest relative frequency). A value corresponding to some other percentile e.g. 80th, 90th or 95th can also be selected as a characteristic value for Ω or Ψ.

Consider a design problem in which failure would occur if $\Omega > \Psi$ success if $\Psi \leq \Omega$. For example, thermal failure of the compartment would occur if severity S exceeds resistance R and success if $R \geq S$. It is usual to provide a structural element with minimum fire resistance, R_p which is greater than the maximum severity S_q likely to be encountered during the post-flashover stage. R_p and S_q can be regarded as the characteristic values R_k and S_k of R and S.

Suppose μ_R and σ_R are the mean and standard deviation of fire resistance R and μ_S and σ_S is the mean and standard deviation of fire severity S. If the values of these parameters are known, then:

$$R_p = \mu_R - \tau_R \sigma_R \qquad (35)$$

$$S_q = \mu_S + \tau_S \sigma_S \qquad (36)$$

If ν_R and ν_S are the coefficients of variation given by:

$$\nu_R = \sigma_R / \mu_R \qquad \nu_S = \sigma_S / \mu_S \qquad (37)$$

then:

$$R_p = \mu_R (1 - \nu_R \tau_R) \qquad (38)$$

$$S_q = \mu_S (1 + \nu_S \tau_S) \qquad (39)$$

According to Chebyshev's inequality [54], whatever the probability distribution of S, the probability of fire severity exceeding S_q given by equation (36) is less than or equal to $(1/\tau_S^2)$. For instance, $\tau_S = 2$ guarantees a safety margin of at least 75 % [i.e. $1 - (½)^2$]. Probability of severity exceeding S_q in this case is, at most, 0.25. The values of τ_S and S_q can be selected according to any specified safety margin. For example, $\tau_S = 3.16$ provides a safety margin of at least 90 %. Probability of severity exceeding S_q in this case is at most 0.10. In the case of minimum fire resistance, if $\tau_R = 3.16$, the probability of resistance being less than R_p given by equation (35) is, at most, 0.10 and the probability of resistance exceeding R_p is at least 0.90.

Suppose the probability distributions of R and S are also known, in addition to their means and standard deviations. If, for example, these are normal, the values of τ_R and τ_S for any specified probability levels can be obtained from tables of standard normal distribution. For example, $\tau_S = 1.96$ corresponds to the fractile value 0.975 of the probability distribution of fire severity. In this case, the probability of severity exceeding the value of S_q given by equation (35) is 0.025. If $\tau_S = 2.33$, corresponding to the fractile value 0.99, the probability of severity exceeding S_q is 0.01. The probability of fire resistance being less than the value of R_p given by equation (35) would be 0.025 if $\tau_R = 1.96$ and 0.01 if $\tau_R = 2.33$.

The mean maximum or any other value representing the characteristic value S_k of fire severity likely to be attained in a compartment can be estimated with the aid of an analytical model such as:

$$t_e = Cw\bar{L} \quad (40)$$

where C is a constant depending on the thermal properties of the compartment boundaries, w is the ventilation factor and $\bar{L}$ is the fire load density. The ventilation factor is given by:

$$w = \frac{A_f}{(A_T A_V \sqrt{h})^{1/2}} \quad (41)$$

where A_f is the floor area of the compartment, A_T is the area of the bounding surfaces of the compartment including the area of ventilation openings (A_V) and h is the weighted mean ventilation height. With area in square metres, h in metres and $\bar{L}$ in megajoules per square metre, fire severity t_e is expressed in minutes. Formulae (40) and (41) relate to "equivalent time of fire exposure" [55]. The relationship has been validated for compartments up to 100 m^2.

In equation (40), the parameters c and w may be regarded as constants for any compartment with known or given structural (thermal) characteristics, dimensions and area and height of ventilation openings. Fire load density $\bar{L}$ may be considered as a random variable such that the mean severity μ_S is estimated by inserting the value $\mu_{\bar{L}}$ of fire load density:

$$\mu_S = Cw\mu_{\bar{L}} \quad (42)$$

The standard deviation of fire severity is given by:

$$\sigma_S = Cw\sigma_{\bar{L}} \quad (43)$$

where $\sigma_{\bar{L}}$ is the standard deviation of the fire load density. Then, from equation (37), it can be seen that the coefficient of variation, ν_S, of severity is equal to that of fire load density given by $\sigma_{\bar{L}}/\mu_{\bar{L}}$.

The fire resistance for a structural element of a compartment may be based on the criterion that the minimum fire resistance R_p given by equation (35) exceeds the maximum severity $S_{\bar{L}}$, given by equation (36). A standard fire resistance test indicates whether the structural element meets this criterion or not. However, the fire resistance is a random variable in a real fire [11]. The variability depends on materials used. For example, fire resistance of a gypsum board wall has a greater variability than the resistance of a concrete block wall. The resistance of a steel wall depends on the thickness of insulation, total mass of insulation and steel, average perimeter of protective material and a factor representing the insulation heat transmittance value for the material.

Fire resistance of a compartment composed of different structural elements is not the same as the fire resistance of any of these elements. Fire resistance of a compartment is affected by weakness caused by penetrations, doors or other openings in barriers. Sufficient data are not available for estimating realistically the mean μ_R and standard deviation σ_R of the fire resistance of a compartment in an actual fire. The values of these parameters can only be assumed according to data provided by standard fire resistance tests and other experiments. These tests and experiments can provide some indication of the standard deviation σ_R or coefficient of variation ν_R as defined in equation (37). For the sake of simplicity, fire resistance may be assumed to have the same probability distribution as that of fire severity, e.g. normal.

The mean fire resistance μ_R required for a compartment is an output estimated according to the input values μ_S and σ_S of fire severity. The output μ_R should satisfy the design criterion that the minimum fire resistance R_p, as given by equation (35), exceeds the maximum severity S_q, as given by equation (36). R_p and S_q include safety margins provided by the standard deviations σ_R and σ_S and the parameters τ_R and τ_S.

As defined in equations (40) and (41), fire severity is the product of several factors. Based on data from fire tests, fire resistance, in some cases, is also expressed as the product of some factors, e.g. thin wall steel members [56]. In all such cases, it might be considered necessary to take account of uncertainties governing all the factors. Generally, if a variable y is a product of several variables x_1, x_2, x_3… which are mutually independent, the mean of y is approximately given by the product:

$$\bar{y} = \bar{x}_1\bar{x}_2\bar{x}_3\ldots \quad (44)$$

where these are the means of the variables. The co-efficient of variation of y is approximately given by:

$$v_y^2 = v_1^2 + v_2^2 + v_3^2 + \ldots \qquad (45)$$

where v_1, v_2, v_3 are the coefficients of variation of x_1, x_2, x_3....

The results in equations (44) and (45) are based on an application of the truncated Taylor series expansion [57] of the function:

$$y = f(x_1, x_2, \ldots)$$

The second and higher derivatives of the functions are neglected in this expansion. The derivation of the above results in detail and the various aspects of probabilistic evaluation of structural fire protection can be found in reference [58].

For the second example relating to building evacuation mentioned in **6.6.1**, the design criterion is that the total evacuation time Δt_{esc} (Ψ as defined previously) should not exceed the time Δt_{ten} (Ω as defined earlier) taken by a combustion product, e.g. smoke to travel from the place of fire origin, and produce an untenable condition, e.g. visual obscuration on an escape route. The total time Δt_{esc} is the sum of three periods. In sequential order, the first period Δt_{det} is the time taken to detect or discover the existence of a fire after it started. The second period Δt_{rec} is known as "recognition time" or "gathering phase" in human behaviour studies. This period is the elapsed time from discovery of fire to the commencement of evacuation. The third period Δt_{evac}, known as "design evacuation time", is the time taken by an occupant to reach the entrance to an escape route, e.g. protected staircase after leaving his/her place of occupation.

The time period Δt_{det} depends on the presence or absence of automatic fire detection systems or suppression systems such as sprinklers. A characteristic value for Δt_{det} can be estimated from fire statistics or detector tests, together with its standard deviation. Human behaviour studies suggest a characteristic value of 2 minutes for Δt_{rec}. For any type of building, the characteristic value of Δt_{evac} and its standard deviation can be estimated from fire drills or computer models of evacuation. A value of 2.5 minutes for Δt_{evac} has been recommended in BS 5588. The actual value of Δt_{evac} depends on building type and the physical capacity of the occupants apart from other factors. Deterministic models, e.g. FAST [59] and associated computer packages can be used to estimate the characteristic value and standard deviation of Δt_{ten} for any type of building. By reducing the rate of growth of fire and smoke, sprinklers increase the value of Δt_{ten} if they fail to extinguish a fire. Sprinklers also have a high probability of extinguishing a fire, in which case Δt_{ten} will have an infinite or high value.

