

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

Part 7: Probabilistic risk assessment

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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.

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This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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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.

Application of fire safety engineering principles to the design of buildings — Code of Practice
BS 7974
(Framework Document Philosophy)

Published Documents
(Handbooks providing supporting information and guidance)

PD 7974-0	PD 7974-1 (Sub-system 1)	PD 7974-2 (Sub-system 2)	PD 7974-3 (Sub-system 3)	PD 7974-4 (Sub-system 4)	PD 7974-5 (Sub-system 5)	PD 7974-6 (Sub-system 6)	PD 7974-7
Guide to design framework and fire safety engineering procedures	Initiation and development at fire within the enclosure of origin	Spread of smoke and toxic gases within and beyond the enclosure origin	Structural response and fire spread beyond the enclosure of origin	Detection of fire and activation of fire protection systems	Fire service intervention	Evacuation	Probabilistic risk assessment
Design approach QDR Comparison with criteria Reporting and presentation	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References	Design approach Acceptance criteria Analysis Data References

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
$G(A_d)$	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)
$\dot{m}_i$	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
$P_{b(ns)}$	Probability of compartment failure, given occurrence of flashover, for a unsprinklered compartment
$P_{b(s)}$	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
$P_{f(ns)}$	Probability of flashover in unsprinklered compartment
$P_{f(s)}$	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

$P_k(\Delta t_{\text{exp}})$	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
$\tilde{P}_{\text{sp}}$	Logit of probability of fire spread beyond room of origin
P_{SV}	Probability of fire severity being less than or equal to S
$P(\phi, \Delta t_{\text{exp}})$	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)
$\dot{Q}_g$	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
$\alpha_{\Delta t, \text{esc}}$	Partial safety factor related to time for escape, Δt_{exp}
$\alpha_{\Delta t, \text{ten}}$	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
Γ	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