The mean value $\mu_{\Delta t,esc}$ of total evacuation time Δt_{esc} is the sum of the mean values of Δt_{det}, Δt_{rec} and Δt_{evac}. The standard deviation $\sigma_{\Delta t,esc}$ of Δt_{esc} is given by:

$$\sigma_{\Delta t,\,sec} = \sigma^2_{\Delta t,\,det} + \sigma^2_{\Delta t,\,rec} + \sigma^2_{\Delta t,\,evac} \qquad (46)$$

where $\sigma_{\Delta t,det}$, $\sigma_{\Delta t,rec}$ and $\sigma_{\Delta t,evac}$ are the standard deviations of Δt_{det}, Δt_{rec} and Δt_{evac}. For any escape route and place of fire origin, the mean value $\mu_{\Delta t,ten}$ is the sum of the means of the Δt_{ten} values for different combustion products. By considering different places of fire origin escape routes and combustion products, the overall mean value of Δt_{ten} can be estimated for any building or any floor of the building. An estimate of this mean is given by the sum of the mean values of Δt_{ten} for all the factors mentioned above. Following equation (46), the square of the standard deviation of the overall value of Δt_{ten} is the sum of squares of the standard deviations of the factors. Equation (45) can be used to provide an approximate estimate of the coefficient of variation of the overall value of Δt_{esc} or of Δt_{ten}.

The model described for building evacuation has been derived using equations similar to those in (35) to (39) [60].

6.6.3 *Design values*

In practical fire safety engineering, it is necessary to determine design values that include partial safety factors α_Ω and α_Ψ to account for uncertainties in the estimation of characteristic values for the random variables Ω and Ψ. The sources of uncertainties are mainly parameters included in or excluded from analytical models, data used, hypotheses and assumptions. The corrections for uncertainties should be in the direction of greater safety after assigning values greater than unity for the partial safety factors α_Ω and α_Ψ.

Consider first the fire protection given by the fire resistance of the structural boundaries of a compartment. With the partial safety factor α_R greater than unity, the design value R_d for fire resistance can be estimated by:

$$R_d = R_k/\alpha_R \quad (47)$$

where R_k is the characteristic value.

R_d will be less than R_k according to equation (47). This design condition will also be satisfied if the minimum value R_p in equation (35) is considered as the design value, and the mean value μ_R is considered as the characteristic value. In this case, from equations (38) and (47), α_R is the reciprocal of $(1 - \nu_R\tau_R)$.

The formula for the design value S_d for fire severity is:

$$S_d = \alpha_S S_k \quad (48)$$

where S_k is the characteristic value and α_S, greater than unity, is the partial safety factor. Accordingly, S_d will be greater than S_k. This design condition will also be satisfied if the maximum value S_q in equation (36) is considered as the design value and the mean value μ_S as the characteristic value. In this case, from equations (39) and (48), α_S is equal to $(1 + \nu_S\tau_S)$.

For example, if the estimate of R_k is correct to 15 %:

$$\alpha_R = 1.176,\ R_d = 0.85R_k$$

It can also be seen that if $\nu_R = 0.2$ and a value of 1.96 is adopted for τ_R, $\alpha_R = 1.64$.

Likewise, if the estimate of S_k is known within 25 %:

$$\alpha_S = 1.25,\ S_d = 1.25S_k$$

Also, if $\nu_S = 0.2$ and $\tau_S = 1.96$, $\alpha_S = 1.39$.

Since the design requirement is $R_d \geq S_d$, from equations (47) and (48):

$$R_k \geq \alpha_R\alpha_S S_k \quad (49)$$

Equation (49) provides a method for adjusting the characteristic value S_k of fire severity to take account of uncertainties with the aid of partial safety factors α_R and α_S. Additional adjustment factors can be included on the right hand side of equation (49) as additional (multiplicative) partial safety factors for adopting to reliability requirements differing from the average or normal requirements. The adjustments for a particular building or type of building should reflect the increase or decrease in fire risk from the average risk, compartment size, effectiveness of sprinklers (if installed), efficiency of fire brigade and other such factors affecting fire severity.

For the evacuation model, the design value $\Delta t_{esc(d)}$ for the total evacuation time Δt_{esc} is given by:

$$\Delta t_{esc(d)} = \Delta t_{esc(k)}\ \alpha_{\Delta t,esc} \quad (50)$$

where $\Delta t_{esc(k)}$ is the characteristic value and $\alpha_{\Delta t,esc}$ is the partial safety factor greater than unity. The maximum total evacuation time:

$$\Delta t_{esc(q,ki)} = \mu_{\Delta t,esc}\ (1 + \nu_{\Delta t,esc}\tau_{\Delta t,esc})$$

can be considered as the design value and the mean $\mu_{\Delta t,esc}$ as the characteristic value. In this case:

$$\alpha_{\Delta t,esc} = (1 + \nu_{\Delta t,esc}\tau_{\Delta t,esc})$$

where $\nu_{\Delta t,esc}$ is the coefficient of variation of Δt_{esc} and $\tau_{\Delta t,esc}$ is a parameter similar to τ_r in equation (35) or τ_s in equation (36).

The design value for the combustion product time Δt_{ten} is given by:

$$\Delta t_{ten(d)} = \Delta t_{ten(k)}/\alpha_{\Delta t,ten} \quad (51)$$

where $\Delta t_{ten(k)}$ is the characteristic value and $\alpha_{\Delta t,ten}$ is the partial safety factor greater than unity. The minimum value of Δt_{ten} given by:

$$\Delta t_{ten(p)} = \mu_{\Delta t,ten}\ (1 - \nu_{\Delta t,ten}\tau_{\Delta t,ten})$$

can be reconsidered as the design value and the mean value $\mu_{\Delta t,ten}$ can be considered as the characteristic value. In this case, $\alpha_{\Delta t,ten}$ is the reciprocal of $(1 - \nu_{\Delta t,ten}\tau_{\Delta t,ten})$. The parameter $\nu_{\Delta t,ten}$ is the coefficient of variation of Δt_{ten} and $\tau_{\Delta t,ten}$ is a constant similar to $\tau_{\Delta t,esc}$.

Since the design criterion for successful evacuation is: $\Delta t_{esc(d)} \leq \Delta t_{ten(d)}$:

$$\Delta t_{esc(k)} \leq \Delta t_{ten(k)}/\alpha_{\Delta t,ten}\alpha_{\Delta t,sec}$$

or: (52)

$$\Delta t_{ten(k)} \geq \Delta t_{esc(k)}\alpha_{\Delta t,ten}\cdot\alpha_{\Delta t,sec}$$

The purpose of including the partial safety factors $\alpha_{\Delta t,\mathrm{ten}}$ and $\alpha_{\Delta t,\mathrm{esc}}$ in the design process is to ensure that the maximum or any other design value for the total evacuation time Δt_{esc} does not exceed the minimum or any other design value for the combustion product time Δt_{ten}.

In the semi-probabilistic approach discussed in here, choices for the values of the partial safety factors are usually based on the expert judgement of the fire safety engineer and the quality of information available to him/her estimating the values of the parameters. Instead of adopting such empirical and intuitive methods, the partial safety factors can be derived from the probability distributions of the variables involved. This method, based on the "design point", can be found in reference [58].

6.7 Beta method

6.7.1 *Probabilistic design criterion*

In a probabilistic procedure, the deterministic design criterion, $\Psi \geq \Omega$, is modified to:

$$P(\Psi \geq \Omega) \geq 1 - P_g \quad (53)$$

where $P(\Psi \geq \Omega)$ denotes the probability of strength Ψ being greater than or equal to stress Ω, which is equivalent to the probability of success. P_g is a (small) target probability (risk) acceptable to a property owner or society at large. The value of P_g depends on consequences in terms of damage to life and property if failure occurs. The probability of failure should be less than P_g:

$$P(\Psi < \Omega) < P_g \quad (54)$$

If Ψ is fire resistance R and Ω is fire severity S, the probabilistic design criterion for compartment success is:

$$P(R \geq S) \geq 1 - P_g \quad (55)$$

Probability of compartment failure should be less than P_g:

$$P(R < S) < P_g \quad (56)$$

For building evacuation, Ω is the time Δt_{ten} taken by a combustion product to produce an untenable condition on an escape route and Ψ is the total evacuation time Δt_{esc}. In this case, equation (53) is modified to:

$$P(\Delta t_{\mathrm{esc}} \leq \Delta t_{\mathrm{ten}}) \geq 1 - P_g \quad (57)$$

for egress success. Probability of egress failure should be less than P_g:

$$P(\Delta t_{\mathrm{esc}} > \Delta t_{\mathrm{ten}}) < P_g \quad (58)$$

Probabilistic methods are concerned with the evaluation of P_g and $(1 - P_g)$ for different combinations of Ω and Ψ. The evaluation procedure takes account of uncertainties through the probability distributions of Ω and Ψ.

6.7.2 *Univariate approach*

In this approach [58], only the stress variable Ω is considered as a random variable, with the strength variable Ψ treated as a constant. This is the approach traditionally adopted by fire safety engineers for determining the fire resistance for a structural element. The cumulative probability distribution function of severity, S, is denoted by $P_S(\Omega)$ which is the probability of severity being less than or equal to Ω. If fire resistance R of a structural element is set equal to Ω, the probability of severity, S, exceeding R is $[1 - P_S(R)]$, which is the probability of failure of the element.

Consider first the exponential probability distribution for fire severity S:

$$P_S(x) = 1 - \exp(-\lambda_S x) \quad (59)$$

According to a property of this distribution, λ_S is the reciprocal of the mean value μ_S of fire severity. Baldwin [36] estimated μ_S = 25 min for office buildings giving λ_S = 0.04. It can be seen from equation (59) that if $R = x$ = 25 min, probability of failure is:

$$\begin{aligned} 1 - P_S(R) &= \exp(-\lambda_S R) \\ &= \exp(-1) \\ &= 0.37 \end{aligned}$$

which is not a small quantity. However, the probability of failure reduces to 0.09 if R = 60 min and to 0.03 if R = 90 min, and so on.

If the fire severity S has a normal distribution with mean μ_S and standard deviation σ_S, the standardized random variable τ given by:

$$\tau = (S - \mu_S)/\sigma_S \qquad (60)$$

has a standard normal distribution with mean zero and standard deviation unity. From equation (60):

$$S = \mu_S + \tau\sigma_S \qquad (61)$$

If the fire resistance of a structural element is set equal to S with $\tau = 0$ such that $R = \mu_S$, the probability of success or failure of the element in a fire is 0.5. But, if $R = S$ with $\tau = 1.96$ in equation (61), the probability of success given by the cumulative distribution function of τ is 0.975 and the probability of failure is 0.025. For $\tau > 1.96$, the probability of failure is less than 0.025. For $\tau = 2.33$, the probability of success is 0.99, with 0.01 for probability of failure. Probabilities of success and failure for different values of τ can be obtained from a table of standard normal distribution. Using this table, the fire resistance required to meet any target level for the probability of failure can be determined by using in equation (61), the value of τ corresponding to this level.

6.7.3 *Bivariate approach*

In this approach [58,60,61], more commonly known as Beta method, both the stress and strength variables are considered as random variables affected by uncertainties. The difference $(\Psi - \Omega)$ is the "safety margin", which is also referred to as the "state function". The expected value of the random variable:

$$\Theta = \Psi - \Omega \qquad (62)$$

is given by:

$$\mu_\Theta = \mu_\Psi - \mu_\Omega \qquad (63)$$

where μ_Ψ and μ_Ω are the mean values of Ψ and Ω. The standard deviation of Θ is given by:

$$\sigma_Z = (\sigma_\Psi^2 + \sigma_\Omega^2)^{1/2} \qquad (64)$$

where σ_Y and σ_Ω are the standard deviations of Ψ and Ω. The "safety index" β is given by:

$$\beta = \mu_\Theta/\sigma_\Theta \qquad (65)$$

First consider the determination of fire resistance required for a structural element to satisfy a specified event for the probability of failure. If the mean and standard deviation of fire resistance R are μ_R and σ_R and the mean and standard deviation of fire severity S are μ_S and σ_S, the mean and standard deviation of the state function $\Theta = R - S$ are:

$$\mu_\Theta = \mu_R - \mu_S \qquad (66)$$

$$\sigma_\Theta = (\sigma_R^2 + \sigma_S^2)^{1/2} \qquad (67)$$

The "safety index" β is given by:

$$\beta = \mu_\Theta/\sigma_\Theta = (\mu_R - \mu_S)/(\sigma_R^2 + \sigma_S^2)^{1/2} \qquad (68)$$

The fire resistance required may be set according to μ_R given by the following equation.

$$\mu_R = \mu_S + \beta(\sigma_R^2 + \sigma_S^2)^{1/2} \qquad (69)$$

If R and S have normal distributions, the parameter β has a standard normal distribution. In this case, the value of β corresponding to any target level for probability of failure can be obtained from a table of standard normal distribution. This value can then be inserted in equation (69) to provide the fire resistance μ_R required for the structure element. As discussed in **6.6.2** in terms of the variable τ, the probability of structural failure would be 0.5 if $\beta = 0$ and $\mu_R = \mu_S$ less than 0.5 if β is positive and $\mu_R > \mu_S$, and greater than 0.5 if β is negative and $\mu_R < \mu_S$. The probability of failure would be 0.025 if $\beta = 1.96$, 0.01 if $\beta = 2.33$ and 0.001 if $\beta = 3.09$. For a selection of values of β, probabilities of structural success and failure are given in Table 6.

Table 6 — Probabilities of structural success and failure (normal distribution)

Probability of success ($1 - P_g$)	Probability of failure (P_g)	β	θ (r = 0.15)
0.000 1	0.999 9	–3.719 0	0.399 3
0.000 5	0.999 5	–3.290 5	0.457 3
0.001 0	0.999 0	–3.090 2	0.484 8
0.002 0	0.998 0	–2.878 2	0.514 5
0.002 5	0.997 5	–2.807 0	0.524 5
0.005 0	0.995 0	–2.575 8	0.557 6
0.010 0	0.990 0	–2.326 3	0.594 1
0.025 0	0.975 0	–1.960 0	0.649 4
0.050 0	0.950 0	–1.644 9	0.699 0
0.100 0	0.900 0	–1.281 6	0.758 7
0.200 0	0.800 0	–0.841 6	0.835 5
0.300 0	0.700 0	–0.524 4	0.894 5
0.400 0	0.600 0	–0.253 3	0.947 7
0.500 0	0.500 0	0.000 0	1.000 0
0.600 0	0.400 0	0.253 3	1.055 2
0.700 0	0.300 0	0.524 4	1.118 0
0.800 0	0.200 0	0.841 6	1.196 9
0.900 0	0.100 0	1.281 6	1.318 1
0.950 0	0.050 0	1.644 9	1.430 7
0.975 0	0.025 0	1.960 0	1.539 8
0.990 0	0.010 0	2.326 3	1.683 2
0.995 0	0.005 0	2.575 8	1.793 4
0.997 5	0.002 5	2.807 0	1.906 4
0.998 0	0.002 0	2.878 2	1.943 7
0.999 0	0.001 0	3.090 2	2.062 6
0.999 5	0.000 5	3.290 5	2.186 9
0.999 9	0.000 1	3.719 0	2.504 3

Consider, now, the determination of the total evacuation time Δt_{esc} that will satisfy a specified level for the probability of egress failure [60]. The state function in this case may be written as $\Theta = \Delta t_{ten} - \Delta t_{esc}$ such that the mean and standard deviation of Θ are:

$$\mu_{\Theta} = \mu_{\Delta t,ten} - \mu_{\Delta t,esc} \qquad (70)$$

$$\sigma_{\Theta} = (\sigma^2_{\Delta t,ten} + \sigma^2_{\Delta t,esc})^{1/2} \qquad (71)$$

The parameters $\mu_{\Delta t,ten}$ and $\sigma_{\Delta t,ten}$ are the mean and standard deviation of Δt_{ten} and $\mu_{\Delta t,esc}$ and $\sigma_{\Delta t,esc}$ are the mean and standard deviation of Δt_{esc}. The safety index β is given by:

$$\beta = \mu_Z / \sigma_Z = \frac{(\mu_{\Delta t,ten} - \mu_{\Delta t,esc})}{(\sigma^2_{\Delta t,ten} + \sigma^2_{\Delta t,esc})^{1/2}} \qquad (72)$$

The total evacuation time required may be set according to $\mu_{\Delta t,esc}$ in the following equation:

$$\mu_{\Delta t,esc} = \mu_{\Delta t,ten} - \beta(\sigma^2_{\Delta t,ten} + \sigma^2_{\Delta t,esc})^{1/2} \qquad (73)$$

If Δt_{ten} and Δt_{esc} have normal distributions as discussed earlier, β has a standard normal distribution. The probability of egress failure is be 0.5 if $\beta = 0$ and $\mu_{\Delta t,esc} = \mu_{\Delta t,ten}$, less than 0.5 if β is positive and $\mu_{\Delta t,esc} < \mu_{\Delta t,ten}$, and greater than 0.5 if β is negative and $\mu_{\Delta t,esc} > \mu_{\Delta t,ten}$. The probability of failure would be 0.025 if $\beta = 1.96$, 0.01 if $\beta = 2.33$ and 0.001 if $\beta = 3.09$. Figures in Table 6 can be used in conjunction with equation (73) for determining the total evacuation time according to a specified level for the probability of egress failure. It should be noted that β has a positive sign attached to it in equation (69) but a negative sign attached to it in equation (73).

To satisfy the condition specified in equation (73), it might be necessary to install automatic detectors and/or sprinklers if the building is not already equipped with these devices. These devices can reduce the detection time Δt_{det} and hence reduce $\mu_{\Delta t,\text{esc}}$. Sprinklers can also increase the combustion product time $\mu_{\Delta t,\text{ten}}$. The total evacuation time $\mu_{\Delta t,\text{esc}}$ can also be reduced by providing additional or wider staircases.