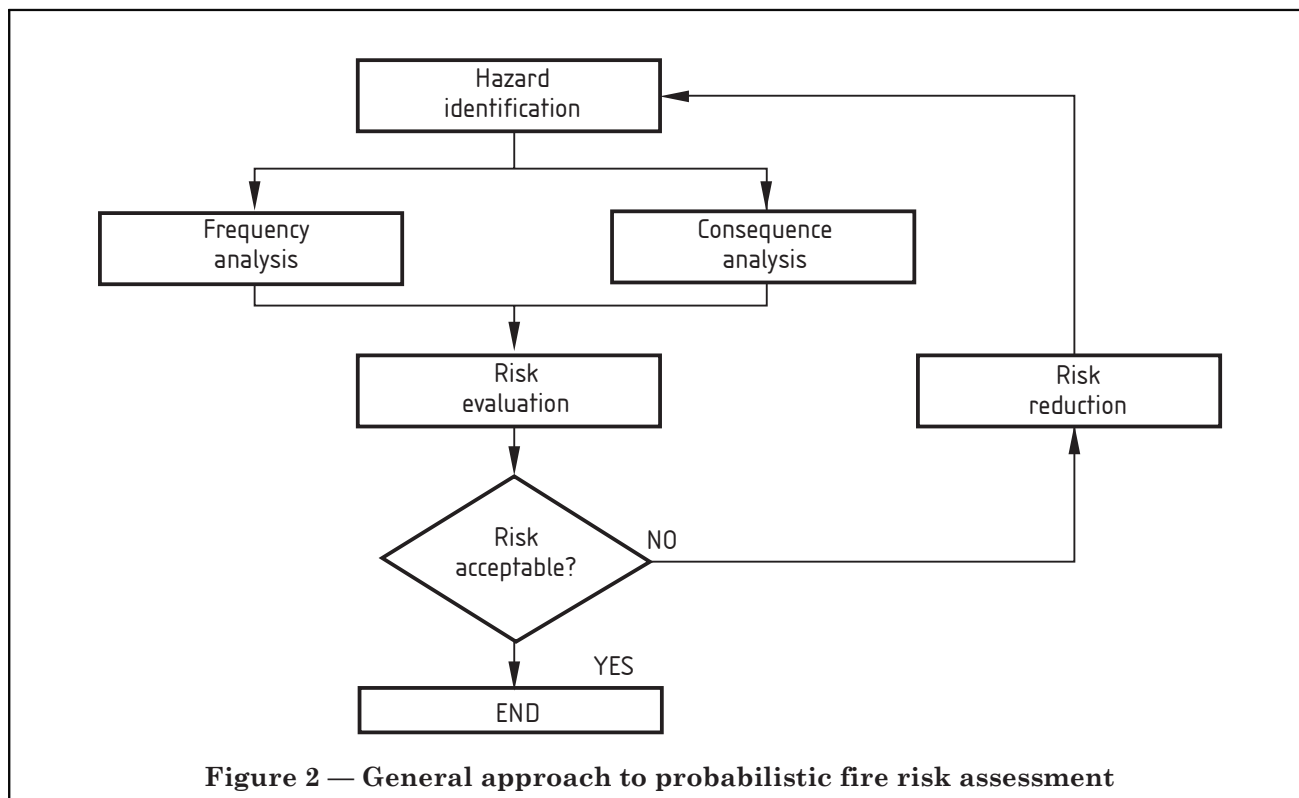
3 Design approach

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.



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 ninetyeth 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.

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

$$F_i = aA_b^b \quad (1)$$

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 m² is 0.28, the probability of damage exceeding 13.5 m² is 0.10 and the probability of damage exceeding 112.9 m² is 0.04. If the room is not provided with sprinklers, the probability of damage exceeding 4.8 m², 16.8 m² and 474.6 m² 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 m² 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:

$$A_d = cA_b^d \quad (2)$$

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 m² for an industrial building of total floor area 1 500 m² 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 m². The maximum damage (worst case) likely in this building in the event of a fire is 1 000 m², if sprinklered, and 2 000 m², 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 m². If a maximum damage of 2 300 m² is acceptable, a textile industry building can be permitted to have a maximum size of 10 000 m² if it has no sprinklers. If sprinklers are installed, the maximum building size can be relaxed to 33 000 m²; this permissible size may be reduced to 28 000 m² 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 m². Equation (2) and the maximum damage of 75.1 m² and 197.4 m² 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 m². According to this figure, a sprinklered compartment of 4 000 m² would be equivalent in damage to a non-sprinklered compartment of 500 m². The permissible size of a sprinklered compartment may be reduced to 3 000 m² to take account of the probability (0.1) of non-operation of the system in a fire developing beyond the “established burning” stage.