If egress failure occurs there is a probability P_{d} that one or more deaths might occur. This probability can be estimated by analysing fire statistics. According to an analysis [60] of these statistics for the period 1978 to 1988, the average detection time for a single and multiple occupancy dwellings was 10 min with Δt_{rec} = 2 min and Δt_{evac} = 3 min, the average total evacuation time $\mu_{\Delta t,\text{esc}}$ was 15 min. The mean value of combustion products time $\mu_{\Delta t,\text{ten}}$ for causing death was assumed to be 15 min such that the probability of egress failure was estimated to be 0.5. With a fatality rate per fire of 0.013, the value of K was estimated as 0.026 (= 0.013/0.5).

6.7.4 *Safety factor*

Corresponding to the safety index β, a safety factor θ may be defined as the ratio between the mean values of the stress and strength variables. In the case of structural failure:

$$\theta = \mu_R/\mu_S \tag{74}$$

such that, from equation (68):

$$\beta = \frac{(\theta - 1)}{(v_R^2\theta^2 + v_S^2)^{1/2}} \tag{75}$$

where, as defined in equation (37), v_R and v_S are coefficients of variation given by:

$$v_R = \sigma_R/\mu_R;\ v_S = \sigma_S/\mu_S$$

For facilitating calculations, equation (75) may be inverted to give:

$$\theta = \frac{1 + \beta(v_R^2 + v_S^2 - \beta^2 v_R^2 v_S^2)^{1/2}}{1 - \beta^2 v_R^2} \tag{76}$$

Equation (70) has a solution only if $v_R < 1/\beta$.

If it is assumed that $v_R = v_S = r$, equation (76) reduces to:

$$\theta = \frac{1 + \beta r(2 - \beta^2 r^2)^{1/2}}{1 - \beta^2 r^2} \tag{77}$$

For r = 0.15, the values of θ corresponding to those of β are given in Table 6 for different failure probabilities.

In the safety factor approach, the mean value of fire resistance μ_R should be set equal to or greater than the value given by ($\theta\mu_S$). Suppose, for example, that the probability of structural failure should be less than 0.005. In this case, from Table 6 for P_{g} = 0.005, β = 2.575 8 and θ = 1.793 4 if r = 0.15. Hence, for achieving the desired target, the mean fire resistance μ_R should be set equal to or greater than 1.79μ_S.

For the evacuation model the safety factor is given by:

$$\theta = \mu_{\Delta t,\text{ten}}/\mu_{\Delta t,\text{esc}} \tag{78}$$

such that, from equation (72):

$$\beta = \frac{(\theta - 1)}{(v_{\Delta t,\text{ten}}^2\theta^2 + v_{\Delta t,\text{esc}}^2)^{1/2}}$$

where $v_{\Delta t,\text{ten}}$ and $v_{\Delta t,\text{esc}}$ are the coefficients of variation of Δt_{ten} and Δt_{esc} given by:

$$v_{\Delta t,\text{ten}} = \sigma_{\Delta t,\text{ten}}/\mu_{\Delta t,\text{ten}},\ v_{\Delta t,\text{esc}} = \sigma_{\Delta t,\text{esc}}/\mu_{\Delta t,\text{esc}}$$

Also:

$$\theta = \frac{1 + \beta(v_{\Delta t,\text{ten}}^2 + v_{\Delta t,\text{esc}}^2 - \beta^2 v_{\Delta t,\text{ten}}^2 v_{\Delta t,\text{esc}}^2)^{1/2}}{1 - \beta^2 v_{\Delta t,\text{ten}}^2} \tag{79}$$

Equation (77) is applicable if $\nu_{\Delta t,\mathrm{ten}} = \nu_{\Delta t,\mathrm{esc}} = r$.

If $r = 0.15$, from Table 6, $\beta = 2.326\,3$ and $\theta = 1.683\,2$, for a target maximum value of 0.01 for the probability of egress failure. For achieving this target, the mean value $\mu_{\Delta t,\mathrm{esc}}$ of total evacuation time should not exceed $0.59\mu_{\Delta t,\mathrm{ten}}$. This result follows from equation (78), according to which $\mu_{\Delta t,\mathrm{ten}}$ should be greater than $\theta\mu_{\Delta t,\mathrm{esc}}$ or $\mu_{\Delta t,\mathrm{esc}}$ should be less than $(\mu_{\Delta t,\mathrm{ten}}/\theta)$. Under such a protection for life safety, the fatality rate per fire would be less than 0.000 26 (= 0.01 × 0.026) if the probability k of one or more deaths occurring, given egress failure is 0.026 as mentioned earlier.

Thus the fatality rate per fire in single and multiple occupancy dwellings can be reduced to 0.000 26 from the current level of 0.013 if the total evacuation time $\mu_{\Delta t,\mathrm{esc}}$ is reduced to 9 min (= 0.59 × 15) from the current level of 15 min. The current value of $\mu_{\Delta t,\mathrm{esc}}$ is 15 min. With Δt_{rec} = 2 min and Δt_{evac} = 3 min, the detection or discovery time Δt_{det} should be reduced to 4 min from the current level of 10 min.

6.7.5 *Log normal safety index*

For structural fire resistance [62], if resistance R and severity S have log normal probability distributions, a design format based on the following state variable is proposed:

$$\Phi = \ln(R/S) \quad (80)$$

Approximate values of the mean μ_Φ and standard deviation σ_Φ are given by:

$$\mu_\Phi = \ln(\mu_R/\mu_S)$$

$$\sigma_\Phi = (\nu_R^2/\nu_S^2)^{1/2}$$

where, as defined earlier, μ_R and ν_R are the mean and coefficient of variation of R, and μ_S and ν_S are the mean and coefficient of variation of S.

The safety index corresponding to the state variable Φ in equation (80) is:

$$\beta_\Phi = \mu_\Phi/\sigma_\Phi$$

$$= \frac{\ln(\mu_R/\mu_S)}{(\nu_R^2 + \nu_S^2)^{1/2}} \quad (81)$$

The fire resistance required may be determined according to μ_R given by:

$$\ln\mu_R = \ln\mu_S + \beta_\Phi(\nu_R^2 + \nu_S^2)^{1/2} \quad (82)$$

The safety factor θ_Φ is given by:

$$\theta_\Phi = (\mu_R/\mu_S) = \exp[\beta_\Phi(\nu_R^2 + \nu_S^2)^{1/2}] \quad (83)$$

The mean fire resistance μ_R should be set equal to or greater than $\theta_\Phi \cdot \mu_S$.

Values of β_Φ for different probabilities of structural failure are the same as those in Table 6. $\theta_\Phi = 1$ if $\beta_\Phi = 0$, less than 1 if β_Φ is negative, and greater than 1 if β_Φ is positive. If $\nu_R = \nu_S = r$:

$$\theta_\Phi = \exp[\beta_\Phi r\sqrt{2}] \quad (84)$$

Calculations based on equation (84) show that, for any target probability of failure less than 0.3, the value of θ given by equation (76) is marginally greater than the corresponding value of θ_Φ. Hence, in this range of failure probability which is of interest in structural fire safety design, an assumption of normal distributions for R and S provide a slightly greater safety margin than an assumption of log normal distributions [58].

It is a somewhat complex statistical problem to construct an appropriate safety index if both R and S have exponential probability distributions or they have different distributions. The safety index proposed in equation (68) or (81) are sufficient for all practical purposes. A detailed discussion on other problems such as “design point”, full probabilistic approach, extreme value technique and determination of tolerable failure probability can be found in reference [58].

7 Data

Unless specifically noted, the data discussed in this clause are considered to be applicable to UK projects. International differences in management and statutory regimes might have a significant effect on the data. The data are summarized in Annex A. This clause provides important information on the background to the data to enable individual engineers to make a reasoned judgement based on local conditions.

7.1 Collation of data for PRA

7.1.1 *General*

Wherever possible, the data used should be directly applicable to the case under consideration. For example, many shopping malls and airports collate data on the time it takes to evacuate the building when the fire alarm goes off. Such data are unlikely to be released into the public domain, but might be available when a study on the development in question is carried out.

Manufacturers often have data on the failure of their systems or the components that make up their systems. Service companies for fire alarms and sprinklers might keep maintenance records that can be interrogated. Again, such data might be confidentially sensitive and difficult to obtain.

The Government Fire Statistics and Research Unit (within the Office of the Deputy Prime Minister) collates a great deal of information with respect to fires that are attended by the fire service. These data are entered on a fire incident report at the fire scene and may be made available in a raw data format.

7.1.2 *Key data*

Some of the most commonly required data for simplistic PRA studies are discussed. Possible sources for the data, typical values and commentary on the application of the data are presented.

7.1.3 *Frequency of fires*

Fires in buildings are rare events. Serious fires that threaten life or property are even rarer. In the UK, up to 80 % of fires are not reported to the fire service.

Most serious fires occur in industrial workplaces. Typical studies suggest that an industrial site is approximately 10 times as likely to experience a fire as an office and nearly 20 times as likely to experience a fire as domestic dwelling. An area of potential concern is that hotels are nearly as likely as industrial sites to experience a reportable fire.

There are a number of different methods that can be applied to predict the actual probability of a fire occurring. The figures discussed are based on a simple correlation between the actual number of serious fires and the total number of properties for occupancy type. This might not always be wholly representative.

It is often suggested that the probability of a fire occurring is related to building size (measured by floor area). Using this basis, an average office covering an area of 1 000 m^2 has the same number of fires (once every 17 years) as a small industrial site covering a similar area. However, a small industrial unit covering say 250 m^2 has the same probability of fire (once every 34 years) as a small office covering 500 m^2. A similarly sized retail unit could be expected to experience a serious fire once every 3 years (approximately the same as a large industrial site covering an area of 21 000 m^2 or a large leisure development (such as a cinema) covering 5 000 m^2.

7.1.4 *Area involved in fire*

Data from the UK fire brigade fire incident reports suggest that generally, only 10 % of reported fires spread beyond the room of origin. Typically, only 2 % spread to other buildings. Given that reported fires make approximately 20 % of all fires, this clearly demonstrates that most fires are not a major hazard and either burn out without significant damage or are quickly extinguished by occupants.

Insurance statistics suggest that less than 1 in every 1 000 fires in hotels, shops, banks, restaurants and other leisure developments will result in a loss of over £1 000 000 (1992 prices). Fires in industrial and educational establishments are up to 4 times as likely to result in a fire of this magnitude.

In shops and offices without sprinklers, approximately 60 % of fires reported to the fire service will not grow beyond 1.0 m^2 with 40 % of reported fires being confined to the item first ignited. The majority of fires in shops and offices (approximately 80 % of reported fires in these occupancy groups) will be confined to an area not exceeding 20 m^2 in area.

7.1.5 ***What are the effects of automatic fire detection and alarm systems?***

One of the most widely used active fire protection systems is automatic fire detection and alarm (AFDA). Typically, AFDA can be used to provide equivalent fire safety with reduced fire safety provisions elsewhere in a building and will often be required as an integral part of smoke control systems.

Statistical data suggests that smoke detectors can improve the likelihood that a fire will be detected within 5 min by 50 % to 60 %. This figure is significant as, unless a fire is discovered immediately or within 5 min, first aid fire fighting is unlikely to be successful.

It should be noted that, in practice, a correctly sited smoke detector should detect a fire well within 5 min of ignition.

In dwellings, smoke detectors do not improve the chances of discovering a fire immediately. However, in other premises, smoke detectors improve the likelihood that the fire will be discovered immediately by nearly 50 %. This can be particularly significant when considering evacuation of occupants from large assembly buildings such as airports where a smoke analysis to determine the time available for escape can be used to introduce significant cost savings into a design.

7.1.6 ***Reliability of automatic fire detection and alarm systems***

If an AFDA system were being used as a trade-off in a building design, the assumption would be made that the system operates on demand, although this will not always be the case.

When considering life safety requirements, an assumption of 100 % reliability for a system is not normally of concern. The assumptions inherent in the models used to evaluate fire growth, smoke development and human response are typically conservative. Also, a "belt and braces" design policy is often adopted, with the fire safety of occupants being assured by applying multiple design features. However, system reliability might be relevant when making a comparison between a number of alternative fire safety design schemes.

When considering property protection, the AFDA might be required to call the fire service or operate automatic fire suppression (AFS) systems. In this case, system reliability is relevant and should be taken into account.

Smoke and rate of rise heat detectors are generally expected to detect a fire in approximately 90 % of cases. This figure might be reduced to approximately 75 % or lower in the case of domestic smoke detectors, which are significantly more prone to poor siting and low maintenance.

Flame detectors are considered to be a less reliable form of fire detection due to the potential for the units to become obscured over the building lifetime.

Studies have suggested that up to 22 % of faults in detection systems can be attributed to design errors, with 53 % of the faults being accounted for by mechanical breakdown. The remaining 25 % of failures are considered to be accounted for by unexpected changes in the circumstances surrounding the design or use of the building in which the system was installed (i.e. "unexpected" failures).

Typically, the reliability of an alarm system is considered to be high, with failures being largely attributed to the non-operation of the detection. This is supported by data, which suggests that when a link to the fire service is provided, the system will operate on 95 % of the occasions that a fire is detected.

7.1.7 ***Human response to alarms***

The reliability of operation of an AFDA system should be considered with respect to the ability of the alarm system to initiate an evacuation.

Systems which use an informative sounder (e.g. a PA based system) might be as much as 70 % more effective than a simple sounder. This suggests that 70 % more people would start their evacuation on the basis of hearing an informative alarm than would do so on hearing a bell.

The magnitude of the improvement in effectiveness between a simple sounder and informative system is largely dependent on the nature of the occupancy. When people are familiar with the building, or in groups, less improvement in effectiveness would be expected from using an informative sounder.

7.1.8 ***Benefits from automatic fire suppression systems***

Many insurance companies require automatic fire suppression systems (usually sprinklers) to be provided in buildings. In the UK, there is no statutory requirement for sprinklers, although this is not the case in the rest of the world and, in particular, the USA.

The generally accepted value for the effectiveness of automatic fire suppression systems is an overall reduction in potential loss of 50 %. Most data for automatic suppression systems is related to the operation of sprinklers (as these are the most widespread types of system). In specialist applications such as in-cabinet protection of computer systems, a much higher loss reduction should be achievable.

7.1.9 ***Reliability of sprinkler systems***

The reliability of sprinklers has been quoted as high as > 99 %. Reliability values of this magnitude have been used to promote the use of sprinklers. However, reliability figures as low as 70 % have also been quoted and, in general, it is considered unlikely that a > 99 % reliability could be achieved. As sprinkler systems vary little in design on an international scale, a variation in reliability values of the magnitude described above should not occur.

The main reason for the variation in quoted reliability values is differences in the criteria used to judge the successful operation of sprinklers. Some studies allow up to 200 heads to be activated (an area affected by fire of up to 2 000 m^2) before a sprinkler operation is considered unsuccessful. Some studies do not count situations when a sprinkler system is cut off from the mains (e.g. due to errors in maintenance procedures) when assessing the reliability of the sprinkler system. The latter exclusion is of particular concern as the failure of a sprinkler system to operate due to accidental (or deliberate) isolation from the mains is the most common cause of failure.

After taking into the above variations in data, the following values for the probability that a sprinkler system will operate successfully on demand are as follows.

— Maximum: 95 % (applicable to new systems in areas where statutory enforcement is in place).

— Typical: 90 % (new life safety systems) or 80 % (new property protection systems).

— Minimum: 75 % (older systems).

The above values assume that no more than four sprinkler heads operate. This was considered as the limiting case for a “successful” sprinkler operation, as no more than four heads operating is the fire size typically used in a fire engineering study.

It is recognized that the use of four heads operating as the cut off criteria for success might give an incomplete picture. In particular, if a significant number of buildings included in the data sample had only four or less sprinkler heads (e.g. a small retail unit), then it is not clear whether the sprinklers controlled the fire.

However, as the majority of the sprinkler data refers to large commercial premises, offices and industrial properties where the number of heads is usually significantly greater than four, the values given here should be appropriate for most applications.

7.1.10 ***Differences between life and property protection sprinkler systems***

Manufacturers of sprinkler systems have, in the past, heralded the reliability of the systems (supported, to some extent, by statistical evidence). However, it is generally considered necessary to provide additional measures (e.g. monitoring at all system valves) and place other restrictions on system design to improve the reliability of sprinkler systems installed for life safety reasons.

Whilst there is some evidence that the additional measures for life safety systems can improve the system reliability, the overall improvement in loss reduction in a building might not be improved by switching from a property protection to a life safety sprinkler system. Indeed, available data suggests that the generally accepted loss reduction of 50 % often accepted for sprinklered buildings are approximately the same for both property protection and life safety systems. However, it should be noted that the exclusion of the additional life safety system requirements from a life safety system can be a contentious issue and is likely to require extensive further justification if applied on a project.

7.1.11 ***Reliability of other automatic fire suppression systems***

The specialist application nature of gas extinguishing, dry powder and water mist suppression systems is such that a higher level of reliability is often required for these systems.

The most common applications for AFS (other than sprinklers) are military, telecommunications and nuclear applications. These sectors normally demand a very high level of system integrity and, typically, reliability rates in excess of 90 % can be achieved.

7.1.12 ***Reliability of smoke control systems***

Whilst smoke control systems have been used in buildings for a number of years, there is little reliability data available. Data available from those in the fire safety engineering community suggests that systems will operate on demand, as required, with a reliability of 85 % to 90 %.

These values might not fully take account of the effects of changes to the building design over the building lifetime. As noted, this can be a significant failure route for other active systems such as alarm systems.

Smoke control systems are particularly sensitive to relatively small, seemingly innocuous, changes in the building design. For example, modifying the frontage of a small shop onto a mall could, in some instances, double the smoke control requirements.