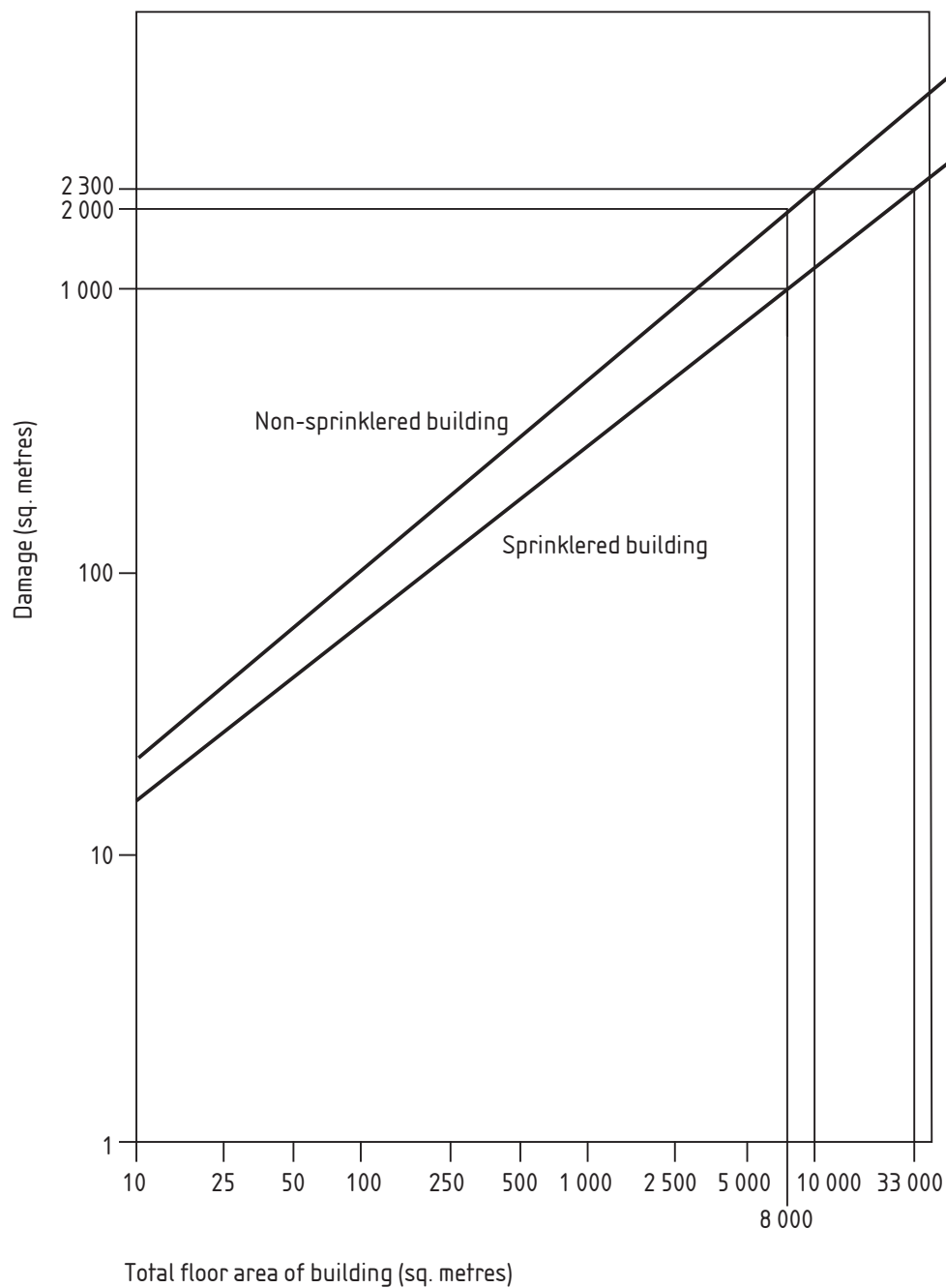


Figure 3 — Damage and building size, textile industry

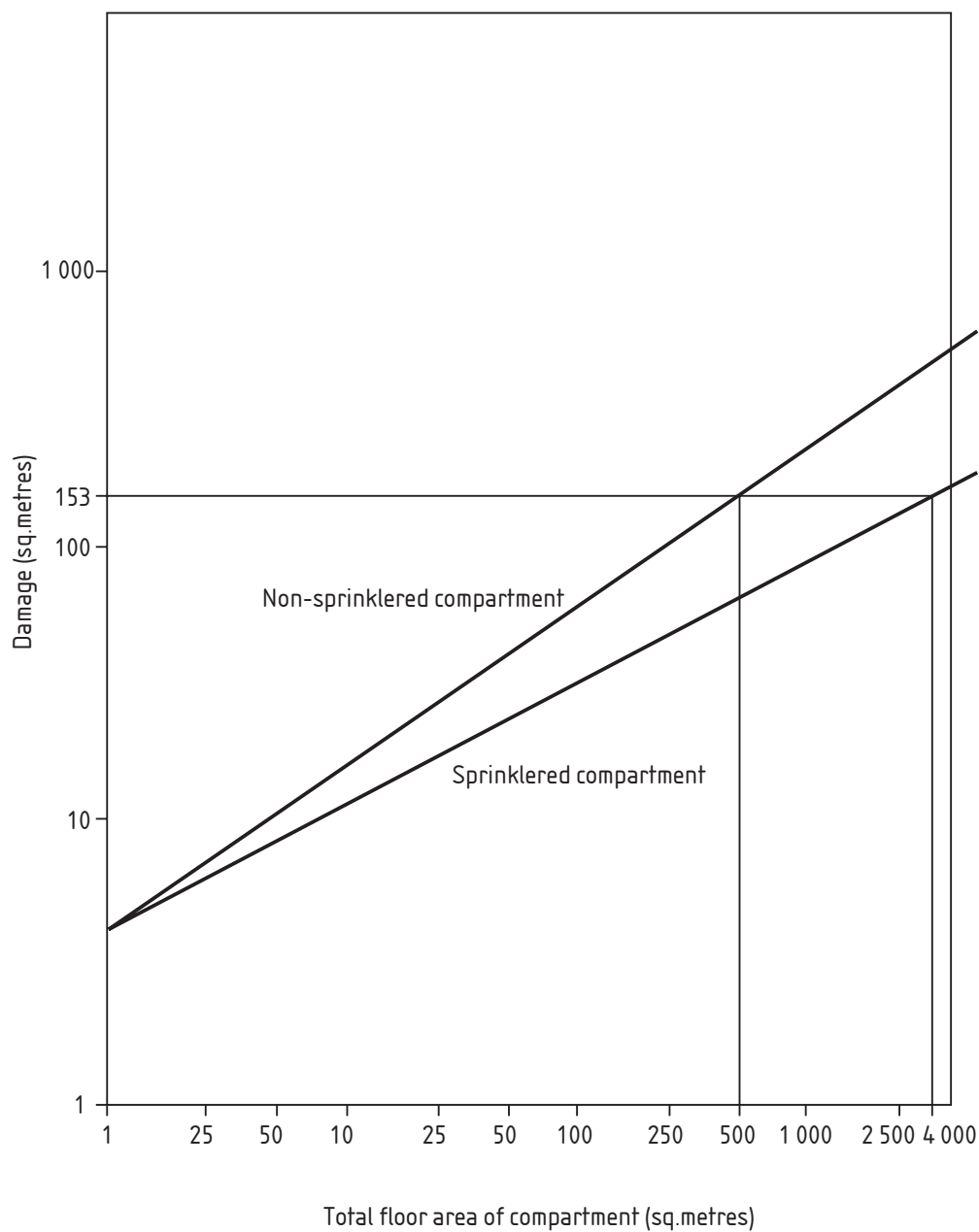


Figure 4 — Damage and compartment size, textile industry

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

$$c' = c \bar{V}^{-d}$$

Likewise, equation (1) may be transformed to:

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

where:

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

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.