If care has been taken in the design of the system, it should be sufficiently robust so that it will be appropriate for the lifetime of the building. However, where uncontrolled alterations to a building have taken place or are likely to take place, an allowance for this should be included in the reliability assumed for the system.

7.1.13 ***Reliability of passive fire protection systems***

Traditionally, the reliability of passive fire-resisting structures has been considered difficult to assess. Much emphasis has been made of the principle that even if, for example, a 60 min fire-resisting wall failed early, whilst it might have technically failed to operate, it is still likely to have survived for a significant period of time. Hence, failure might have only been partial. This problem is not unique to passive fire protection, as it is likely that, when active, fire protection systems such as smoke exhaust or sprinkler systems might only fail partially. For example, a smoke extract system would be considered to fail if it does not perform as designed, but even a 50 % performance would be of some benefit and might be sufficient to meet the objectives of the system (e.g. maintaining clear escape routes).

A complete failure is less likely in passive systems. This would be analogous to a smoke exhaust system failing to start. As many "passive" fire safety systems have "active" elements to them, complete failure cannot always be ruled out. For example, roller shutters in a factory compartment wall will often be held open for day to day operation. If they fail to operate, the wall might be considered to have no fire resistance (although parts of the wall would still provide limited benefit).

It is possible to consider the performance of passive structures as a normal distribution. This allows one to consider a range in the performance of the structures to allow for variations in construction and maintenance. For example, it could be stated that 75 % of masonry walls provide 75 % more fire resistance than they had been tested to in a laboratory test. This approach allows comparative studies to be made, and it has been suggested that 25 %, 40 % and 65 % of suspended ceilings, glazed elements and partition walls respectively are likely to exhibit 75 % or more of the design fire resistance.

It is often suggested that passive fire protection is preferable to active fire systems on the basis that the passive systems do not suffer from the same design and maintenance issues as a mechanical system. However, many passive systems do rely on regular control and maintenance if they are to perform in a fire. For example, one of the most common cause of failure for compartment walls is penetrations added after construction (e.g. for IT cabling).

Similarly, fire doors which are not kept closed or which have faulty self-closers are of little or no benefit. Available data suggests that up to 23 % of fire doors are be blocked open. Further, approximately 20 % of hinged fire doors that are not blocked open could be expected to fail to close correctly (based on on-site inspections). This suggests that fire doors could fail to act as intended in over 40 % of installations.

7.1.14 ***Other data and future work on data collation***

There has been an effort in recent years to collate data with respect to the performance of passive fire protection systems (i.e. compartmentation). Preliminary data suggests that the higher the fire resistance rating of a structure, the higher the probability that it will perform as designed. Further, traditional construction such as studwork and masonry are considered more likely to achieve the designed level of fire resistance than glazing or suspended ceiling structures.

The management regime of a building has a central role to play in maintaining the integrity of passive fire protection. In particular, procedures should be in place to ensure that holes made through walls for building services are made good and that all services passing through compartment walls or floors are adequately fire-stopped.

Good data is available on the overall probability of death or injury from fire (as this is collated by most fire authorities throughout the world). However, the relatively low number of deaths by fire is such that the individual circumstances of a particular case can easily introduce statistical anomalies. Not withstanding this, fire casualty data can be used to correlate a PRA to give confidence to the results produced.

In particular, the relative risk of death is of significant interest. The overwhelming majority of persons who die in fires do so in their own homes. Further, over 65 % of fire casualties in dwellings and over 50 % of fire casualties in other buildings can be attributed to persons over the age of 60. (This takes account of the population demographics.)

Reasons for the high casualty rates amongst the elderly are complex. The old have a significantly lower tolerance to toxic fumes and hence could be more readily overcome by smoke from a fire than younger persons. This problem is amplified because the elderly might also be unable to move as quickly as younger persons and hence are unable to escape from a fire. Aside from the physical differences between the old and the young, there are also important sociological differences. Many old people live alone and in circumstances where a fire is more likely (e.g. a higher incidence of smoking and old, poorly maintained electrical/gas appliances).

Very limited data is available on the reaction of people to fire. Traditionally, people have been assumed to panic when confronted with an emergency. More recent studies have suggested that members of the general public can evacuate in an efficient, orderly manner.

However, interesting trends such as a desire to remain in a building (e.g. when being served in a shop) have recently been studied. This allows fire safety engineers to better understand and plan evacuations (e.g. shutting down a bar before evacuation starts can improve the efficiency of an evacuation).

Whilst some trends in human behaviour when confronted by fire are beginning to be understood, it is evident that a great deal of work remains to be done before satisfactory data is available in this area.

7.2 Key issues in the application of PRA data

7.2.1 *General*

It is difficult to give comprehensive guidance on what pitfalls one should look out for when using fire safety data for PRAs. A simple flowchart that can be used to assess the suitability of data for use in PRA is included (Figure 20).

Suggested key points that the engineer carrying out or reviewing a study should consider are given in **7.2.2**, **7.2.3** and **7.2.4**.

7.2.2 *Data applicability*

Consider the following.

— What is the set of cases that the data are drawn from?

— What case are the data measuring?

— How similar is my system to the cases considered?

— If the data are from another country, will variations in statutory controls or design practices skew the data?

7.2.3 *Data quality*

Consider the following.

— How old are the data (10 years is considered a typical cut off age for high quality data)?

— Are corroborative data available?

— Are the data from statistical studies or based on engineering judgement?

7.2.4 *Check study results*

Consider the following.

— Do the answers look realistic?

— How sensitive are the results to questionable data?

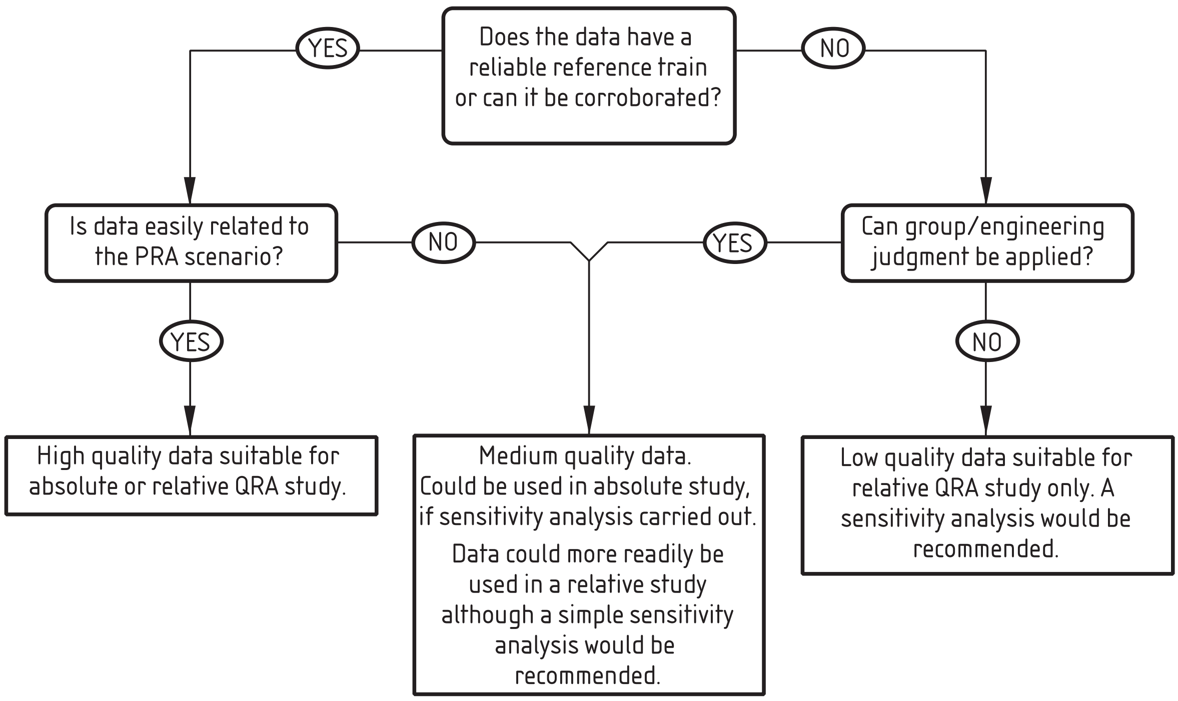


Figure 20 — Flowchart for checking data suitability

8 Future developments

8.1 General

Probabilistic risk assessment is a developing field, as is its application to the fire safety engineering of buildings. This subclause provides a brief discussion of some general and specific developments in data and analysis techniques.

8.2 Data

For data, there are two general types of development.

a) Data already being collected for other purposes, such as the measurement of the performance of Fire Brigade activity, are analysed in a way that provides data for probabilistic risk assessment. This has already happened to a degree, but is likely to increase in future.

b) New data are being collected specifically for probabilistic risk assessment of fire safety in buildings. Developments of this nature include the work on risk based fire cover by the Fire Research Division, Office of the Deputy Prime Minister, and the "Real Fires" database by the London Fire and Emergency Planning Authority.

8.3 Analysis

The other type of developments are in analysis techniques where, again, there are likely to be two types of development.

a) The simple analysis techniques presented in this Published Document will be applied in an increasingly wide and complex way, leading to development of more automated ways of applying analysis to a whole building.

b) Use of the complex analysis techniques will increase as better and more comprehensive data becomes available, and the complex analysis techniques such as Monte Carlo become more generally available.

Annex A (normative) Tables

Table A.1 — Probability of fire starting

Occupancy	Probability of fire per year	
	a	b
Industrial buildings		
Food, drink and tobacco	0.001 1	0.60
Chemical and allied	0.006 9	0.46
Mechanical engineering and other metal goods	0.000 86	0.56
Electrical engineering	0.006 1	0.59
Vehicles	0.000 12	0.86
Textiles	0.007 5	0.35
Timber, furniture	0.000 37	0.77
Paper, printing and publishing	0.000 069	0.91
Other manufacturing	0.008 4	0.41
All manufacturing industry	0.001 7	0.53
Other occupancies		
Storage	0.000 67	0.5
Shops	0.000 066	1.0
Offices	0.000 059	0.9
Hotels, etc.	0.000 08	1.0
Hospitals	0.000 7	0.75
Schools	0.000 2	0.75

Table A.2 — Overall probability of fire starting in various types of occupancy

Occupancy	Probability of fire starts per occupancy y^{-1}
Industrial	4.4×10^{-2}
Storage	1.3×10^{-2}
Offices	6.2×10^{-3}
Assembly entertainment	1.2×10^{-1}
Assembly non-residential	2.0×10^{-2}
Hospitals	3.0×10^{-1}
Schools	4.0×10^{-2}
Dwellings	3.0×10^{-3}

Table A.3 — Probability of fire starting within given floor area for various types of occupancy

Occupancy	Probability of fire starting $y^{-1}m^{-2}$
Offices	1.2×10^{-5}
Storage	3.3×10^{-5}
Public assembly	9.7×10^{-5}

Table A.4 — Area damage and percentage of fires for each category of fire spread (textile industry)

Category of fire spread	Sprinklered		Unsprinklered	
	Area damage m^2	Percentage of fires	Area damage m^2	Percentage of fires
Production area				
Confined to item first ignited	5	72	5	43
Spread beyond item but confined to room of origin				
i) contents only	13	18	17	32
ii) structure involved	113	6	475	13
Spread beyond room	694	4	694	12
Average	40	100	152	100
Storage area				
Confined to item first ignited	4	72	10	19
Spread beyond item but confined to room of origin				
i) contents only	19	24	17	18
ii) structure involved	19	24	262	38
Spread beyond room	1 712	4	1 712	25
Average	76	100	539	100
Other areas				
Confined to item first ignited	2	66	2	42
Spread beyond item but confined to room of origin				
i) contents only	11	22	4	25
ii) structure involved	68	8	68	18
Spread beyond room	1 007	4	1 007	15
Average[a]	49	100	165	100

[a] Source: UK Fire Statistics, 1984–86.

Table A.5 — Area damage and percentage of fires for each category of fire spread (pubs, clubs, restaurants – all areas)

Category of fire spread	Sprinklered		Unsprinklered	
	Area damage m^2	Percentage of fires	Area damage m^2	Percentage of fires
Confined to item first ignited	1	59	1	26
Spread beyond item but confined to room of origin				
i) contents only	1	15	2	12
ii) structure involved	4	19	15	45
Spread beyond room	50	7	101	17
Average[a]	5	100	24	100

[a] Source: UK Fire Statistics, 1984–86.

Table A.6 — Office buildings: frequency distribution of area damage (in terms of number of fires)

Area damage m^2	Office rooms		Other rooms	
	Without sprinklers	With sprinklers[a]	Without sprinklers	With sprinklers[a]
1 and under	908 (51.2)	13 (27.8)	2 588 (40.8)	95 (25.2)
2 – 4	379 (30.8)	3 (11.1)	902 (20.1)	17 (11.8)
5 – 9	144 (23.1)	—	303 (13.2)	9 (4.7)
10 – 19	116 (16.8)	2	199 (8.6)	2 (3.2)
20 – 49	154 (8.6)	—	180 (4.5)	3 (0.79)
50 – 99	69 (4.8)	—	75 (2.8)	1
100 – 199	35 (3.0)	—	53 (1.6)	—
200 – 499	33 (1.2)	—	40 (0.7)	—
500 – 999	13 (0.5)	—	18 (0.3)	—
1 000 and above	9	—	11	—
Total number of fires	1 860	18	4 369	127
λ	0.668 6	0.698 7	0.714 6	0.871 1
M (m^2)	0.774 9	0.159 9	0.464 7	0.264 6

NOTE Figures within brackets are percentages of fires exceeding the upper limits of damage ranges in the first column.

[a] Figures relate to fires in which sprinklers operated Source: Home Office fire statistics for 1979 and 1984 to 1987.

Table A.7 — Retail premises: frequency distribution of area damage (in terms of number of fires)

Area damage m^2	Assembly areas		Storage areas		Other areas	
	Without sprinklers	With[a] sprinklers	Without sprinklers	With[a] sprinklers	Without sprinklers	With[a] sprinklers
1 and under	4 197 (48.9)	154 (31.3)	1 679 (67.4)	261 (26.3)	4 066 (43.5)	135 (26.2)
2 – 4	1 987 (24.7)	37 (14.7)	1 306 (42.0)	51 (11.9)	1 638 (20.7)	22 (14.2)
5 – 9	619 (17.1)	9 (10.7)	722 (27.9)	22 (5.7)	490 (13.9)	8 (9.8)
10 – 19	463 (11.5)	13 (4.9)	543 (17.4)	11 (2.5)	404 (8.3)	9 (4.9)
20 – 49	430 (6.2)	6 (2.2)	476 (8.1)	6 (0.9)	323 (3.8)	5 (2.2)
50 – 99	221 (3.5)	4 (0.5)	177 (4.7)	1 (0.6)	128 (2.0)	2 (1.1)
100 – 199	127 (2.0)	—	116 (2.4)	—	68 (1.1)	2
200 – 499	100 (0.8)	—	74 (1.0)	2	57 (0.3)	—
500 – 999	29 (0.4)	—	24 (0.5)	—	15 (0.1)	—
1 000 and above	34	—	27	—	5	—
Total number of fires	8 207	224	5 144	354	7 194	183
λ	0.694 7	0.864 4	0.730 4	0.885 8	0.893 6	0.699 1
M (m^2)	0.596 8	0.415 6	1.158 3	0.285 2	0.794 2	0.214 2

NOTE Figures within brackets are percentages of fires exceeding upper limits of damage ranges in the first column.

[a] Figures relate to fires in which sprinklers operated Source: Home Office fire statistics for 1979 and 1984 to 1987.

Table A.8 — Hotels: frequency distribution of damage (in terms of number of fires)

Area damage m²	Assembly areas without sprinklers	Bedrooms without sprinklers	Storage and other areas	
			Without sprinklers	With sprinklers[a]
1 and under	321 (38.0)	643 (46.6)	2 789 (27.0)	31 (11.4)
2 – 4	76 (23.4)	324 (19.8)	459 (15.0)	2 (5.7)
5 – 9	31 (17.4)	94 (12.0)	162 (10.8)	1 (2.9)
10 – 19	17 (14.0)	59 (7.1)	136 (7.2)	1
20 – 49	30 (8.3)	54 (2.6)	124 (4.0)	—
50 – 99	10 (6.4)	18 (1.1)	67 (2.2)	—
100 – 199	13 (3.9)	4 (0.8)	31 (1.4)	—
200 – 499	13 (1.4)	2 (0.6)	31 (0.6)	—
500 – 999	6 (0.2)	7	8 (0.4)	—
1 000 and above	1	—	14	—
Total number of fires	518	1 205	3 821	35
λ	0.660 3	0.773 4	0.639 2	0.631 0
M (m²)	0.590 7	0.454 3	0.217 6	0.032 2

NOTE Figures within brackets are percentages of fires exceeding upper limits of damage ranges in the first column.

[a] Figures relate to fires in which sprinklers operated. Source: Home Office fire statistics for 1979 and 1984 to 1987.