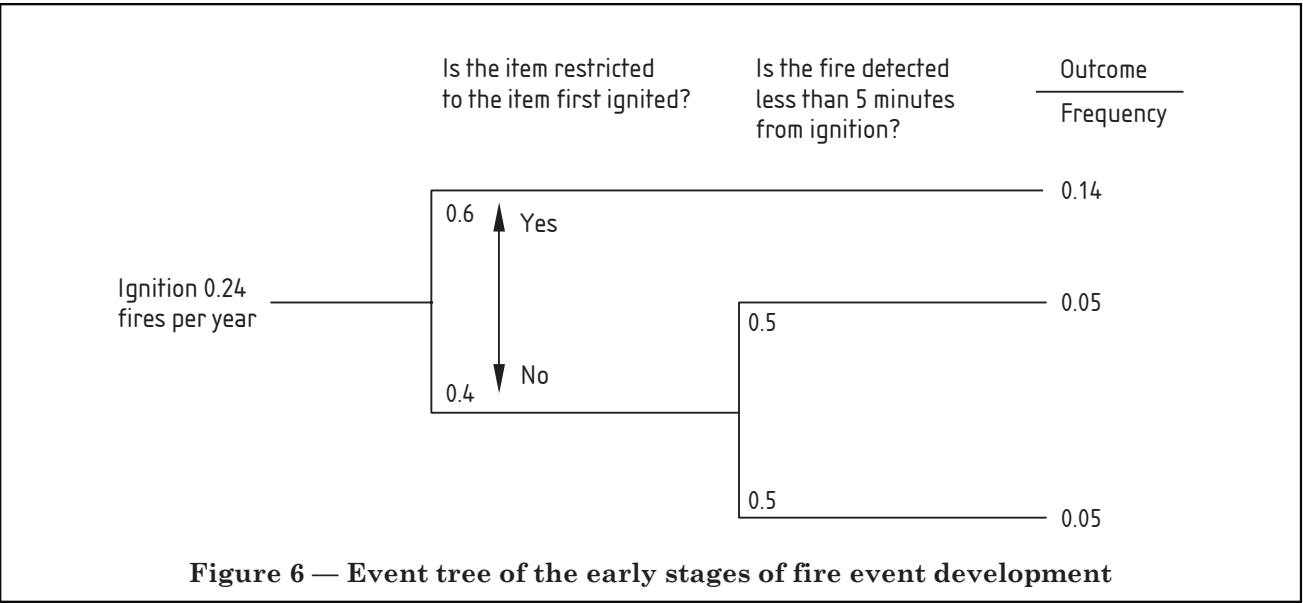
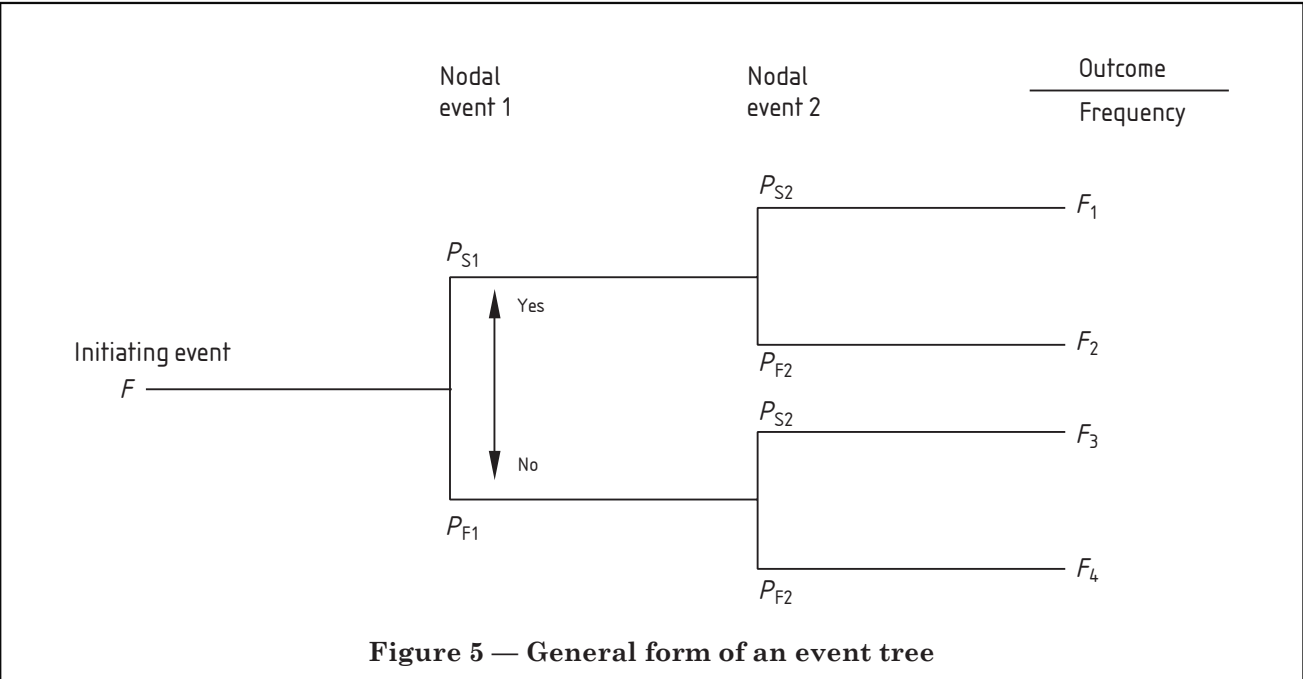
Event trees work forward from an initiating event (such as ignition) to generate branches defining events and paths resulting from secondary (or nodal events) to give a whole range of outcomes. Some of the outcomes can represent a very low risk event others can represent very high-risk events.

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.



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].