Table A.9 — Probable damage in a fire: parameters of equation 2

Occupancy	Parameters	
	c	d
Industrial buildings		
Food, drink and tobacco	2.7	0.45
Chemical and allied	11.8	0.12
Mechanical engineering and other metal goods	1.5	0.43
Electrical engineering	18.5	0.17
Vehicles	0.80	0.58
Textiles	2.6	0.39
Timber, Furniture	24.2	0.21
Paper, printing and publishing	6.7	0.36
Other manufacturing	8.7	0.38
All manufacturing industry	2.25	0.45
Other occupancies		
Storage	3.5	0.52
Shops	0.95	0.50
Offices	15.0	0.00
Hotels, etc.	5.4	0.22
Hospitals	5.0	0.00
Schools	2.8	0.37

Table A.10 — Spinning and doubling industry: places of origin of fires and sources of ignition

Sources of ignition	Production and maintenance		Assembly	Storage areas			Miscellaneous areas	Total
	Dust extractor (not cyclone)	Other areas		Store/stock room	Loading bay packing dept.	Other areas		
A Industrial appliances								
i) Electrical dust extractor	14	3	—	—	—	—	—	17
Other fuels	12	—	—	—	—	—	—	12
ii) Other electrical appliances	6	111	—	—	—	—	—	117
Other fuels	—	22	—	1	—	—	2	25
B Welding and cutting equipment	—	10	—	6	—	—	7	23
C Motor (not part of other appliances)	—	7	—	—	—	—	—	7
D Wire and cable	1	12	—	—	—	—	2	15
E Mechanical heat or electrical sparks	27	194	—	—	—	—	—	221
Others	52	387	—	2	—	—	—	441
F Malicious or intentional ignition	—	9	—	3	—	—	3	15
Doubtful	—	13	—	7	—	—	—	20
G Smoking materials	2	29	1	15	1	—	7	55
H Children with fire e.g. matches	3	4	—	12	2	4	5	30
J Others	4	29	2	3	2	—	12	52
Unknown	11	78	—	14	—	—	9	112
TOTAL	132	908	3	63	5	4	47	1 162

Table A.11 — Extent of fire spread and average area damaged (Textile industry, U.K.)

Extent of spread	Sprinklered[a]			Non-sprinklered		
	Average area damaged m^2	Percentage of fires	Time min	Average area damaged m^2	Percentage of fires	Time min
Confined to item first ignited	4.43	72	0	4.43	49	0
Spread beyond item but confined to room of fire origin						
i) contents only	11.82	19	8.4	15.04	23	6.2
ii) structure involved	75.07	7	24.2	197.41	21	19.4
Spread beyond room	1 000.00	2		2 000.00	7	
Average	30.69	100		187.08	100	

[a] System operated.

Table A.12 — Average loss per fire at 1966 prices (£'000)

Occupancy	Sprinklered single storey	Sprinklered multi storey	Non-sprinklered single storey	Non-sprinklered multi storey
Textiles	2.9	3.5	6.6	25.2
Timber and furniture	1.2	3.2	2.4	6.5
Paper, printing and publishing	5.2	5.0	7.1	16.2
Chemical and allied	3.6	4.3	4.3	8.2
Wholesale distributive trades	—	4.7	3.8	9.4
Retail distributive trades	—	1.4	0.4	2.4

Table A.13 — Discovery time and fatal casualties

Discovery time (Δt_{det}) and occupancy type	Number of deaths	Number of fires	Fatality rate per fire, P_d
Single occupancy dwellings			
Discovered at ignition	445	76 243	0.005 837
Discovered under 5 min after ignition	686	212 519	0.003 228
Discovered between 5 and 30 min after ignition	2 156	141 462	0.015 241
Discovered more than 30 min after ignition	2 766	53 677	0.051 530
Total	6 053	483 901	0.012 509
Multiple occupancy dwellings			
Discovered at ignition	204	27 805	0.007 337
Discovered under 5 min after ignition	334	123 648	0.002 701
Discovered between 5 and 30 min after ignition	1 281	110 078	0.011 637
Discovered more than 30 min after ignition	1 703	28 125	0.060 551
Total	3 522	289 656	0.012 159
Single occupancy dwelling δ = 0.000 801 K = 0.001 626 Multiple occupancy dwelling δ = 0.000 596 K = 0.001 509 Source: Fire Statistics United Kingdom 1978 – 1991.			

Table A.14 — Frequency distribution of number of deaths

Number of deaths	Single occupancy dwellings		Multiple occupancy dwellings	
	Number of fires	Percentage of fires	Number of fires	Percentage of fires
0	491 532	98.915 1	292 747	98.901 4
1	4 794	0.964 8	3 002	1.014 2
2	421	0.084 7	194	0.065 5
3	110	0.022 1	40	0.013 5
4	45	0.009 1	10	0.003 4
5 or more	21	0.004 2	6	0.002 0
Total	496 923	100.000 0	295 999	100.000 0

Table A.15 — Probability of flashover

Occupancy type area of fire origin	Sprinklered building			Unsprinklered building			Parameter
	P_{F1}	P_{F2}	Prob. of flashover	P_{F1}	P_{F2}	Prob. of flashover	ω
Textile industry							
Production	0.28	0.36	0.10	0.57	0.44	0.25	2.50
Storage	—	—	0.28	0.81	0.78	0.63	2.25
Other areas	0.34	0.35	0.12	0.58	0.57	0.33	2.75
Chemical etc. industry							
Production	0.20	0.20	0.04	0.61	0.41	0.25	6.25
Storage	0.37	0.41	0.15	0.81	0.67	0.54	3.60
Other areas	0.29	0.31	0.09	0.61	0.61	0.37	4.11
Paper etc. industry							
Production	0.23	0.26	0.06	0.49	0.39	0.19	3.17
Storage	0.29	0.34	0.10	0.78	0.72	0.56	5.60
Other areas	0.28	0.36	0.10	0.73	0.71	0.52	5.20
Timber etc. industry							
Production	0.36	0.39	0.14	0.80	0.69	0.55	3.93
Storage	0.38	0.42	0.16	0.83	0.83	0.70	4.38
Other areas	0.30	0.40	0.12	0.76	0.76	0.58	4.83
Retail trade							
Assembly	0.28	0.32	0.09	0.67	0.60	0.40	4.44
Storage	0.24	0.25	0.03	0.82	0.76	0.62	10.33
Other areas	0.27	0.41	0.11	0.71	0.68	0.48	4.36
Wholesale trade							
All areas	0.26	0.42	0.11	0.85	0.75	0.64	5.82
Office premises							
Rooms used as offices	0.21	0.43	0.09	0.78	0.71	0.55	—
Other areas				0.65	0.65	0.42	4.67

Table A.16 — Building characteristics

Occupancy	No. of fires (1993)	No. of fatalities (1993)	Non-fatal injuries (1993)	No. of employee (1995)	No. of occupants	Fires no ext. by FB (%) (1993)	Fires ext. by FB (%) (1993)
Single dwelling	32 843	33	5 954	N/A	5 643 000	36.19	63.81
Multiple dwelling	27 229	189	5 199	N/A	Unknown	35.96	64.04
Hotels, etc.[a]	895	5	93	211 000	178 174	35.41	64.59
Banking insurance, etc.	1 038	0	44	2 763 000	—	23.21	76.79
Public admin, defence	1 404	2	192	1 344 000	—	57.62	42.38
Schools	1 953	0	43	1 341 000	9 162 100	21.45	78.55
Further education	432	0	10	410 000	435 617	37.96	62.04
NHS[b]	1 033	0	43	949 470	325 888	69.21	13.93

[a] Figures exclude N. Ireland.
[b] Figures taken from Jan - Dec 1995.

Table A.17 — Reliability data

General fire data			Reference
Probability of fire occurring and not being reported to the local authority fire service (UK)	Industrial	0.5	[63]
	Commercial	0.8	[64]
	Dwellings	0.8	[65,66]
	Average	0.8	[63,64,65,66]
Frequency of reported fires per occupancy per year	Industrial	4.4×10^{-2}	—
	Storage	1.2×10^{-2}	—
	Shops	8.4×10^{-3}	—
	Offices	5.7×10^{-3}	—
	Hotels, etc.	3.7×10^{-2}	—
	Dwellings	2.7×10^{-3}	—
Probability of a reported fire causing property loss in excess of £1M (1992 prices)	Industrial	0.004	[67]
	Other commercial	0.001	[67]
	Educational	0.003	[67]
Typical probability of fire spread for reported fires	Beyond room of origin	0.1	[68]
	To other buildings	0.2	[68]
Fire alarm and detection systems			
Improvement in probability of early detection in buildings with AFDA	General value	0.5 to 0.6	—
Reliability of alarm box, wiring and sounders	General value	0.95 to 1	—
Reliability of detectors	Commercial smoke	0.9	—
	Domestic smoke	0.75	—
	Aspirating smoke	0.9	—
	Heat	0.9	—
	Flame	0.5	—
Automatic fire suppression systems			
Overall reduction in loss due to provision of sprinklers	General value	50 %	—
Probability of successful sprinkler operation	Maximum	0.95	—
	General:		—
	Property protection	0.9	—
	Life safety	0.8	—
	Minimum	0.75	—
Probability of successful operation of other AFS systems	General value	0.9	—
Smoke control systems (mechanical and natural)			
Probability of system operating as designed, on demand	General value	0.9	—
Passive fire systems			
Probability that fire-resisting structures will achieve at least 75 % of the designated fire resistance standard	Masonry walls	0.75	—
	Partition walls	0.65	—
	Glazing	0.4	—
	Suspended ceilings	0.25	—
Probability of fire doors being blocked open	General value	0.3	—
Probability of self-closing doors failing to close correctly on demand (excluding those blocked open)	General value	0.2	—

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